Ecological intensification pathways for vegetable production systems in south Uruguay

Mariana Scarlato García

Propositions

1 - Variability is essential for ecological intensification.
(this thesis)

2 - Contextual information is indispensable in functional biodiversity management studies.
(this thesis)

3 - Scientists should not have more than one scientific paper per year as first author.

4 - The importance of pre-analytical choices in science is underexposed.

5 - Talking about sustainability without addressing inequality is futile.

6 - Nature-based solutions should not only focus on relationships between humans and nature but also on those between humans.

Propositions belonging to the thesis, entitled

Ecological intensification strategies for vegetable production systems in south Uruguay

Mariana Scarlato García
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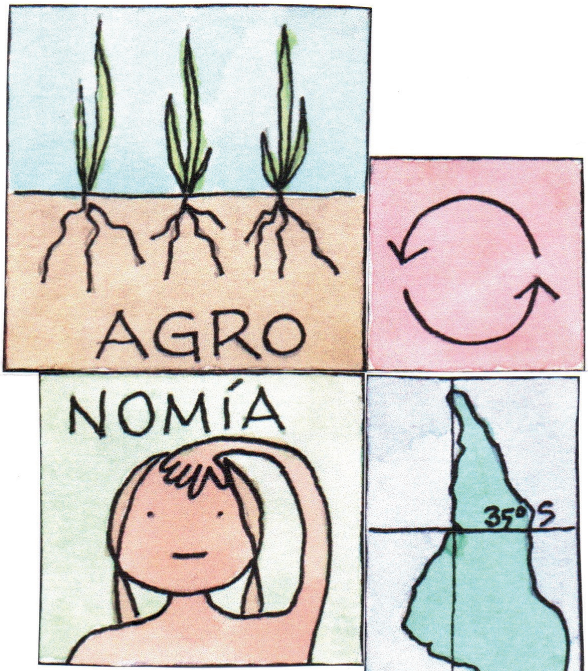
For my parents,
Margarita and Guillermo

Contents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Chapter 1

General introduction

1.1. Towards ecological intensification of farming systems

The challenge of feeding a growing world population has been the main argument for promoting the intensive industrial agriculture model. Regardless of the farm size, intensive industrial agriculture promotes the specialisation and consequent simplification of farming systems with a strong dependency on pesticides, fertilisers, and fossil energy inputs. Although this strategy has certainly increased agricultural production, it has contaminated and degraded the environment (soil, water, biodiversity) (Mahmood et al., 2016; Tilman et al., 2002; Tittonell et al., 2016; UNCTAD, 2017), generated negative impacts on human health (Mie et al., 2017; Pimentel, 1996; UNCTAD, 2017), and created dependency relations, marginalisation and deprivation in the rural and agrarian sector (Patel, 2009; van der Ploeg, 2008). Therefore, the intensive industrial agriculture model is under scrutiny, and its viability and desirability are increasingly questioned (IPBES, 2019; Tittonell et al., 2016; Tittonell, 2014).

The concerns about the impacts of the intensive industrial agriculture model have sparked interest in agroecology (Altieri, 2002) and ecological intensification (Tittonell, 2014) as more sustainable agricultural production models (FAO, 2015; UNCTAD, 2017). Ecological intensification focuses primarily on the biophysical and ecological dimension of agricultural systems (Tittonell, 2014), while agroecology, in addition to a way of farming, also encompasses the need for fair social relations, equity and power distribution, questions knowledge generation and technological dependency (Giraldo & Rosset, 2018; Wezel et al., 2009). At the production level both agroecology and ecological intensification aim to maintain or increase production by enhancing ecological processes, such as carbon, nutrient and water cycling, energy flows, and biotic regulation, reducing the use of external inputs and minimising negative impacts on the environment and society (Nicholls et al., 2016). These ecological processes function and respond to management in a context-specific way (e.g. depending on soil type, climate and production system). Therefore, agroecology and ecological intensification do not constitute unique and homogeneous technological packages but are based on guiding principles for system design and management revolving around recycling, efficiency, diversity, regulation, and synergies promoting ecological processes (Tittonell, 2015).

Guiding principles for designing and managing agroecological systems are crucial, particularly those aimed at enhancing and managing soil quality and biodiversity over time and space (Nicholls et al., 2016). Improving the physical, chemical, and biological quality of soils provides better conditions for plant growth, carbon sequestration, water storage, disease suppression and fostering beneficial associations of microorganisms with plant roots (Altieri et al., 2012; Hoffland et al., 2020; Nicholls et al., 2016). In addition, systems with greater plant diversity are more efficient in solar energy capture and carbon sequestration, water, and nutrient use, and support greater above and belowground biodiversity, which supports natural population regulation mechanisms (Jones et al., 2023; Nicholls et al., 2016). However, while there is an increasing interest in agroecology, the principles are often too general to be directly translated into concrete designs and context-specific management practices (Altieri, 2002; Duru et al., 2015; Nicholls & Altieri, 2018). Further research is therefore urgently needed to develop and operationalise agroecology in each specific situation in conjunction with a methodological approach to foster co-learning between farmers and researchers.

The transition process from the intensive industrial agriculture model towards ecologically intensive or agroecological systems needs to be specifically defined for each country, region, or farm. For example, situations with high productivity and high input use may require an "ecologisation" strategy to reduce inputs while maintaining productivity. In contrast, for situations with low productivity and low input use, an "ecological intensification" strategy may be more suitable as an affordable and sustainable way to increase productivity with limited dependence on external inputs (Tittonell et al., 2016). But how to achieve these different desirable pathways? The transition process can be conceptualised at different levels, which are not necessarily sequential (Gliessman et al., 2007; Hill & MacRae, 1992). Level 1 consists of increasing conventional input use efficiency. Level 2 involves the substitution of inputs or practices for more sustainable alternatives. Level 3 entails redesigning the production system based on ecological processes (Hill & MacRae, 1992), and level 4, the transition towards a change in ethics and values (Gliessman et al., 2007).

In recent years, input substitution tools have been developed and promoted (e.g. Bajsa & Fabiano, 2023; van Lenteren et al., 2020; van Lenteren et al., 2018). However, the substitution strategies, when used as isolated tools without addressing the root causes of sustainability problems, maintain the need for repeated use of externally derived curative solutions and inputs (Hill & MacRae, 1992; Rosset et al., 1997). Reaching higher degrees of farm system sustainability through ecological intensification cannot be achieved by adjusting input use or some management practices but requires redesigning the farming system as a whole (Dogliotti et al., 2014; Nicholls & Altieri, 2018). Such redesign should be case-specific, aiming to make the farm system more ecologically and economically diverse, resource-self-reliant and self-regulating (Hill & MacRae, 1992).

Agroecological redesign implies changing management practices and the way of observing, evaluating, and making decisions about the production system (Doré et al., 2011; Madsen & Wezel, 2020; Tittonell, 2019). These changes require generating "usable" or "actionable knowledge" (context-specific knowledge that assists decision making and consequent actions of stakeholder) while generating interest and commitment that enables learning (Clark et al., 2016; Geertsema et al., 2016; Rossing et al., 2021). Agroecological transitions require a profound understanding of the main ecological processes and their interconnectedness that modulate the functioning of the agroecosystem by all actors involved (Prost et al., 2023). They also require building a shared vision of the structure and functioning of current systems and what the desirable situation would look like to define how to move from the former to the latter (Darnhofer, 2015; Hoffecker, 2021; Krzywoszynska, 2019). Thus, supporting agroecological transitions requires, apart from knowledge about relationships between ecology, ecosystem services and practices, learning-support tools that are used in an adaptive management perspective (Duru et al., 2015); "what to do" and "how to do it" are essential questions for practitioners as well as researchers.

Research in agroecology requires a systemic, transdisciplinary and participatory approach (Méndez et al., 2013), and to work with a medium and long-term perspective, building collaborative platforms that allow experimentation, collective learning and the generation of alternatives on a local scale (Dogliotti et al., 2014; Sachet et al., 2021). The systemic nature of the processes that determine the functioning of production systems, and the practices for their management, requires a holistic analysis framework to understand the underlying ecological processes (Nicholls & Altieri, 2018). Such a framework should consider the interaction with farm resources, their management, and the performance of production systems while considering the sociocultural, technical and economic dimensions of change (Martin et al., 2018; Savary et al., 2006). Co-innovation has been a successful approach in Latin America and Europe to improve farm sustainability by building conceptually on three pillars: complex adaptive systems thinking, social learning, and monitoring and evaluation (Rossing et al., 2021). While in Europe, the approach evolved to a complexity-aware project governance method (Douthwaite & Hoffecker, 2017), co-innovation in Latin America maintained its basis in work at the farm level through a step-by-step methodological approach, including characterisation, diagnosis, redesign, implementation-monitoring and evaluation (Dogliotti et al., 2014).

1.2. The case of vegetable production in Uruguay

Vegetable production in Uruguay has social, economic and environmental relevance. It involves around 2,600 farms, cultivating an area of 14,000 ha of vegetable crops (DIEA-MGAP, 2022). About 80% of those farms and 70% of the vegetable crop area are concentrated in the south of the country in a radius of 70 km around the capital Montevideo (Ackermann & Díaz, 2016). Despite occupying only 0.1% of the country's cultivated land, vegetable production comprises 6% of the farms and 7% of the permanent workers in agriculture (DIEA-MGAP, 2011). The estimated yearly production of vegetables is around 290,000 Mg (DIEA-MGAP, 2022), and the gross product is around 340 million dollars, accounting for 5.5% of the country's agricultural gross product (Ackermann & Díaz, 2016).

Potato, onion, pumpkin and sweet potato are the most important open-field crops in Uruguay, encompassing around 80% of the crop area, 56% of the production, and 65% of the farmers with open-field production (DIEA-MGAP, 2022. Fig. 1.1-A, B). Tomato and sweet pepper are the most important greenhouse crops encompassing around 51% of the greenhouse area, 75% of the production, and 71% of the farmers with greenhouse production (DIEA-MGAP, 2022. Fig. 1.1-C, D). Approximately 90% of vegetable production is sold fresh on local markets, while vegetable imports account for less than 10% of the total market in Uruguay (Ackermann & Díaz, 2016). Around 85% of horticultural farms are family farms (Ackermann & Díaz, 2016). Therefore, besides its importance in food production, vegetable production has an important cultural and social role (Zoppolo & Colnago, 2021).

In the last decades, the Uruguayan horticultural sector has experienced a reduction of about 50% in the number of farms, which was accompanied by a doubling of the production volume per farm (Ackermann & Díaz, 2016; DIEA-MGAP, 2011, 2022). In conjunction with this process, to maintain the family income, vegetable farms followed a strategy of product specialisation, reducing the number of crops and increasing their area, and producing based on the introduction of new high-yielding varieties and hybrids, an increase of agrochemical inputs, mechanisation, irrigation, and increasing soil tillage frequency and intensity (Dogliotti et al., 2014). This strategy has contributed to soil erosion and soil fertility decline (Alliaume et al., 2013; Dogliotti et al., 2014. Fig. 1.1-E, F), water pollution (Barreto et al., 2017; Rodríguez-Bolaña et al., 2023), biodiversity loss (MVOTMA, 2016), and human health hazards (Burger & Pose Román, 2012; Burger, 2013). Despite the high external input levels, there are yield gaps of around 50% (Berrueta et al., 2019; Colnago et al., 2023; Dogliotti et al., 2014; Dogliotti et al., 2021; Scarlato et al., 2017), resulting in low labour productivity and family income (Berrueta et al., 2019; Colnago & Dogliotti, 2020; Colnago et al., 2023; Dogliotti et al., 2014). Therefore, the intensive vegetable production model and the associated adverse side effects jeopardise the long-term sustainability of vegetable production, food security and food sovereignty in Uruguay.

The reasons for the low farmers' income and crop yield gaps are not related to input use or resource availability but to general farm organisation and management, e.g. sowing and planting dates and crop cycles length, soil management and quality, the timing of operations, high weed, pests and diseases pressure (Berrueta et al., 2019; Berrueta et al., 2021; Colnago et al., 2023; Dogliotti et al., 2014; Dogliotti et al., 2021; Scarlato et al., 2017). Adjustment of specific practices, such as through input substitution, will not solve the magnitude of sustainability problems faced by vegetable farms in south Uruguay.

Instead, improving vegetable farm sustainability involves strategic decisions on land use planning and resource allocation according to resource availability at the farm and regional level, where labour plays a central role (Colnago & Dogliotti, 2020; Dogliotti et al., 2014).

There are several successful examples of co-innovation approaches guided by ecological intensification principles that resulted in major improvements in the agronomic, economic, social and environmental performance of vegetable farms within their current

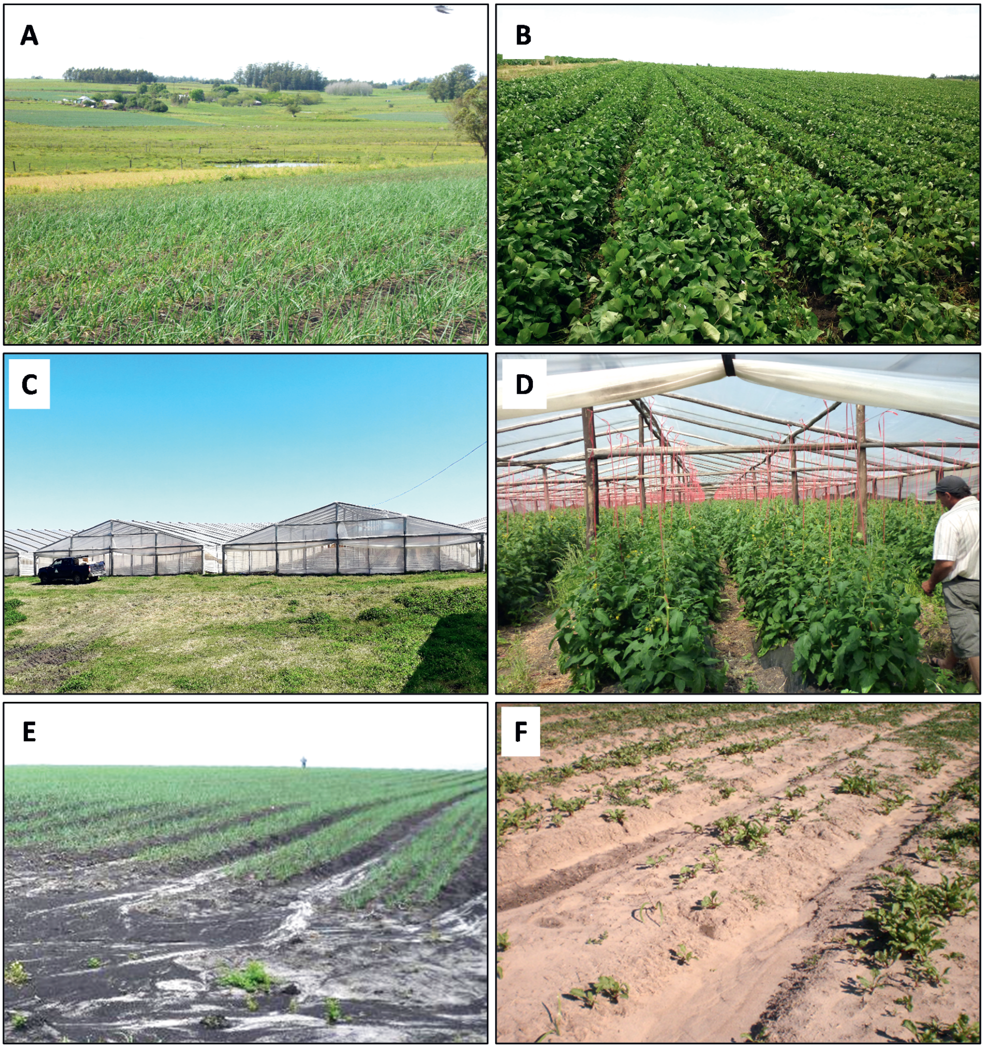


Fig. 1.1. Open-field winter onion crops (A) and sweet potato crop (B) in south Uruguay, typical greenhouse infrastructure and tomato greenhouse crop in south Uruguay (C, D), soil erosion during winter onion crop (E) and degraded soil under high intensive vegetable production evidencing low organic matter (F) frequently found in south Uruguay.

resource availability (Berrueta et al., 2021; Colnago et al., 2023; Dogliotti et al., 2014). Therefore, improving farm system sustainability requires thinking about the farm systematically while promoting social learning. Although co-innovation is certainly congruent with an agroecological perspective, previous co-innovation experiences in Uruguay did not explicitly attempt to work towards agroecological transitions. Most participant farmers were conventional farmers with no interest in switching to organic or agroecological farming. They wanted to improve profitability and labour productivity while reducing environmental impacts, particularly soil quality. To contribute to an agroecological transition, there is a need to adapt and improve the coinnovation approach to foster the learning of farmers, technical advisors, agronomy students and researchers, particularly focusing on farm system redesign based on enhancing ecological processes (Gliessman et al., 2007; Hill & MacRae, 1992).

Organic agroecology-based vegetable production has been practised in Uruguay since the end of the 1980s. Since the early 1990s, there have been agroecological and organic organisations, such as the first organic farmers' organisation established in 1996, which became the National Agroecology Network in 2015 (Gazzano & Gómez Perazzoli, 2017). The Uruguayan law defines organic and agroecological as synonyms, and until 2021, the Agroecology Network of Uruguay was the only certification body in Uruguay. In 2021, there were around 170 certified agroecological farms in Uruguay, most of them vegetable farms that together comprised 1200 ha of land. In recent years, the concerns expressed by various stakeholders and society in general (Blum et al., 2006; CEUTA, 2006; Chiappe et al., 2003; CNFR, 2016, 2017), along with the robust growth and influence of agroecology networks, have resulted in the enactment of a national law on agroecology. This law recognises the significance of promoting and developing production, distribution, and consumption systems based on agroecology to enhance food sovereignty and security, contribute to environmental preservation, and improve the quality of life for the population (Poder Legislativo ROU, 2018). In 2021, the National Agroecology Plan was approved, in which the generation of actionable knowledge was identified as a constraint at the national level and specifically defined as one of the strategic lines of policy (CHPNA, 2021).

1.3. Study objectives

The overarching objective of this study was to generate actionable knowledge to support the ecological intensification of vegetable production systems in Uruguay. I approached this main objective through four specific research questions associated with four specific objectives (Fig. 1):

Research questions:

- What is the relationship between pesticide and fertiliser use and yield in vegetable crops in Uruguay? Are these crop-level relationships related to farm characteristics?
- What is the feasibility and potential of agroecological practices to improve farm performance?
    - How does introducing flowering plant species in open greenhouses influence arthropod communities, pest and natural enemy abundances and tomato yield?
    - How does applying green manure and reduced tillage combined with using native effective microorganisms influence the performance of organic onion crop systems?
- How can the co-innovation approach from Uruguay be adapted to reflect an agroecological perspective?

Specific research objectives:

- Evaluate the efficacy of agrochemical input use in enhancing vegetable yields in main vegetable crops in Uruguay and identify opportunities for ecological intensification in a context-specific manner (Chapter 2).
- Assess the influence of flowering plants in organically and conventionally managed greenhouse tomato crops on the abundance of pests, natural enemies and pollinators, and crop performance (Chapter 3).
- Assess the effects of the tillage system (reduced tillage vs. conventional tillage) and the application of native effective microorganisms (presence vs. absence) on weed densities, N dynamics, and onion productivity after a summer cover crop, without using herbicides or synthetic fertilisers (Chapter 4).
- Develop and apply a framework to engage participants in a profound diagnosis of farm systems to support agroecological transitions during a co-innovation process (Chapter 5).

The thesis was part of the overarching project "Horticultural food systems based on ecologically intensive production and socio-economically sustainable value chains in the transition economies Chile and Uruguay" (HortEco), aiming to study, support and share knowledge on how to organise production and marketing of high-value, low-or-no-pesticide vegetables in Chile and Uruguay (Rossing et al., 2020). This project focused on the food system level and had three main components: i. Ecologically intensive horticultural production; ii. Socio-economically sustainable horizontal and vertical value chain collaboration models; and iii. How change agents in the innovation system can support the transition to sustainable horticultural farms and markets.

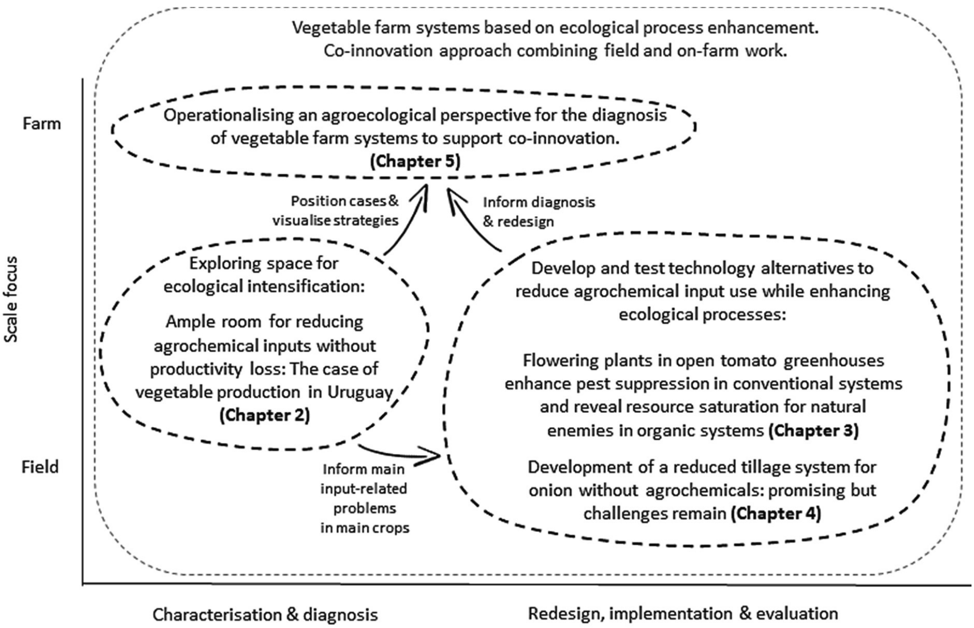


Fig. 1.2. Graphical overview of the thesis outline. Chapters are positioned based on the main spatial scale of application (from field to farm level) and on the main phase in the co-innovation process (characterisation & diagnosis of current practices or redesign, implementation & evaluation).

1.4. Outline of the thesis

The outline of this thesis is graphically represented in Fig. 1.2. In Chapter 2, I start by analysing the current situation regarding pesticide and fertiliser use and their relation with the yields of main vegetable crops. I studied crop yield and input use in tomato, onion, sweet potato, and strawberry at 82 farms and 428 fields collected between 2012 and 2017 in the south of Uruguay. The analysis gives insight into the heterogeneity of crop production systems. It highlights the need for different transition strategies (e.g. maintaining production while reducing inputs, increasing production while maintaining inputs, or increasing production while reducing inputs) based on a specific diagnosis of each situation.

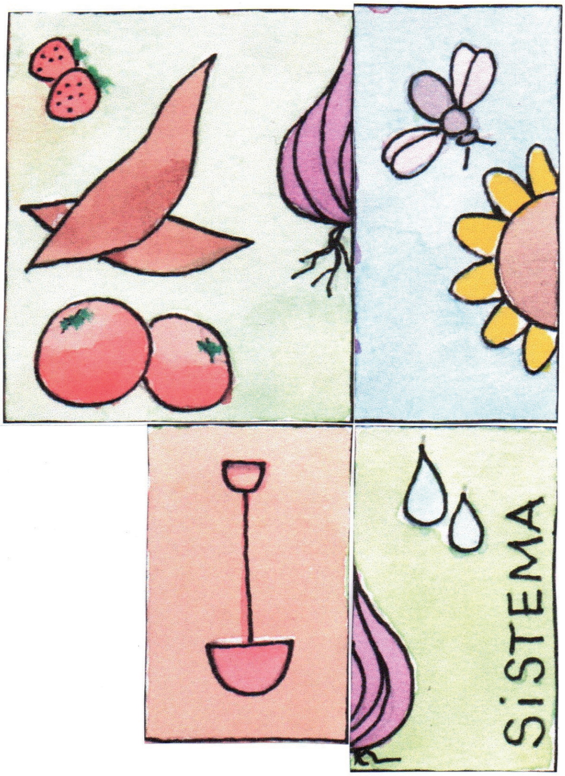
In Chapter 3, I studied the effect of introducing flower islands in organically and conventionally managed greenhouse tomato on the abundance of pests, natural enemies and pollinators, and tomato crop performance (Fig. 1.3-A, B). The study encompassed a two-year experiment in eight commercial farms in south Uruguay. The study demonstrates that providing floral resources in conventionally managed greenhouses can help to reduce pest abundance and, thus, pesticide use, but a more holistic approach is required to effectively maintain pests at low densities. The study highlights the potential of agroecological and organic management to reduce the reliance on synthetic pesticides without yield reduction, while evidenced the context-dependency of the effect of habitat manipulation practices.

Fig. 1.3. On-farm experimentation introducing flower islands in greenhouse tomato (A) and annual workshops with farmers and technical advisors (B) reported in Chapter 3. On-farm and experimental station development of cover crop and reduced tillage technology in onion without agrochemicals (C) and regular workshops and field-days for monitoring the experiments (D) reported in Chapter 4. Co-innovation work with five case study farms developing regular visits (E) and strategic discussion meetings (F) presented in Chapter 5.

In Chapter 4, I present the results of two years of experimentation at an experimental station and at two commercial farms with a reduced tillage technology for (winter) onion production based on a summer cover crop without using herbicides or synthetic fertilisers (Fig. 1.3-C, D). The results show that reduced tillage technology benefits soil health. However, further research, particularly focusing on weed suppression and increasing N availability, is needed to make it feasible under organic management.

In Chapter 5, I present a new diagnosis framework (MEDITAE) based on an agroecological perspective and the results of its application during a co-innovation process in five farms in south Uruguay (Fig. 1.3-E, F). I worked with farmers to characterise and diagnose the farms from an agroecological perspective and to design specific strategies to transition towards agroecology-based systems. In this context, the diagnosis framework was developed to engage participants in profoundly diagnosing their farm systems based on an agroecological perspective. The knowledge generated in Chapter 2 allowed positioning each farm in a regional perspective according to their agrochemical input use and yields and identify the scope of applying different transition strategies. Chapters 3 and 4 generated key practical and contextualised elements to inform farm redesign strategies focusing on diversity and soil health enhancement.

Throughout the chapters, a systemic, comprehensive and participatory approach was used, involving an interdisciplinary research team and generating space for discussion and interaction at the experimental station and on commercial farms working with farmers and technical advisors of the region (Fig. 1.3-B, D, F).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Chapter 2

Ample room for reducing agrochemical inputs without productivity loss: The case of vegetable production in Uruguay

This chapter has been published as:

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Abstract

Vegetables are commonly produced with high inputs of pesticides and fertilisers to boost production and meet cosmetic market standards. Yet, reports on the relationships between agrochemical inputs and crop productivity are scattered and an overview is missing. We assessed the relationship between pesticide and nutrient inputs and crop productivity for five vegetable crops in the south of Uruguay at field and farm level and explored the relation with farm resource endowment. We analysed crop yield and input use for tomato, onion, sweet potato, and strawberry with a dataset of 82 farms and 428 fields constructed between 2012 and 2017. Clear crop-specific patterns in pesticide and nutrient input levels were found, despite considerable variation across fields within the same crop. Strawberry and long cycle tomato had the greatest pesticide input regarding of the number of applications (20 and 18, respectively) and pesticide load (21 kg AI per ha). Cumulative nutrient inputs were greatest for long cycle tomato (1127 kg per ha). The relationships between inputs and yield were weak or non-significant, indicating inefficiencies and overuse of inputs, and there was no agronomical rationale for input use. We found substantial variation in management practices between fields and farms. In several cases, 21% of the fields and 17% of the farms producing onion, strawberry and tomato, attained relatively high yield levels with limited input levels. Yield and input use levels were not related to farm resource endowment. Our findings question the efficiency of the current high levels of pesticide and nutrient inputs in Uruguayan vegetable systems. The inputs may pose environmental and human health risks and in most cases did not increase yields. Learning from positive deviant farmers in combination with guided farm redesign, high-quality extension services, and use of context-specific knowledge and technologies may equip farmers to use more sustainable management practices.

Keywords: pesticide use, fertiliser use, crop yield, ecological intensification, agroecology, sustainability, inefficiencies

2.1. Introduction

Closing yield gaps while decreasing pesticide and fertiliser use is a major challenge for increasing the sustainability of production systems. Feeding a growing world population has been the main argument to promote a high-input industrial agriculture model, promising high crop yields. Although this strategy has boosted agricultural production, it has also negatively impacted human health and the environment (FAO, 2017; UNCTAD, 2017). For instance, the copious use of synthetic pesticides and artificial fertilisers has been found to contaminate and degrade the environment, pose human health hazards, and reduce the nutritional value of food (Mahmood et al., 2016; Tittonell et al., 2016; UNCTAD, 2017). Therefore, the industrial agriculture model is under scrutiny, and its viability and desirability are increasingly questioned (IPBES, 2019; Tittonell et al., 2016).

The industrial production model was introduced in Uruguay in the 1970s and, over time, became adopted in large-scale grain cropping (Baraibar Norberg, 2020; Ernst et al., 2016; Gazzano & Gómez Perazzoli, 2017) as well as in vegetable production. Even though vegetable production is concentrated on a relatively small fraction of Uruguay's agricultural area, it generates a substantial environmental impact. The high input of pesticides and synthetic fertilisers, among other management practices, in intensively managed vegetable farms has contributed to soil degradation (Alliaume et al., 2013; Dogliotti et al., 2014), water pollution (Barreto et al., 2017), biodiversity loss (MVOTMA, 2016), and human health hazards (Burger, 2013). These concerns have been expressed by researchers, farmers, consumers, and society in general (Blum et al., 2006; CEUTA, 2006; Chiappe et al., 2003; CNFR, 2016, 2017). Farmers have experienced a lack of yield responses despite high pesticide and synthetic fertiliser inputs, and resistance development in pest populations are common, triggering even greater pesticide use. Therefore, the industrial model of vegetable production and the associated adverse side effects jeopardise the long-term sustainability and productivity of vegetable production in Uruguay.

Concerns about the impacts of the industrial agriculture model have sparked interest in agroecology (Altieri, 2002) and ecological intensification (Tittonell, 2014) around the world (FAO, 2015; UNCTAD, 2017) and also in Uruguay (Poder Legislativo ROU, 2018). These approaches aim to maintain or increase production supported by ecological processes, reducing external input use, and minimising negative impacts on the environment and society. Agroecology is based on principles revolving around recycling, efficiency, diversity, regulation, and synergies promoting ecological processes (Tittonell, 2015). However, while there is increasing interest in agroecology, the principles and transition strategies are often too general to be directly translated into concrete designs and context-specific management practices (Altieri, 2002; Duru et al., 2015). Even in a particular context, specific pathways may be needed for different farming systems.

Reducing agrochemical inputs is a crucial agroecological principle (Altieri, 2002) often related with the first steps of agroecological transitions (Gliessman, 2015). Although vegetable production is usually associated with extensive use of pesticides and fertilisers to boost production and meet cosmetic market standards., there is considerable variability among farms in their management and in the associated input use efficiencies and crop performances (Abunyuwah et al., 2020; Ahovi et al., 2021; Lechenet et al., 2016). Farmers make their crop management decisions within the realm of their production situations, i.e., the physical, biological, technical, social, and economic context in which production occurs (Savary et al., 2006), and their decisions, in turn, shape their production situations. As a result, systems that evolved based on higher or lower input use may require different strategies for an agroecological transition. Farms with high productivity and high input use may follow an "ecologisation" strategy to reduce inputs while maintaining productivity. In contrast, farms with low productivity and low input use may follow an "ecological intensification" strategy as an affordable and sustainable way to increase productivity at the same or lower levels of inputs (Tittonell et al., 2016).

Insight into the relationships between the types and levels of inputs and the performance and productivity of farming systems is essential to inform the design of appropriate agroecological transition strategies and offers opportunities for learning from positive deviant situations (Herington & van de Fliert, 2018; Modernel et al., 2018; Steinke et al., 2019). However, these evaluations often lack underpinning by quantitative data on the use of agrochemical inputs (Larsen et al., 2019; but see Maeso et al., 2007; Blum et al., 2006) and their relation to crop productivity. Therefore, there is a need for a quantitative diagnosis of input use in vegetable production systems and a systemic overview of the relationship between agrochemical inputs and crop performance.

This study aims to evaluate the efficiency of agrochemical inputs in enhancing vegetable yields, to understand differences in terms of farm context, and to identify opportunities for ecologisation and ecological intensification in a context-specific manner. First, we assess the relationships between pesticide and nutrient inputs and crop productivity in greenhouse long cycle tomato, greenhouse short cycle tomato, onion, sweet potato, and strawberry, which are major vegetable crops in the south of Uruguay. Second, we identify groups of fields and farms with contrasting performances based on a conceptual model of ecological intensification (Tittonell et al., 2016) and considering the relationship between yield and pesticide and nutrient inputs. Third, we explore the association between farm input use and yield performance and farm resource endowment. Finally, we discuss the implications of our findings for environmental and health risks and ways to identify production systems that support an agroecological transition in a context-specific manner.

2.2. Materials and methods

2.2.1. Site description

The study was conducted in the south of Uruguay, where most of the vegetable production is concentrated. The area encompasses the departments of Canelones, San José, and Montevideo (34º21´S to 34º57´S – 55º40´W to 56º40‘W) and covers approximately 4800 km^2. The climate in the region is humid subtropical. The average mean temperature is 17 °C (minimum: 11 °C, maximum: 23 °C), with light frosts between the end of May and September. Mean annual precipitation is 1200 mm, evenly distributed throughout the year, but with significant variation between years (Castaño et al., 2011). Main soil types in the region are classified as Mollic Vertisols (Hypereutric), Luvic/Vertic Phaeozems (Pachic), and Luvic Phaeozems (Abruptic/Oxyaquic) (Alliaume et al., 2013).

There are around 2000 vegetable farmers in the study area producing 7300 ha of field-grown crops and 350 ha of greenhouse crops (DIEA-MGAP, 2017). Typical greenhouses are "open greenhouses" made with nylon and wooden posts, ranging between 380 and 1000 m^2. Tomato is the main greenhouse crop produced in short (200 days or less) or long (more than 200 days) cycles. The most common short cycle tomato crops are grown in spring-summer (transplanted in August-September and harvested until January) or in summer-autumn (transplanted in January-February and harvest until June-July). Most common long cycle crops are transplanted between August and October and harvested until April-June (Berrueta et al., 2019). Onion is the main open field crop. The most common varieties are sown in April and May, transplanted from July till September, and harvested in December and January (Gimenez et al., 2013). Sweet potato is a summer open field crop, typically transplanted from October till December and harvested between March and April (Gimenez et al., 2013). Strawberry is mainly planted in open fields at the end of February and March, with imported cold-stored plants. The harvest period depends on the variety and management, but for most crops, production peaks from September to December (Scarlato et al., 2017).

2.2.2. Analytical framework

In our analysis, we focused on two categories of agrochemical inputs: nutrients and pesticides. From a production ecology perspective, nutrient inputs are growth limiting factors as they contribute directly to crop growth and their input levels determine the attainable yield level (van Ittersum & Rabbinge, 1997; Zhengfei et al., 2006). On the other hand, pests and diseases pressure are growth reducing factors, which define the actual yield level (van Ittersum & Rabbinge, 1997). Pesticides can be considered as facilitating inputs as these indirectly affect yield by controlling or altering growth conditions (Zhengfei et al., 2006). Yet, pesticides are not directly involved in the basic biological processes of crop growth, such as nutrients are. We analysed the relationship between nutrients and pesticides inputs on yield separately and combined.

For our analysis, we adapted the concept of ecological intensification proposed by Tittonell et al. (2016) to represent the relationship between yield and pesticide and nutrient inputs in four quadrants (Fig. 2.1). The most favourable combination is high yields with low input levels. Intermediate combinations are high yields with high input levels, and low yields with low input levels, and the least desirable combination is low yields and high input use. This representation allows visualising pathways of change: "Ecologisation" as the process of maintaining yields while reducing input use, "Intensification" as the process of increasing yields with the same or lower input levels, or a combination of "Ecologisation" and "Intensification" (Fig. 2.1).

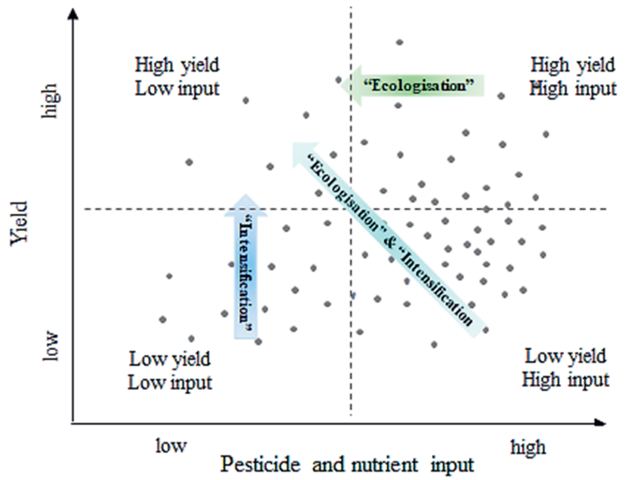

Fig. 2.1. Conceptual representation of pathways towards more sustainable commercial vegetable production systems in Uruguay. The four quadrants reflect combinations of yield and levels of pesticide and nutrient inputs (Tittonell et al., 2016). The two quadrants with high inputs represent an inefficient and polluting production situation. In contrast, the quadrant of low yields and low input levels constitute a situation where efficiency gains are possible. Different pathways of change can be identified: "Ecologisation" entails maintaining crop productivity while reducing inputs, and "Intensification" increasing productivity at sustainable input levels.

2.2.3. Data collection

We assembled a dataset on crop management and performance of long cycle tomato, short cycle tomato, onion, sweet potato, and strawberry crops by combining data from previous studies. The dataset contained data on 82 farms and 428 fields over the period 2012 to 2017 (Table 2.1). The farm sample was based on a typology of vegetable farms using the database of the Vegetable Growers Survey of the Ministry of Agriculture for south Uruguay and captured 5% of the farms producing onion and sweet potato and 10% of the farms producing strawberry and greenhouse tomato. For each crop, groups of farms were identified based on cluster analysis of crop yield, crop area and total crop production per farm. A representative sample of farms per crop was obtained by selecting farms proportional to the number of farms in each group and considering their geographic distribution with the assistance of the technical advisers of the region (Dogliotti et al., 2021; Scarlato et al., 2017). Self-subsistence farms and farms with more than 50% of off-farm income were excluded, resulting in a dataset of only commercial farms. According to Dogliotti et al. (2019) classification, the sample included 13% small family farms, 50% medium family farms, 20% specialised greenhouse farms, and 18% large family farms and medium entrepreneurs. For each crop, one to four fields were monitored per farm throughout two growing seasons.

The dataset contained information on crop yield, pests and diseases pressure, and crop management. Management variables were selected using a functional analysis based on production ecology theory (van Ittersum & Rabbinge, 1997), where growth factors affecting yield are classified as growth defining, growth limiting, or growth reducing. The associated management variables collated in the database were plant density, crop cycle length, and planting date (growth defining factors), soil organic matter, soil nutrient, nutrient inputs and water availability (growth limiting factors), and pest and disease incidence, pesticide inputs, frequency of the same crop in the preceding three to five years (growth reducing factors). The dataset also contained information on farm resource endowment (farm size, vegetable crop area, labour type and availability, mechanization level, and diversification of farm activities; Appendix A2.1).

Table 2.1. Overview of the crops, number of fields and farms, and assessment period in the dataset.

Crop	Number of fields	Number of farms*	Years evaluated	Reference
Onion	125	31 + 1 ES	2014/2015, 2015/2016	Dogliotti et al., 2021
Strawberry	76	13 + 1 ES	2012, 2013	Scarlato et al., 2017
Sweet potato	118	31	2015/2016, 2016/2017	Dogliotti et al., 2021
Short cycle tomato	70	20	2014/2015, 2015/2016	Berrueta et al., 2019
Long cycle tomato	39	18	2014/2015, 2015/2016	Berrueta et al., 2019

*ES: experimental station

2.2.4. Data analysis

We conducted the analysis in five steps. First, we quantified the use of pesticides and nutrients and explored the associations between these inputs in each of the five crops using the complete dataset of 428 fields. Pesticide load in kg active ingredient (AI) per ha was derived by summing the AI applied at each application. Nutrient input was calculated as the cumulative amount of N, P, and K in organic and synthetic fertiliser inputs. We explored the relationships between pesticide load and the number of pesticide applications and between N, P, and K inputs by Pearson correlation coefficients for each crop. Associations between herbicide, insecticide, fungicide, and total pesticide load, number of pesticide applications, N, P, and K amounts were analysed by principal component analysis (PCA).

Second, we explored the relationship between yield and inputs of pesticides and nutrients, in conjunction with year, crop cycle length, planting date, plant density, soil organic carbon, pest and disease incidences (explanatory variables) in the five crops. We used Pearson correlation coefficients and mixed linear models to explore the associations. For each crop, mixed models included yield as response variable, and year, input use, and crop management variables as fixed effects, and farm was included as a random effect. Multicollinearity was assessed through the Variance Inflation Factor (VIF), and variables with VIF higher than five were excluded from the analysis. Residual plots confirmed that the models met homogeneity of variance criteria (Zuur & Ieno, 2016; Zuur et al., 2010). We used the complete data set of each crop except for onion where we excluded three fields due to incomplete data, resulting in 122 fields.

Third, to explore the underlying drivers of the observed pesticide and nutrient input levels, we tested several hypotheses. For pesticide inputs, we considered variables related to pest and disease incidence and severity, crop and soil management, and environmental conditions that determine pest and disease occurrence. We analysed the relationships between pesticide inputs, other crop management, year, and pest or diseases incidence using PCA and linear mixed models for the crops where a significant relationship between yield and pesticide input was found. Linear mixed models included pesticide load as response variable, and year, pest or diseases incidence, and crop management variables as fixed effects (variables detailed in Appendix A2.3, Table A2.3.1), and farm as a random effect.

For nutrient inputs, we considered soil nutrient status before crop establishment and crop nutrient balance. The relationship between N, P, and K inputs and soil organic carbon, soil P content, and soil K content was explored by Pearson correlation coefficients and PCA. Nitrogen, phosphorus, and potassium balances for each crop were estimated as:

$$Bal_X = Input_X - Yobs * C_X \qquad \text{eq. 1}$$

Where Bal_X is the balance for nutrient X (kg ha^{-1}). X refers to N, P, or K. $Input_X$ is the supply of nutrient X (kg ha^{-1}). Yobs is the observed crop yield (Mg ha^{-1}), and C_X is the concentration of nutrient X in the harvested product (kg nutrient X Mg^{-1} product). C_X was based on Ciampitti and García (2012). For onion, strawberry, and sweet potato, we considered the nutrient concentration in the harvested product, assuming that crop residues are left in the field, which corresponds with standard farmer practices. For short and long-cycle tomato, we considered nutrient content in the entire crop because farmers remove all crop residues from the greenhouses at the end of the harvest period.

As most nutrients are applied before planting the crops, farmers base their fertiliser application rates on the expected attainable yields. We therefore also calculated nutrient balances for the attainable yield (Yatt) estimated as the 90^{th} percentile highest yield per crop, using equation 1 and replacing Yobs by Yatt. The attainable yields were 41.1 Mg ha^{-1} for onion, 35.2 Mg ha^{-1} for strawberry, 44.9 Mg ha^{-1} for sweet potato, 23 kg m^{-2} for long cycle tomato, and 15 kg m^{-2} for short cycle tomato.

Fourth, we positioned the data in the four quadrants of the conceptual model in Figure 2.1. Pesticide and nutrient inputs were converted to indices ranging from 0 to 50, where 0 equalled 0 kg input, and 50 was equivalent to the maximum amounts of pesticides or nutrients applied. The sum of both indices resulted in the input index, which ranged from 0 to 100. The boundary between the high and low yield and input quadrants was taken to be the average of yield and input index across all fields, respectively.

Fifth, we explored the effect of farm resource endowment on the relationship between yield and input index. We used the farm-level dataset, excluding data from experimental stations (one onion and one strawberry case). We projected the data in the four quadrants diagram of Fig. 2.1 based on yield and input index averaged across the farm's fields for each crop. Each of the four groups were characterised in terms of farm size (ha), area of vegetable crops (ha), area of the crop of interest (ha), greenhouse area (ha), total labour (full-time equivalent), ratio family labour/total labour, ratio permanent labour/total labour, mechanisation level, and diversity of activities. Characteristics of the farm groups were compared using Kruskal-Wallis tests.

Data analyses were performed using R 3.6.3 (2020-02-29) using the following R-packages: "ggplot2" (Wickham, 2016), "factoextra" (Kassambara & Mundt, 2020a), "gridExtra" (Auguie, 2017), "PerformanceAnalytics" (Peterson & Carl, 2020), "corrplot" (Wei & Simko, 2017), "tydiverse" (Wickham et al., 2019), "lme4" (Bates et al., 2015), "ggpubr" (Kassambara, 2020a), and "rstatix" (Kassambara, 2020b).

2.3. Results

2.3.1. Assessment of pesticide and nutrient inputs

Pesticide input was greatest in strawberry and long cycle tomato, both in terms of the number of applications (20 and 18, respectively) and pesticide load (21 kg AI per ha in both crops; Table 2.2). Short cycle tomato and onion revealed intermediate pesticide input levels, and sweet potato had the lowest pesticide input (Table 2.2). In strawberry and onion, fungicides were the most prevalent pesticides, while in short and long cycle tomato, both insecticides and fungicides were common (Table 2.2). Nutrient inputs were greatest for long cycle tomato (N, P, and K totalling 1127 kg per ha), followed by short cycle tomato, strawberry, onion, and sweet potato (Table 2.2). The data showed clear crop-specific patterns in pesticide and nutrient input levels (Fig. 2.2), despite considerable variation across fields within the same crop.

Table 2.2. Yield, amounts of N, P, and K applied per ha, amounts of active ingredient (AI) per ha, and number of pesticide applications per ha for the five focal crops.

Crop	Yield	N	P	K	Total
	Mg ha^{-1}	kg ha^{-1}			
Onion	26.5 ± 10.3	128 ± 78	52 ± 25	41 ± 67	222 ± 127
Strawberry	21.5 ± 10.7	123 ± 77	85 ± 53	168 ± 414	376 ± 242
Sweet potato	29.6 ± 11.0	39 ± 28	26 ± 24	16 ± 22	81 ± 50
Long cycle tomato	157.0 ± 54.7	341 ± 228	146 ± 140	640 ± 349	1127 ± 536
Short cycle tomato	82.9 ± 37.3	222 ± 164	83 ± 77	354 ± 222	659 ± 344

Table 2.2. (cont.)

Crop	Fungicides	Insecti-cides	Herbicides	Total	Fungicides	Insecti-cides	Herbic-ides	Total
	(kg AI ha^{-1})				Number of applications			
Onion	10.7 ± 8.0	0.5 ± 0.6	1.2 ± 0.9	12 ± 9	7 ± 4.	2 ± 2	3 ± 2	10 ± 5
Strawberry	18.9 ± 19.9	0.9 ± 1.1	1.7 ± 0.9	21 ± 21	15 ± 14	5 ± 5	5 ± 3	20 ± 16
Sweet potato	0	0.2 ± 0.4	0.5 ± 0.4	0.7 ± 0.6	0	1 ± 1	1 ± 1	2 ± 1
Long cycle tomato	12.2 ± 12.5	8.5 ± 6.9	0.02 ± 0.10	21 ± 17	12 ± 7	15 ± 6	0 ± 0	18 ± 6
Short cycle tomato	7.7 ± 8.9	3.3 ± 3.0	0.01 ± 0.09	11 ± 10	7 ± 5	9 ± 4	0 ± 0	11 ± 4

There was a positive correlation between the number of pesticide applications and pesticide load per ha in all crops (Pearson’s r ranging between 0.3 and 1.0, $p<0.05$). There were significant positive correlations between the number of applications and pesticide load per ha of the main type of pesticide (insecticides, fungicides, and herbicides) used per field (r range 0.3-0.9, $p<0.05$; Appendix A2.2). In addition, there were positive correlations between N, P, and K inputs per field (r range 0.3-0.8, $p<0.001$). These significant positive correlations indicate that farmers who used a higher amount of a particular pesticide or nutrient type also tended to use higher amounts of other types of pesticides or nutrients.

2.3.2. *Relationship between yield and pesticide and nutrient inputs*

The relationships between yield and pesticide and nutrient inputs were crop-specific and often weak (Table 2.3, Appendix A2.3). Yields of sweet potato and short cycle tomato were not significantly associated with pesticide input, and strawberry yield was negatively related to fungicide use. There was a marginally significant positive association between insecticide applications and the yield of long cycle tomato, which was also significantly associated with pesticide load ($r=0.34$, $p=0.03$). Onion yield was positively associated with fungicide use ($r=0.40$; $p<0.01$; Table 2.3). However, pest incidence in long cycle tomato was not significantly associated with insecticide use in both years, and downy mildew incidence and severity in onion were not significantly associated with fungicide use. Pesticide input was positively related to crop cycle length (tomato long cycle, $p<0.05$; onion, $p<0.01$) (Appendix A2.3).

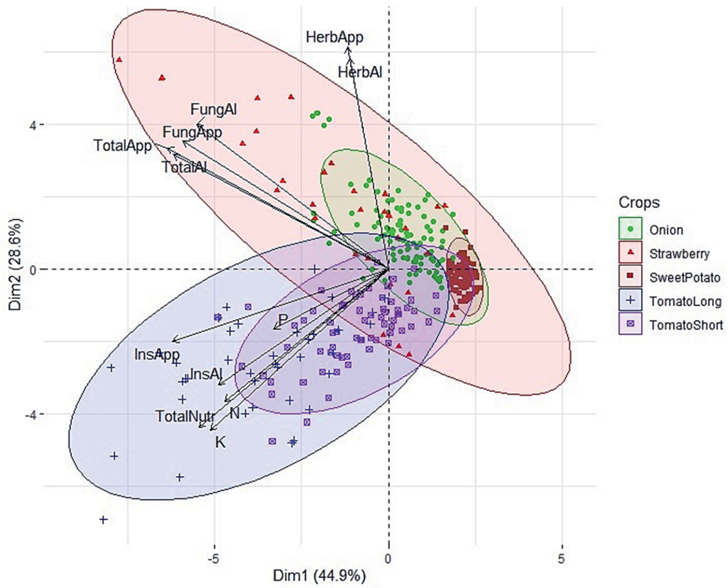

Fig. 2.2. Principal component analysis considering herbicides (Herb), fungicides (Fung), insecticides (Ins) and total (Total) number of pesticides applications (App) and AI load per ha (AI), N, P, K and total (TotalNutr) nutrient input per ha. Crops are indicated with specific markers. N = 428 fields. The total variation explained by the first two principal components is 74%.

Yields of strawberry, short cycle tomato, and sweet potato were not associated with N, P, or K inputs. In contrast, long cycle tomato yield was positively related to N, and onion yield was weakly and positively associated with K inputs, but negatively associated with N inputs (Table 2.3, Appendix A2.4). There were positive correlations between N input and SOC ($r=0.20$, $p<0.001$), P input and soil P content ($r=0.26$, $p<0.001$), and K input and soil K content ($r=0.63$, $p<0.001$), indicating that decisions on nutrient input levels

Table 2.3. Yield determinants of the five crops based on linear mixed models with the variable Farm as random effect.

Variable	Units	Onion	Strawberry	Sweet potato	Long cycle tomato	Short cycle tomato
FungAI	kgAI ha^{-1}	**439 (105) *****	**-217 (101)***	NA	19 (665)	-61 (461)
InsAI	kgAI ha^{-1}	185 (1337)	-818 (1766)	-930 (2210)	-554 (1190)	1248 (1648)
HerbAI	kgAI ha^{-1}	-126 (924)	NA	3470 (2167)	NA	NA
InsApp	Number of applications	High VIF	High VIF	High VIF	2659 (1539) ˙	1692 (1325)
N	kg ha^{-1}	**-28 (12) ***	30 (21)	-79 (42)	**108 (41) ***	-45 (30)
P	kg ha^{-1}	42 (13)	High VIF	24 (53)	-46 (82)	55 (53)
K	kg ha^{-1}	30 (17) ˙	High VIF	-6 (48)	-5 (32)	27 (21)
Year	2 years per crop	2644 (1452)	-1444 (2576)	**9795 (2328) *****	-17410 (15180)	**-19872 (9664) ***
Season cycle	Spring/Autumn	NA	NA	NA	NA	**58268 (9141)*****
Plant density	Number of plants m^2	**924 (179) *****	2895 (1930)	**4368 (1278) *****	-8673 (19680)	4926 (8682)
Crop Length	Number of days	**147 (48) ****	NA	**218 (76) ****	**818 (250)****	**817 (198) *****
Planting Date	Number of days (Strawberry 1=27/2, Sweet potato 1=1/1	NA	**-99 (45)***	-13 (58)	NA	NA
Completing Date	Number of days (1=26/3)	NA	-58 (37)	NA	NA	NA
Soil organic carbon	%SOC	**6052 (1980) ****	-2077 (3087)	1173 (26001)	**35070 (14340) ***	2909 (6908)
N during crop cycle	kg ha^{-1}	NA	**375 (110)****	NA	NA	NA
Whitefly	Scale 0-3	NA	NA	NA	-10690 (8455)	-3133 (4264)
Tomato leaf miner	Scale 0-2	NA	NA	NA	-5768 (9531)	-8661 (4995)
Tomato Frequency	From 0 to 2	NA	NA	NA	**-29040 (12510)***	-2467 (6899)
Tomato Sequence	From 0 to 3	NA	NA	NA	21470 (13610)	2680 (5625)
Mildew Incidence	From 0 to 4	-4315 (3857)	NA	NA	NA	NA
Mildew Severity	From 0 to 1	-2019 (1809)	NA	NA	NA	NA
Water during cycle	mm	NA	NA	1 (12)	NA	NA
Number of fields		122	76	118	39	70
Number of farms		32	14	31	18	20

FungAI, InsAI, HerbAI: Active ingredient (AI) load per ha for fungicides (Fung), insecticides (Ins), and herbicides (Herb). InsApp: number of insecticides applications. N, P, K: nutrient input in kg per ha. High VIF: variables excluded from the model due to high collinearity. NA is not applicable for the crop. Estimates are shown, with standard error between brackets and statistical significance in bold and with asterisks *. *$p < 0.05$; ** $p < 0.01$; *** $p < 0.001$; ˙ $p < 0.1$.

were not based on soil nutrient status (Appendix A2.4). Moreover, most fields had nutrient imbalances, irrespective of whether nutrient uptake was estimated from observed yields or from attainable yields (Appendix A2.4), indicating that fertilisation was not tailored to crop nutrient demands. P balances were generally positive for all crops, while K balances were generally negative, except for strawberry, where most fields had a positive K balance. N balances were generally positive in strawberry and onion, and negative in tomato and sweet potato fields.

2.3.3. Variability in yields and associated inputs

There was a high variation in pesticide and nutrient input levels in onion, strawberry, long and short cycle tomato (Fig. 2.3). High yields and low input index was achieved in 16% of the onion fields, 24% of the strawberry fields, 29% of the short cycle tomato greenhouses, and 18% of the long cycle tomato fields (Fig. 2.4). In long cycle tomato, we found three cases with low yields and high input index (Fig. 2.4). Overall, there were few cases with an input index higher than 60, indicating that fields with relatively high pesticide and nutrient inputs were rare.

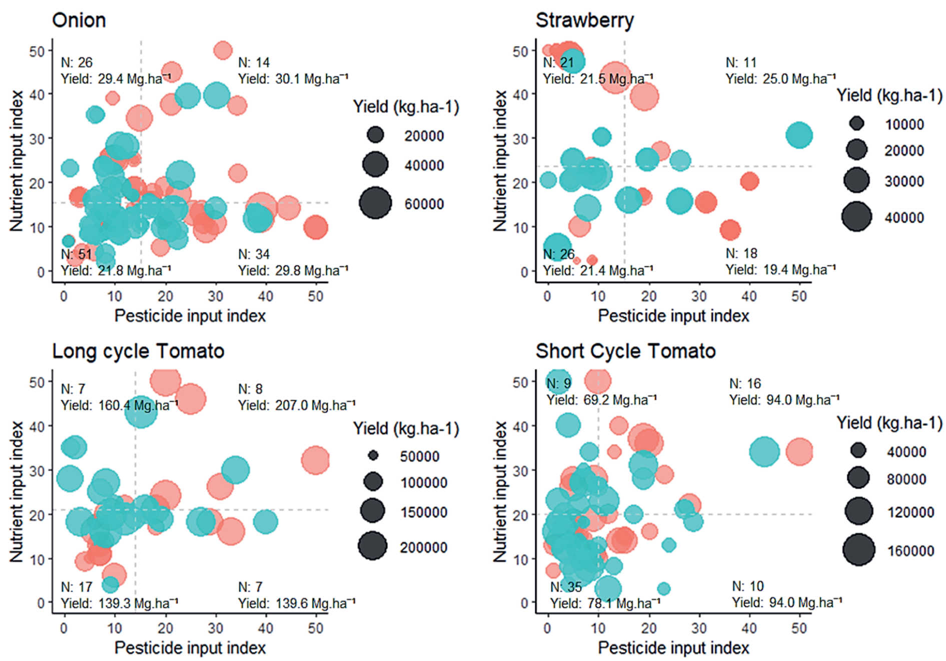

Fig. 2.3. Relationships between yields and pesticides and nutrients input index for onion, strawberry, and long and short cycle tomato. Each bubble corresponds to one field. Bubble size corresponds with yield. Colours indicate years: red corresponds to the first year, and green corresponds to the second year. Each panel is divided into four quadrants based on average values per axis. In each quadrant the number of fields (N) and the average yield are shown.

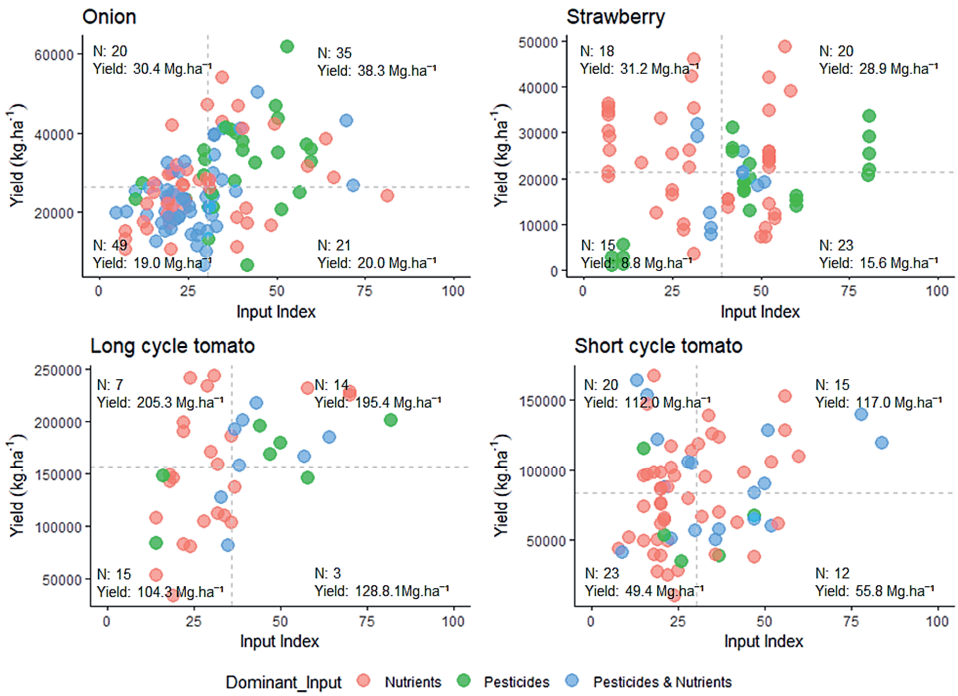

Fig. 2.4. Relationships between yield and input index for onion, strawberry, long cycle tomato, and short cycle tomato. Input index represents the sum of pesticide and nutrient input index values. Each panel is divided into four quadrants based on average values per axis. In each quadrant, the number of fields (N) and the average yield are shown. The colour of markers indicates the dominant input: red (≥60% nutrient input), green (≥60% pesticide input), or blue (both pesticides and nutrients between 41 and 59%).

2.3.4. Farm-level performance

For all crops, variability in yield exceeded variability in input index at the farm level (mean coefficients of variation 27% and 20%, respectively), indicating that input management was relatively constant across fields and years at most farms. High yields and low input index values at the farm level were achieved on 10% of the farms for onion, 15% for strawberry, 30% for short cycle tomato, and 17% for long cycle tomato (Fig. 2.5). The main type of input differed among farms, with some mainly using pesticides while others mainly used nutrients.

There was a statistically significant difference in yield and input index between the farms in the four quadrants for all crops (Kruskal-Wallis test $p<0.05$). Farms in the four quadrants did not differ significantly in size, vegetable crop area, area of the crop of interest, total labour, mechanisation level, and diversification in farm activities (Kruskal-Wallis test $p>0.05$), except for of onion, where farms of the low yield - low input index

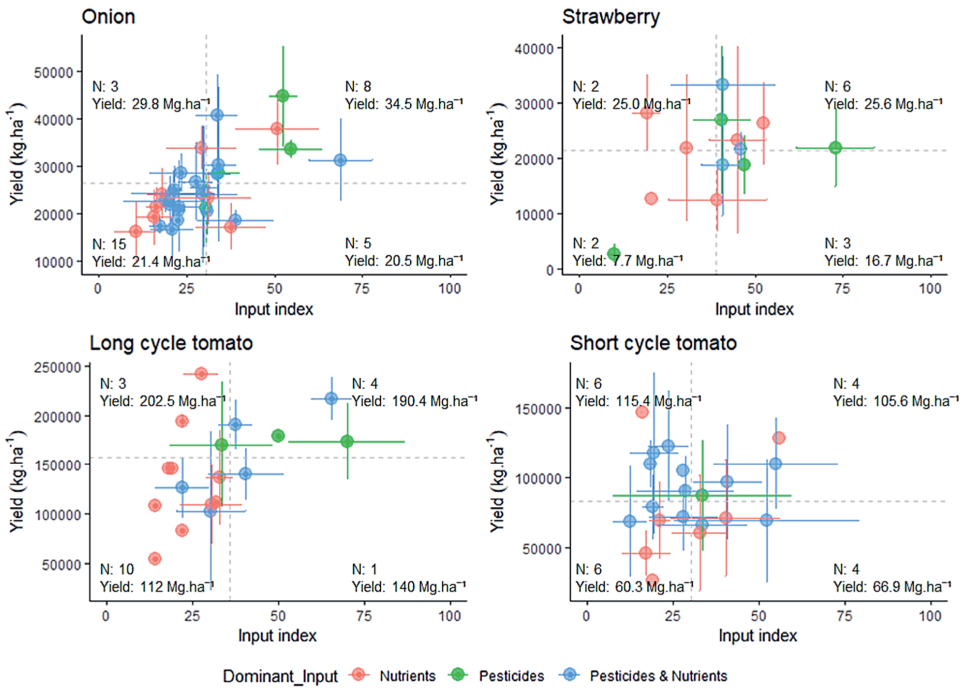

Fig. 2.5. Relationships between yield and input index at the farm level for onion, strawberry, short cycle tomato, and long cycle tomato. Each panel is divided into four quadrants based on average values per axis. In each quadrant, the number of farms (N) and the average yield is shown. Markers indicate the average yield and average input index of each farm, and bars are standard deviations of yield and input index for each farm. The colour of markers indicates the dominant input: red (≥60% nutrient input), green (≥60% pesticide input), and blue (both pesticides and nutrients between 41 and 59%). Number of farms: 31 for onion, 13 for strawberry, 18 for long cycle tomato, and 20 for short cycle tomato.

quadrant had a higher ratio of family to total labour than farms in the high yield - high input index quadrant ($p<0.05$) (Appendix A2.5).

2.4. Discussion

In this study, we assessed the relationships between pesticide and nutrient inputs and yield in onion, sweet potato, short cycle tomato, long cycle tomato, and strawberry during two years per crop on 5-10% of the farms in the south of Uruguay. We reported four key findings. First, relationships between pesticide and nutrient inputs and yield were generally weak or non-significant, indicating inefficiencies and overuse of inputs. In many cases, we could not find agronomic explanations for the level of pesticide and nutrient use. Second, while we generally report high agrochemical input levels in

Uruguayan vegetable production systems, we also showed substantial variation in input use among crops, fields (including tomato greenhouses), and farms. Third, combinations of high yields and low input levels were found on 21% of the fields and on 17% of the farms for onion, strawberry, and tomato, indicating better than average management practices. Finally, relationships between yield and input use at farm level were not related to farm resource endowment, except for onion where farms with a low yield - low input index quadrant had a relatively high family to total labour ratio.

We found that in many cases yield levels were not related to input levels. For instance, pesticide use was not related to short cycle tomato yield or sweet potato yield and negatively related to strawberry yield. Although fungicides were strongly associated with onion yields and insecticides were weakly associated with long cycle tomato yields, there was no relation between disease or pest incidence and pesticide use. We found a positive association between yield and crop length and between crop length and pesticides use in onion and long cycle tomato. These findings are in line with results of yield gap analyses of Scarlato et al. (2017), Berrueta et al. (2019), and Dogliotti et al. (2021), who found that yield gaps were mainly explained by other factors than pesticides. Our findings align with findings from previous studies from France (Lechenet et al., 2014) and worldwide (Popp et al., 2013), questioning the need to use large amounts of synthetic pesticides to achieve high yield. Apart from agronomic reasons, there are also compelling reasons to reduce pesticide inputs from an environmental and worker health and safety perspective (Jepson et al., 2014; Jepson et al., 2020; Pimentel, 2005) as an average pesticide input of 21 kg AI ha^{-1} in long cycle tomato and strawberry are likely to lead to substantial impacts.

Nutrient inputs only explained yields in long cycle tomato and onion, and, consistently across all crops, nutrient inputs were not related to crop requirements or soil nutrient status. We detected nutrient imbalances for all crops. Nutrient input levels were positively related to soil nutrient contents before establishing the crop, suggesting that farmers do not base their fertilisation decision making on soil nutrient status. On the contrary, our data suggest that the imbalanced soil nutrient status might be the result of a standard fertilisation routine that is repeated each year. Strong imbalances in nutrient inputs and crop demand and their impact on nutrient accumulation, leaching, or depletion of soil stocks have been reported as a global phenomenon and as particularly intense in developing countries (Bennett et al., 2001; Tan et al., 2005). Indeed, in Uruguay high N and P accumulation in surface water in vegetable production areas have been reported (Barreto et al., 2017). Our findings also point towards major risks of N leaching, P accumulation, and K depletion in vegetable systems in south Uruguay, and stress the need for better informed fertilisation decision making.

While our study quantified for the first time the high agrochemical input levels in Uruguayan vegetable production systems, we also showed substantial variation in management among crops, fields, and farms. The same yield level was achieved with a wide range of input levels in all crops. Our results align with findings of Lechenet et al. (2016), who found no relation between pesticides use and productivity on vegetable crops in France, Abunyuwah et al. (2020), who found pesticide overuse and high variability among tomato crops in Ghana, and Ahovi et al. (2021) who found overuse and high inefficiencies of pesticides and fertilisers in Dutch greenhouse vegetable production, but also high variability among farms. Although most of the farms in our sample were conventional, some conventional farms had low input levels, which were comparable to organic farms. Similar to what Marliac et al. (2016) and Pépin et al. (2021) found for organic vegetable farms in France, our results show that "conventional farming" may entail a wide variation in practices and performances.

For onion, strawberry, and the two tomato crops, 21% of the fields and 17% of the farms were identified as "positive deviants" (Herington & van de Fliert, 2018), which combined high yields and low pesticide and nutrient inputs. These positive deviants show that there is space to reduce input use while maintaining or increasing yields. The identification, understanding, and sharing of these successful examples may provide insights into how to transition to more sustainable production systems and may help promote changes in other farmers´ attitudes and practices (Bakker et al., 2021; Modernel et al., 2018). A more detailed analysis of farmers' decision-making on input use and the factors driving this process (Bakker et al., 2021; Daxini et al., 2019; Doran et al., 2020) could shed further light on effective incentives to support policies for the transition towards more sustainable farming practices. In addition, along with other studies (Ahovi et al., 2021; Lechenet et al., 2016), our findings also point towards the difficulty for farmers to reduce their agrochemical input use within the current agricultural innovation system which revolves around agrochemical marketing and sales (Jallow et al., 2017; Jin et al., 2015; Schreinemachers et al., 2017). Therefore, besides research, targeted governmental policies are needed to regulate agrochemical input use and promote the transition to a more sustainable food system (Tittonell, 2014).

Yield–input relations were not clearly related to farm resource endowment with except for onion where smallholders tended to have low input levels and low yields. This implies that farm resource endowment would not be limiting the scope to improve yields while decreasing inputs use. We found similarities between the use of inputs and their relation to yields for different fields of a farm, and we consistently found that higher inputs of one type of pesticide coincided with higher inputs of other types of pesticides across years and crops and without apparent relation to agronomic factors. We also found imbalances between the required and supplied amounts of crop nutrients. These findings support the idea that current pesticide and nutrient management is not so much driven by agronomic criteria or best management practices, but relies on personal experience, tradition, or intuition (Nuthall & Old, 2018), i.e., a consistent *"way of doing"* or *"routine of doing*" of each farmer that is congruent across fields and years, which therefore manifests itself at the farm level. Although our study focused on input use at the field level, our findings indicate that farmers use a standard field-level management approach across the whole farm and years, irrespective of variation in soil and weather conditions. This emphasises the need to consider changes from a systemic, whole-farm perspective.

To assess possible transition routes to strengthen agronomic and environmental performance (Fig. 2.4, Fig 2.5), we positioned commercial vegetable systems in Uruguay in a productivity-input use plane based on Tittonell et al. (2016). The 90% quartile yields in the commercial fields were consistently higher or equal to yields attained under experimental conditions for all five crops (Berrueta et al., 2019; Gimenez et al., 2013; Scarlato et al., 2017). However, yields gaps were on average around 50% (Berrueta et al., 2019; Dogliotti et al., 2021; Scarlato et al., 2017). The difference in input index between the high yield - high input index and high yield - low input index farm groups for all crops was 50% (Table A2.5.1), indicating that in many situations high yield could be achieved with half of the input used. Moreover, for tomato and strawberry crops, the timing of nutrient applications did not match crop requirements in most cases, leading to nutrient losses and inefficiency (Berrueta et al., 2019; Scarlato et al., 2017). Therefore, by using best management practices yields can be increased with less pesticide and fertiliser inputs. Previous studies showed that the main changes required to reduce yield gaps are not input-related, but revolve around choice of planting dates and planting density, soil organic matter content, and frequency of the crop in the rotation (Berrueta et al., 2019; Dogliotti et al., 2021; Scarlato et al., 2017). In some cases more efficient use of inputs was required, e.g. through timing of nutrient applications and avoiding calendar pesticide applications. Such strategies would contribute to both ecological intensification and ecologisation processes. Moreover, there are alternative practices to reduce pest damage without using pesticides contributing to an ecologisation process, such as soil solarisation in greenhouses and crop rotation in field crops, or the use of alternative inputs, like entomopathogenic fungus and predators for biological control that could substitute chemical pesticides (Basso et al., 2020).

We found considerable variation in the amount and type of inputs used among farms. Some farmers tended to overuse only pesticides, others overused only nutrients, yet others overused both input types. Furthermore, and in line with findings of Larsen et al. (2019), the main type of pesticide or nutrient used differed among farms according to their crops. Consequently, the changes needed to reduce the reliance on agrochemicals are largely farm specific. This calls for a detailed diagnosis and systemic redesign that considers the specific situation of each farm and the synergies and trade-offs between the crop and farm level, as has been done in co-innovation projects in the Rio de la Plata region (Colnago et al., 2021; Dogliotti et al., 2014; Rossing et al., 2021). Berrueta et al. (2021) showed that recommendations from crop research need to be tailored to farm context and objectives, and consider synergies and trade-offs to have greater economic and environmental impacts. The beginning of such a systemic diagnosis and redesign could focus on what has been defined as levels one and two of the agroecological transition (Gliessman, 2015; Nicholls & Altieri, 2016), which implies increasing efficiencies and changes in the type of inputs used, and paves the way for redesign as the third level of the agroecological transition.

Various studies have recently addressed how such sustainability transitions may be fostered (Berrueta et al., 2021; Lacombe et al., 2018; Markard et al., 2012; Melchior & Newig, 2021; Ollivier et al., 2018). Starting an agroecological transition from a systemic diagnosis and redesign requires investment in high-quality long-term and systemically oriented extension services capable of contributing to this process. It also requires the development of local context-specific knowledge and technologies to deepen the ecologisation process. Such knowledge and technologies should be developed with a holistic and systemic perspective, focused on promoting and enhancing ecological processes to support production. For example, an Agroecological Crop Protection (ACP) approach may be more promising than an Integrated Pest Management (IPM) approach because IPM often still revolves around the (reduced) use of pesticides (Deguine et al., 2021). ACP aims to promote the ecological health of agroecosystems by directly or indirectly optimising interactions between living communities (plant, animal, microbial) below and aboveground, based on two pillars, biodiversity and soil health (Deguine et al., 2021). These principles are well known in agroecology (Nicholls & Altieri, 2007), but we lack context-specific actionable knowledge to help farmers apply them. For example, how to improve crop nutrition based on soil organic matter management and organic amendment dynamics? Or, how to design and manage crop diversity and soil microbiome diversity to promote natural pest regulation? New knowledge on translating general principles into practices in a concrete situation would foster and support redesign processes for an agroecological transition.

2.5. Conclusion

This paper documents the high pesticide and fertiliser use in vegetable production systems in south Uruguay using two years of data on five vegetable crops and 428 fields. In most fields, input levels were not reflected in yield output, demonstrating a lack of agronomic justification for agrochemical input. Such overuse of inputs imposes serious environmental and human health risks and highlights the need to rethink current agronomical practices to arrive at context specific, judicious input use. Positive deviant farms, which combined high yields with low input levels, were found in all five crops in the study, refuting the often held belief that high agrochemical use is required to obtain high productivity and providing inspiring examples of alternative management. Transitioning to a more sustainable state calls for a detailed diagnosis and systemic redesign at the crop and farm level involving farmers to bring about changes in engrained practices, investment in high-quality systemically oriented extension services to support farmers in the changes, and the generation of local context-specific knowledge and technologies to enhance ecologisation.

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Appendix 2

A2.1. Description of variables included in the dataset at field and farm level

Table A2.1.1. Overview of variables included in the dataset at field level

Variable	Units and explanation
All crops	
Year	Two years assessed per crop. Strawberry: 2012 and 2013, Onion: 201/2015 and 2015/2016, Sweet potato: 2015/2016 and 2016/2017, long and short cycle tomato: 2014/2015 and 2015/2016.
Yield	Mg of fresh matter of product per ha
Number of pesticide applications	Number of applications in the cycle, divided into: insecticides, fungicides, herbicides, and total number of application. As in most cases different types of pesticide were applied together, the total is not the sum of applications per type of pesticides.
Pesticides load	kg active ingredient (AI) per ha, divided into: insecticides, fungicides, herbicides, and total.
Nutrient input	kg of nutrient per ha, divided into: N, P, K, and total (the sum of N, P and K).
Soil organic carbon	% Soil organic carbon
Soil nutrients	P Bray I (ppm), K (Meq/100 g soil)
Crop cycle length	Number of days between transplanting and end of harvest. In onion, number of days between transplanting and start of bulbing.
Crop density	Number of plants per square meter, measured at harvest or bulbing initiation in onion.
Strawberry, sweet potato and short cycle tomato	
Planting date	Number of days counting from the earliest planting date registered. In strawberry 1 = 27th Feb. In sweet potato 1 = 1st Oct.
Completing date	Only for strawberry. Farmers install the imported cold-stored plant at the end of summer, and use between 1 and 3 "sons" to complete the final crop density during autumn. Number of days counting from the earliest date registered were the crop had the final crop density (all the "sons" installed), 1 = 26th March.
Season	Only for tomato short cycle: spring / autumn.
Onion	
Downy mildew (disease caused by *Peronospora destructor*) incidence and severity	30 random plants per field, scored on a 0-4 scale: 0 (no disease), 1 (≤ 10% leaf injury), 2 (> 10 % and ≤ 40 % leaf injury), 3 (> 40 % and ≤ 80 % leaf injury), and 4 (> 80 % leaf injury). Incidence is the number of plants injured per number of plants assessed and severity is the weighted average of injury level.
Preventive and curative fungicide load per ha	Preventive: action avoiding pathogen infection. Curative: action killing or reducing sporulation after pathogen infection
Frequency of alliacea	Number of alliacea crops in the previous 5 years
Whitefly (*Trialeurodes vaporariorum*)	Scale 0-3: 0 (Not present), 1 (Limited to few spots), 2 (Widespread distribution), 3 (Widespread presence and honeydew with sooty mold fungus on the leaves) (Berrueta et al., 2019)
Tomato leaf miner (*Tuta absoluta*)	Scale 0-2: 0 (Not present), 1 (Leaf damage in specific places), 2 (Leaf and fruit damage, widespread presence) (Berrueta et al., 2019)
Tomato frequency	From 0 to 2. Frequency of tomato crops in the previous 3 or 4 years (Bertoni et al., 2020).
Tomato sequence	From 0 to 3. Period between the planting date of the current crop and the planting date of the previous tomato in years (Bertoni et al., 2020)

Table A2.1.2. Overview of variables included in the dataset at farm level

Variable	Units and explanation
Farm size	ha managed by the farmer
Vegetable crop area	ha of vegetable crops per year
Greenhouse area	ha of greenhouses in the farm
Area of the crop of interest	ha of the crop per year
Total labour	Full time equivalent (FTE). 1 FTE = 300 days of work and 8 hours per day = 2400 hours per year of labour.
Ratio family labour / total labour	Range 0 to 1. Family labour (FTE) / Total labour (FTE)
Ratio permanent labour / total labour	Range 0 to 1. Permanent labour (FTE) / Total labour (FTE)
Mechanisation level	Scale 1 to 5: 1: no tractor or 1 tractor but no tractor sprayer, greenhouse nebulizer, mulching machine, disc ridger, rotary tiller, cultivator; 2: 1 tractor and one implement mentioned in 1; 3: 1 tractor and 2 or more implements, or 2 tractors and 2 implements; 4: 2 tractors and more than two implements; 5: 3 or more tractors and 2 or more implements.
Activities diversification	Scale 1 to 5: 1. Only vegetable production, less than 3 crops, 2. Only vegetable production, between 3 and 5 crops, 3. Only vegetable production more than 5 crops or 1-2 crops + other productive activity, 4. Vegetable production 3 or more crops + other productive activity, 5. Vegetable production 3 or more crops + 2 other productive activities.

A2.2. Association between pesticide input and between nutrient input

Table A2.2.1. Correlation between number of pesticide applications (TotalApp) and pesticide load (TotalAI) per crop. Significant correlations (p < 0.05) are represented in bold typeface.

Crop	n	Pearson coefficient	p-value
Short cycle tomato	70	**0.27**	**0.0215**
Long cycle tomato	39	**0.29**	**0.0469**
Onion	125	**0.82**	**<0.0001**
Strawberry	76	**0.97**	**<0.0001**
Sweet potato	118	**0.73**	**<0.0001**

There were significant positive correlations between the number of applications and pesticide load of insecticides, fungicides and herbicides in onion and strawberry (between 0.2 - 0.4 and 0.3 - 0.9, respectively, p < 0.05), insecticide and fungicide load and number of applications in short and long cycle tomato (between 0.4 and 0.5, p < 0.05), and insecticide and herbicide in sweet potato (0.2, p < 0.05) (Table B2).

Table A2.2.2. Correlation between types of pesticide used per crop. Significant correlations (p < 0.05) are represented in bold typeface.

Variable(1)	Variable(2)	n	Pearson coefficient	p-value
Short cycle tomato				
HerbApp	InsApp	70	0.08	0.4977
HerbApp	FungApp	70	0.05	0.6980
InsApp	FungApp	70	**0.42**	**0.0003**
HerbAI	InsAI	70	0.03	0.7792
HerbAI	FungAI	70	-0.05	0.7089
InsAI	FungAI	70	0.17	0.1653
Long cycle tomato				
HerbApp	InsApp	39	-0.03	0.8452
HerbApp	FungApp	39	-0.07	0.6937
InsApp	FungApp	39	**0.54**	**0.0004**
HerbAI	InsAI	39	-0.03	0.8704
HerbAI	FungAI	39	-0.03	0.8334
InsAI	FungAI	39	**0.39**	**0.0151**
Onion				
HerApp	InsApp	125	0.14	0.1219
HerApp	FunApp	125	**0.22**	**0.0128**
InsApp	FunApp	125	**0.41**	**<0.0001**
HerbAI	InsAI	125	**0.20**	**0.0228**
HerbAI	FungAI	125	**0.38**	**<0.0001**
InsAI	FungAI	125	**0.24**	**0.0077**
Strawberry				
HerApp	InsApp	76	**0.47**	**<0.0001**
HerApp	FunApp	76	**0.46**	**<0.0001**
InsApp	FunApp	76	**0.86**	**<0.0001**
HerbAI	InsAI	76	**0.44**	**0.0001**
HerbAI	FungAI	76	**0.31**	**0.0071**
InsAI	FungAI	76	**0.67**	**<0.0001**

Sweet potato				
HerApp	InsApp	118	0.1	0.2898
HerApp	FunApp	118	0	>0.9999
InsApp	FunApp	118	0	>0.9999
HerbAI	InsAI	118	**0.21**	**0.0200**
HerbAI	FungAI	118	0	>0.9999
InsAI	FungAI	118	0	>0.9999

Abbreviations correspond to: App: number of application, AI: kg AI per ha; Herb: herbicide, Fung: fungicides, Ins: insecticides.

Table A2.2.3. Percentage of applications per type of pesticide per crop. Significant correlations ($p < 0.05$) are represented in bold typeface.

Crop	n	Variable	Average	SD	%	Variable	Average	SD	%
short cycle tomato	70	HerbAI	0.01	0.09	0	HerbApp	0.04	0.26	0
	70	InsAI	3.47	3.51	31	InsApp	9.29	4.09	**55**
	70	FunHa	7.63	8.65	**69**	FungApp	7.49	5.04	45
	70	TotalAI	11.11	9.78		TotalApp	16.82	4.39	
long cycle tomato	39	HerbAI	0.02	0.11	0	HerbApp	0.03	0.17	0
	39	InsAI	8.51	6.84	40	InsApp	15.03	5.69	**57**
	39	FunHa	12.63	13	**60**	FungApp	11.14	6.84	43
	39	TotalAI	21.16	16.97		TotalApp	26.2	6.51	
onion	125	HerbAI	1.18	0.89	10	HerbApp	2.84	1.58	25
	125	InsAI	0.52	0.61	4	InsApp	1.47	1.71	13
	125	FunHa	10.68	8.01	**86**	FungApp	6.9	4.05	**62**
	125	TotalAI	12.37	8.57		TotalApp	11.21	5.19	
strawberry	76	HerbAI	1.73	0.93	8	HerbApp	4.54	2.56	19
	76	InsAI	0.85	1.11	4	InsApp	5.07	5.44	21
	76	FunHa	18.9	19.95	**88**	FungApp	14.55	14.17	**60**
	76	TotalAI	21.48	21.02		TotalApp	24.16	15.56	
sweet potato	118	HerbAI	0.46	0.41	**67**	HerbApp	1.33	1.1	**73**
	118	InsAI	0.23	0.42	33	InsApp	0.49	0.85	27
	118	FunHa	0	0	0	FungApp	0	0	0
	118	TotalAI	0.69	0.64		TotalApp	1.82	1.46	

Abbreviations correspond to: App: number of application, AI: AI load per ha; Herb: herbicide, Fung: fungicides, Ins: insecticides.

A2.3. Relation between pesticide input and yield per crop, and pest and disease incidence and pesticide input in onion and long cycle tomato.

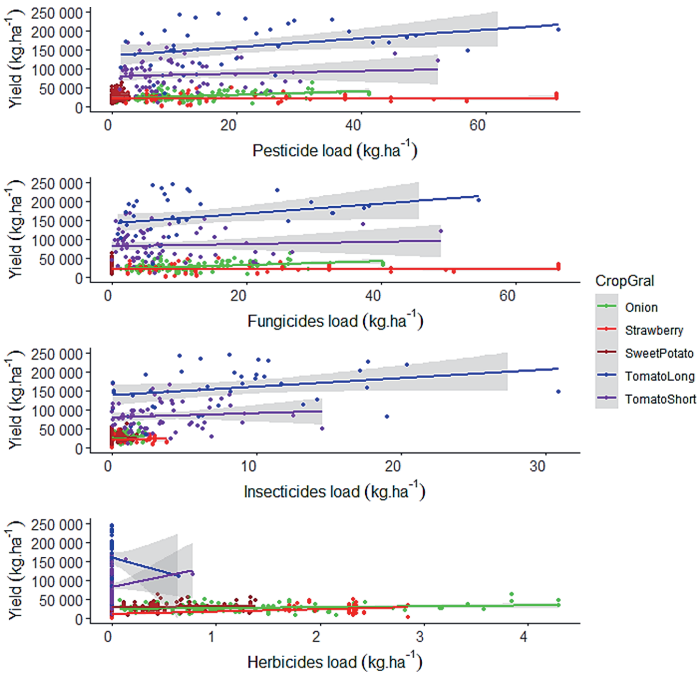

Fig. A2.3.1. Relation between yield and pesticide load (total, fungicides, insecticides and herbicides) for each focal crop. Colours correspond to crops, and each dot correspond to a field.

Table A2.3.1. Determinants of fungicide input in onion and of insecticide input in long cycle tomato from general linear mixed model analysis. Farm was used as random effect in the mixed models analysis. NA is: not applicable for the crop. Estimates are shown, with standard error between brackets and statistical significance in bold and with asterisks *. *$p < 0.05$; ** $p < 0.01$; *** $p < 0.001$; $^{\cdot}$ $p < 0.1$.

Fixed effect	Onion	Tomato Long cycle
Year	-1.714 (0.883)$^{\cdot}$	0.138 (2.503)
Plant density	0.067 (0.147)	-1.889 (2.800)
Crop Length	**0.084 (0.031)****	**0.081 (0.030)***
Soil organic carbon	-1.397 (1.515)	-1.962 (1.744)
N application	NA	0.005 (0.005)
Whitefly	NA	-0.759 (1.159)
Tomato leaf miner	NA	2.291 (1.585)
Aliaceae/Tomato Frequency	1.691 (2.466)	1.319 (1.818)
Tomato Sequence	NA	0.233 (1.558)
Mildew Incidence	-0.655 (2.589)	NA
Mildew Severity	0.452 (1.187)	NA
Number of fields	122	38
Number of farms	32	18

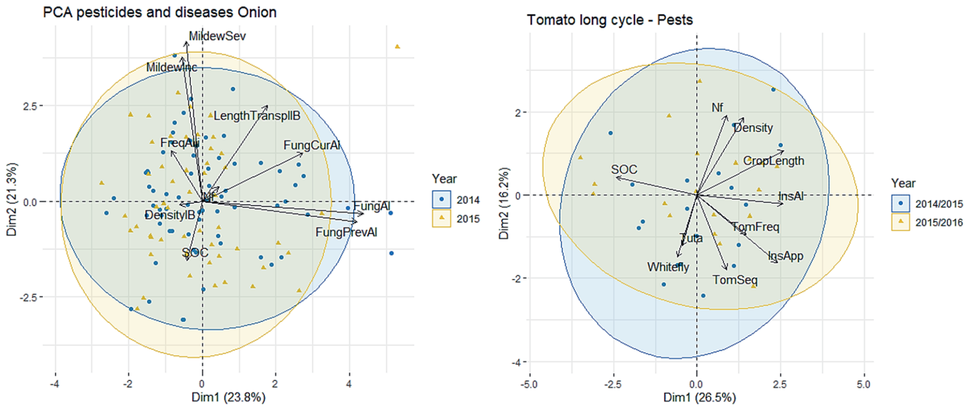

Fig. A2.3.2. (A) Principal component analysis for onion considering total (FungAI), preventive (FungPrevAI) and curative fungicide (FungCurAI) load (kg AI ha^{-1}), downy mildew incidence and severity, and other variables that could be related to fungicides input and downy mildew: cycle length between transplanting and bulbing initiation (LengthTranplIB), N input (Nf), soil organic carbon (SOC), crop density (DensityIB), frequency of alliaceas in the previous 5 years (FreqAlli). N = 122 fields. Total variation explained by the first two principal components: 45%. (B) Principal component analysis for long cycle tomato considering whitefly and tomato leafminer (Tuta) incidence, insecticides application (InsApp) and load (InsAI), soil organic carbon (SOC), N input (Nf), tomato frequency (TomFreq), tomato sequence (TomSeq), crop density and crop length. N = 39 fields. Total variation explained by the first two principal components: 43%. Different shapes and colours correspond to different years.

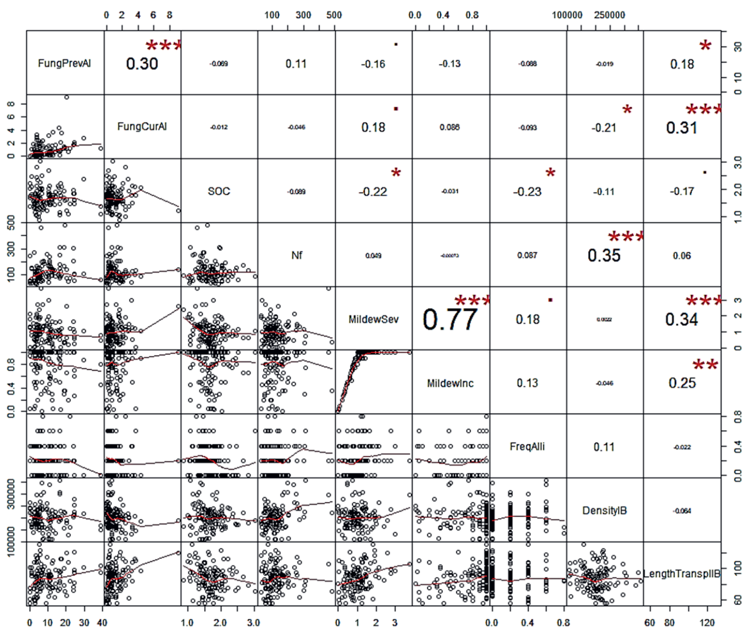

Fig. A2.3.3. Correlation matrix for pesticides input and mildew incidence and severity in onion. p-value: *** <0.001, ** <0.05, *<0.10

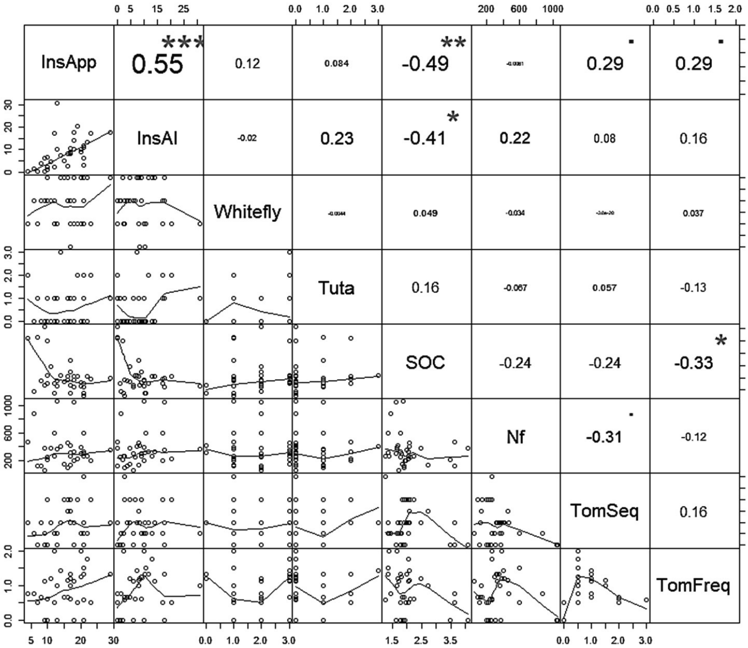

Fig. A2.3.4. Correlation matrix for insecticide input and whitefly and tomato leafminer (Tuta) incidence in long cycle tomato. p-value: *** <0.001, ** <0.05, *<0.10.

A2.4. Relation between nutrient input and yield per crop

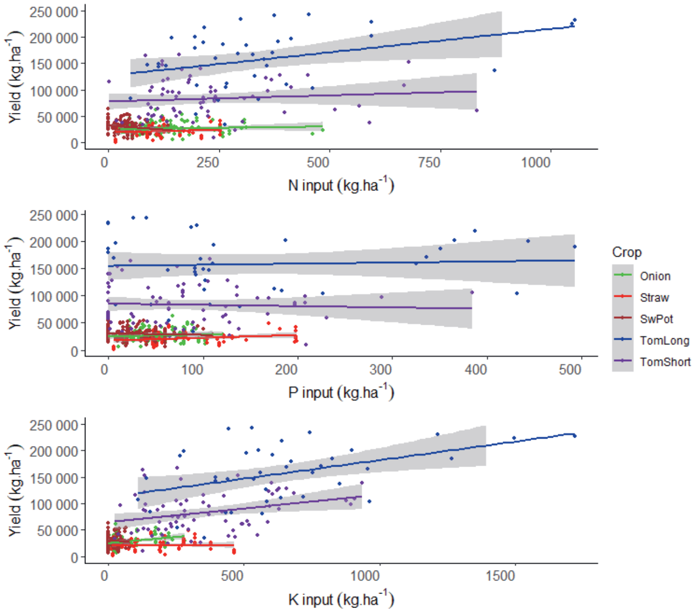

Fig. A2.4.1. Relation between yield and N, P and K application for each crop. Colours correspond to crops, and each dot correspond to a field.

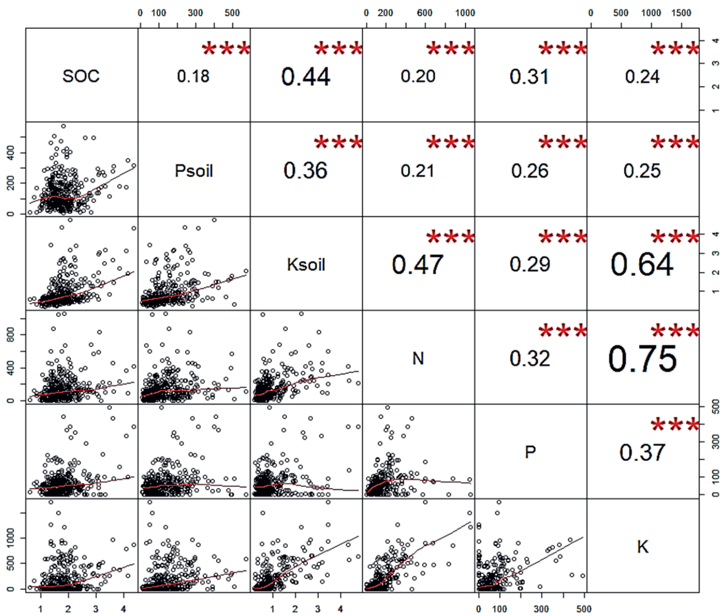

Fig. A2.4.2. Correlation matrix between soil nutrient status and nutrient input considering all the fields (N=428). SOC: soil organic carbon (%), Psoil: soil P Bray I content (ppm), Ksoil: soil K content (meq/100g), N, P, K: N, P and K input (kg.ha^{-1}). *** p-values < 0.001.

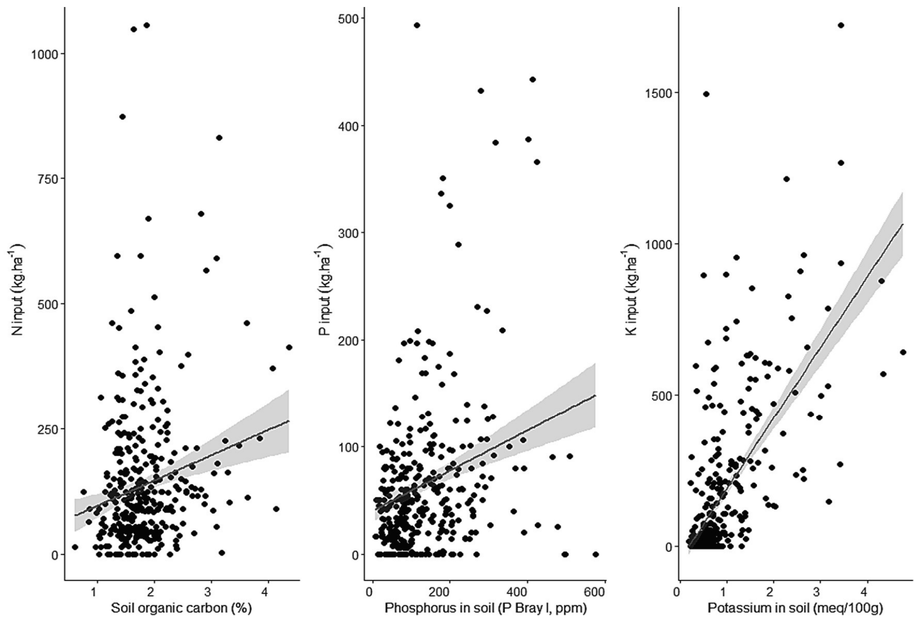

Fig. A2.4.3. Relationships between N, P, and K input and soil organic carbon, P, and K in the soil, respectively (N=428 fields).

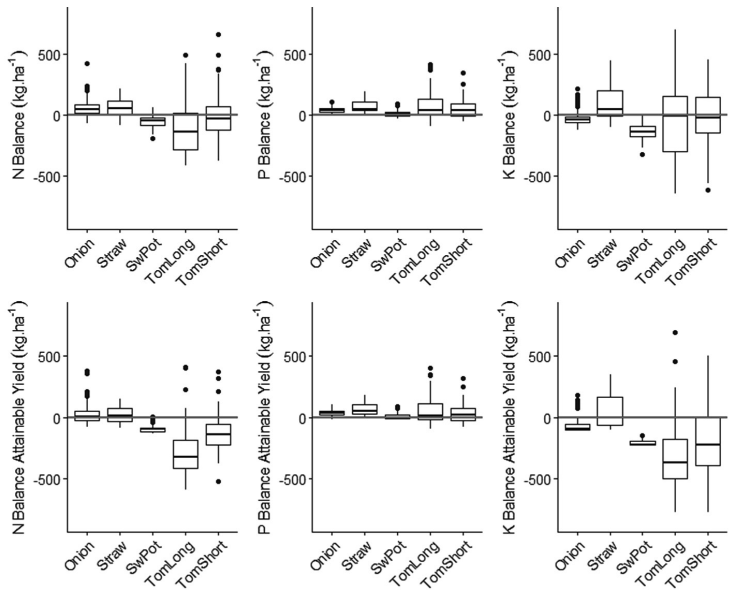

Fig. A2.4.4. Boxplots of nitrogen (N), phosphorus (P), and potassium (K) balance for onion, strawberry (Straw), sweet potato (SwPot), long cycle tomato (TomLong) and short cycle tomato (TomShort) considering (A) the nutrient uptake estimated for the observed yield, and (B) nutrient uptake for attainable yield (90th percentile yield) (B). Attainable yields were 41.1 Mg ha^{-1} for onion, 35.2 Mg ha^{-1} for strawberry, 23 kg m^{2} for long cycle tomato, 15 kg m^{2} short cycle tomato, and 44.9 Mg ha^{-1} for sweet potato.

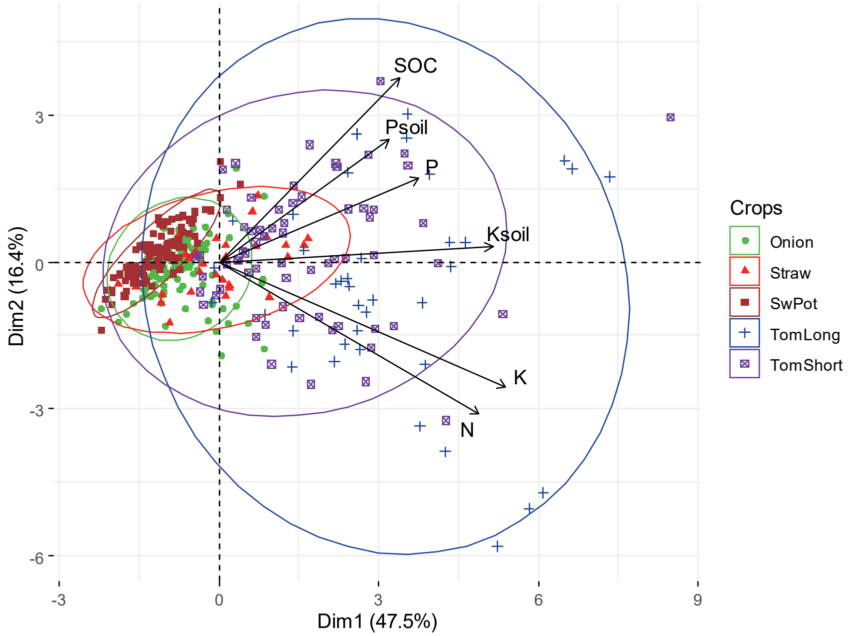

Fig. A2.4.5. Principal component analysis considering N, P, K input (kg per ha), soil organic carbon (SOC), P and K soil content. Crops are indicated with specific markers. N = 428 fields. The total variation explained by the first two principal components is 64%.

A2.5. Description of farm groups distinguished on the basis of yield-input index

Table A2.5.1. Structural characteristics of farms according to farm groups defined by yield and input index. For each crop, values with the same letter or no letter are not significantly different between farm groups at the p=0.05 level.

Group yield-input [1]	N	Yield (Mg ha^{-1})*	Input Index*	Farm size (ha)*	Area vegetable crops (ha)*	Area crop of interest (ha)*	GH area (ha)*	Total labour (FTE)*[2]	Ratio Family /Total labour*	Ratio Permanent /Total labour*	Mecha-nisation Level** [3]	Activities Diversifi-cation** [4]
Onion		**9.6e-05**	**2.7e-05**	n.s	n.s	n.s		n.s	**0.026**	n.s	n.s	n.s
High-High	8	35 ± 6 a	45 ± 13 a	43 ± 36	17.3 ± 20.3	5.9 ± 4.8	NA	4.2 ± 2.1	0.6 ± 0.2 b	0.8 ± 0.2	4.5 (2 - 5)	3.5 (2 - 5)
High-Low	3	30 ± 4 a	27 ± 3 b	94 ±109	7.0 ± 5.2	2.2 ± 1.0	NA	2.6 ± 0.4	0.9 ± 0.1 ab	0.9 ± 0.1	4 (2 - 5)	4 (3 - 4)
Low-High	5	20 ± 2 b	34 ± 4 a	15 ± 8	6.5 ± 3.2	2.4 ± 1.2	NA	2.8 ± 1.5	0.9 ± 0.2 ab	0.9 ± 0.1	3 (2 - 4)	3 (3 - 4)
Low-Low	15	21 ± 3 b	21 ± 5 b	25 ± 21	8.1 ± 4.8	2.3 ± 1.8	NA	2.8 ± 0.9	0.9 ± 0.2 a	0.9 ± 0.2	3 (1 - 5)	3 (1 - 4)
Strawberry		**0.032**	**0.040**	n.s	n.s	n.s		n.s	n.s	n.s	n.s	n.s
High-High	6	26 ± 4 a	50 ± 12a	22 ± 21	8.5 ± 8.9	1.2 ± 1.6	NA	3.8 ± 1.3	0.7 ± 0.2	0.9 ± 0.1	3.5 (2 - 5)	3 (2 - 4)
High-Low	2	25 ± 5 a	25 ± 8 b	9 ± 6	4.3 ± 2.5	0.2 ± 0.1	NA	2.6 ± 0.5	1	1	2.5 (2 - 3)	3 (2 - 4)
Low-High	3	17 ± 3 b	42 ± 4 a	19 ± 14	7.8 ± 6.5	2.2 ± 1.9	NA	3.8 ± 1.6	0.6 ± 0.4	0.9 ± 0.1	4 (1 - 5)	1 (1 - 5)
Low-Low	2	8 ± 7 b	15 ± 8 b	9 ± 10	1.3 ± 0.4	0.1 ± 0.0	NA	1.6 ± 0.9	0.8 ± 0.3	1	1.5 (1 - 2)	4.5 (4 - 5)
Long cycle tomato		**0.006**	**0.012**	n.s	n.s	n.s	n.s	n.s	n.s	n.s	n.s	n.s
High-High	4	190 ± 19 a	56±15 a	8 ± 6	1.1 ± 0.7	0.3 ± 0.2	0.6 ± 0.2	4.5 ± 1.6	0.7 ± 0.2	0.8 ± 0.1	3.5 (3 - 4)	2 (1 - 4)
High-Low	3	203 ± 37 a	28 ± 6 b	18 ± 8	1.1 ± 1.6	0.4 ± 0.4	0.4 ± 0.1	2.2 ± 0.4	0.8 ± 0.3	0.9 ± 0.1	3 (2 - 3)	2 (1 - 4)
Low-High	1	140 b	41 a	13	0.1	0.1	0.1	2	1	1	2	2
Low-Low	10	112 ± 29 b	24 ± 7 b	18 ± 26	3.0 ± 3.5	0.6 ± 0.6	0.8 ± 0.9	5.1 ± 4.5	0.6 ± 0.3	0.8 ± 0.2	3 (2 - 5)	3 (1 - 4)
Short cycle tomato		**0.002**	**0.003**	n.s	n.s	n.s	n.s	n.s	n.s	n.s	n.s	n.s
High-High	4	106 ± 18a	46 ± 11 a	12 ± 6	3.2 ± 2.8	0.7 ± 0.5	0.5 ± 0.3	4.4 ± 1.3	0.6 ± 0.1	0.9 ± 0.1	3.5 (3 - 4)	3 (1 - 5)
High-Low	6	115 ± 19 a	22 ± 5 b	28 ± 32	2.7 ± 2.8	0.6 ± 0.4	0.7 ± 0.6	5.7 ± 5.6	0.8 ± 0.3	0.7 ± 0.2	3 (2 - 5)	3.5 (1 - 4)
Low-High	4	67 ± 5 b	40 ± 9 a	7 ± 7	0.9 ± 1.0	0.3 ± 0.1	0.6 ± 0.5	2.8 ± 0.9	0.7 ± 0.3	1.0 ± 0.1	3 (2 - 5)	2.5 (2 - 4)
Low-Low	6	60 ± 20 b	20 ± 5 b	10 ± 7	2.2 ± 4.0	0.4 ± 0.3	0.5 ± 0.3	2.6 ± 0.5	0.8 ± 0.2	0.8 ± 0.2	3 (2 - 4)	2.5 (2 - 4)

*Average ± SD. **Median (min – max). n.s. no significant (p >0.05). NA: not applicable. [1]Label correspond to: yield level – input index level. [2]Full time equivalent (FTE) = 300 days of work and 8 hours per day = 2400 hours per year of labour. [3]Mechanisation level: see Appendix A. [4]Activities diversification: Appendix A. Within each crop Kruskal-Wallis test performed for testing differences among the four farm groups, "n.s" no significant (p <0.05).

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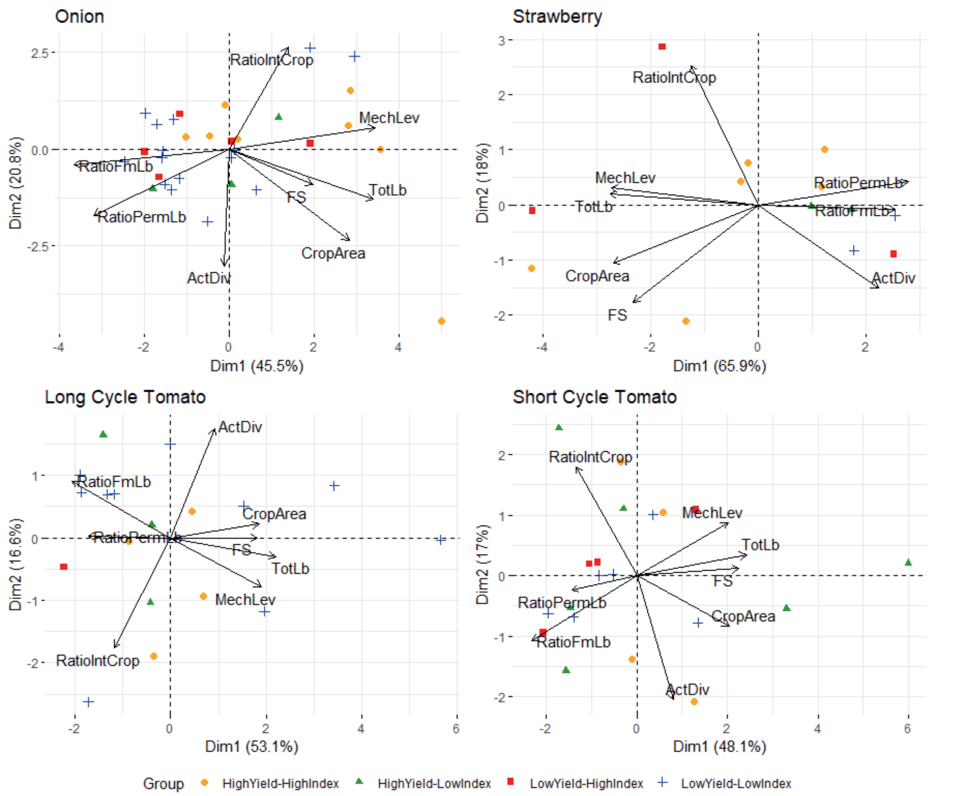
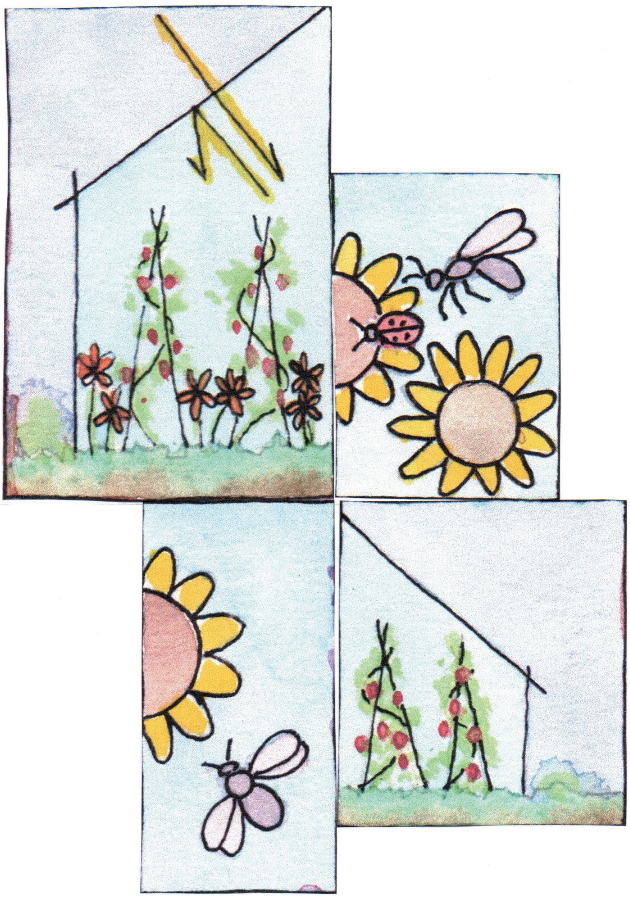


Fig. A2.5.1. Principal component analysis per crop according to farm characteristics: Farm size (FS), Total labour (TotLb), Ratio family to total labour (RatioFmLb), Ratio permanent to total labour (RatioPermLb), Area of vegetable crops (CropArea), Ratio area of the crop of interest to total crop area (RatioIntCrop), Activities diversification (ActDiv), Mechanization level (MechLev). Different shapes and colours correspond to different farm groups according to yield level and input index level. Onion: N = 31, variation explained by first two principal components is 66%. Strawberry: N = 13, variation explained: 84%. Long Cycle Tomato: N = 15, variation explained: 68%. Short Cycle Tomato: N = 19, variation explained: 65%



Chapter 3

Flowering plants in open tomato greenhouses enhance pest suppression in conventional systems and reveal resource saturation for natural enemies in organic systems

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Abstract

Vegetable production in open greenhouses is often associated with high inputs of synthetic pesticides. Introducing flowering plants into such greenhouses may promote the top-down pest suppression by natural enemies and reduce the reliance on pesticide use. However, it is not known how effective this practice is in organically and conventionally managed greenhouse crops. We assessed the influence of introducing flowering plants into open greenhouses with organically and conventionally managed tomato crops on the abundance of pests, natural enemies (NE), pollinators, and crop yield. We monitored tomato crops during two years in two greenhouses at four organic farms and four conventional farms that used integrated pest management (IPM). On each farm one greenhouse contained flower islands of basil (*Ocimum basilicum*), marigold (*Tagetes patula*) and alyssum (*Lobularia maritima*), and the other greenhouse served as a control. Organic farms had yields comparable to conventional farms, a lower abundance of pests, less pest injury, and a higher abundance of NE. The cumulative pest:NE ratio was 9 for organic and 38 for conventional management. The effect of introducing flowering plants on arthropods depended significantly on the type of farm management. Conventionally managed tomato crops in greenhouses with seven flower islands per 100 m^2 had 18% lower pest abundance compared to the control greenhouses without flowers, while flower islands did not significantly influence arthropod abundances in organically managed tomato crops. Tomato plants had a higher abundance of pests than the three introduced plant species in conventionally managed greenhouses, while marigold had a higher abundance of pests than tomato in organically managed greenhouses. Alyssum supported a relatively low pest abundance and high abundance of NE and pollinators. Our findings indicate that NE in IPM-conventionally managed greenhouses can benefit from resources provided by flowering plants, resulting in reduced pest abundance, while in organically managed greenhouses the conditions are already favourable for the suppression of pests and addition of floral resources does not further improve the effectiveness of NE. This finding highlights the potential of agroecological and organic management to reduce the reliance on synthetic pesticides without yield reduction.

Keywords: Conservation biological control; agroecology; integrated pest management; farm management; biodiversity; pest regulation

3.1. Introduction

Vegetable cultivation in (semi-)open greenhouses is often associated with the extensive applications of synthetic pesticides (van Lenteren, 2000), which can have adverse effects on the environment and human health (Mahmood et al., 2016; Tittonell et al., 2016; UNCTAD, 2017). Moreover, pest populations can quickly develop resistance against pesticides, triggering further pesticide use and potentially giving rise to a pesticide treadmill (Bommarco et al., 2011; van Lenteren, 2020). While approaches that strengthen biological control can reduce the reliance on chemical insecticides in vegetable greenhouse production (van Lenteren, 2000), growers often still lack context-specific and actionable knowledge of implementing such approaches on their farms.

There have been several examples of successful biological control in closed greenhouses by introducing natural enemies (Bueno, 2005; van Lenteren et al., 2020; van Lenteren et al., 2018), so-called classical or augmentative biological control strategies (Stenberg et al., 2021). However, in many parts of the world, greenhouses are open structures with an active exchange of arthropods with the surroundings. In open greenhouses, crop production is influenced by the agroecosystem within the greenhouse and the surrounding landscape that may act as a source for potential pests, natural enemies, and pollinators (Ardanuy et al., 2022; Aviron et al., 2016; Castañé et al., 2004; Gabarra et al., 2004; Messelink et al., 2021; Tscharntke et al., 2012; van Lenteren, 2000). In this context, conservation biological control (CBC) based on plant and habitat diversification is a promising approach to enhance natural enemy populations and disfavour pests (Stenberg et al., 2021), but has received limited attention for open greenhouse cultivation (Li et al., 2021).

Habitat manipulation is a cornerstone of CBC (Begg et al., 2017), which involves the provision of shelter and food, pollen and alternative prey/hosts to support effective populations of natural enemies (Landis et al., 2000; Messelink et al., 2014). Introducing flowering plants providing pollen, nectar, and shelter can be a promising strategy to attract and enhance the activity of natural enemies in greenhouses (Wäckers et al., 2005). This may be especially important for crops, such as tomato, that do not provide sufficient floral food resources to support effective natural enemy populations (Wäckers & van Rijn, 2012). The efficacy of several flowering plant species to enhance natural enemies has been assessed under controlled conditions (Arnó et al., 2018; Conboy et al., 2019; Kopta et al., 2012; Sivinski et al., 2011), but it is not clear how this unfolds under commercial open-greenhouse conditions (but see Li et al., 2021) and what flowering plant species are best suited for the specific agroecological context.

In open greenhouses, the effectiveness of CBC strategies is influenced by farm management (Aviron et al., 2016; Balzan et al., 2016; Begg et al., 2017). For instance, the introduction of flowering plants may play out differently in conventional systems where synthetic pesticides and synthetic fertilisers are used than in organic systems. Furthermore, within organic (Marliac et al., 2016; Pépin et al., 2021) or conventional management (Scarlato et al., 2022; Sumberg & Giller, 2022) there is a great diversity of management practices that could influence pest and natural enemy dynamics, such as crop diversity and vegetation management (Yang et al., 2021; Zehnder et al., 2007; Marliac et al., 2016), nutrients (Hsu et al., 2009; Stavisky et al., 2002) and soil management (Altieri et al., 2012; Magdoff & van Es, 2009). Moreover, the efficacy of CBC strategies in open greenhouse settings may be modulated by landscape complexity (Tscharntke et al., 2016, 2012). Following the intermediary landscape-complexity hypothesis proposed by Tscharntke et al. (2005, 2012) the effectiveness of biodiversity-based management interventions should be higher in simple, intermediately complex landscapes than in extremely simplified landscapes where additions to the impoverished species pool are not sufficient to instigate a meaningful response in the short term, or in highly complex landscapes where there is no discernible effect of adding more diversity (Tscharntke et al., 2005; Tscharntke et al., 2012). The wide variation in production situations calls for context-specific and actionable knowledge to support the design and adoption of more sustainable farm management (Altieri, 2002; Duru et al., 2015; Rossing et al., 2021).

This study assessed the influence of flowering plants in organically and conventionally managed greenhouse tomato on the abundance of pests, natural enemies and pollinators, and crop performance. To do so, we first characterised the management practices in organically and conventionally managed tomato greenhouses and the surrounding landscape. We then compared for each management system how the addition of flower islands influenced the abundances of pests, predators, parasitoids, pollinators and other phytophagous arthropods. Finally, we assessed the abundances of these arthropod groups on the flowering plant species.

3.2. Materials and methods

3.2.1. Study area and research approach

The study was conducted in the department of Canelones in the south of Uruguay, where most vegetable production is concentrated (34º21'S to 34º57'S – 55º40'W to 56º40'W). The climate is humid subtropical, with an average mean temperature of 17 °C (minimum: 11 °C, maximum: 23 °C) and light frosts between May and September. Mean annual precipitation is 1200 mm, evenly distributed throughout the year but with significant variation between years (Castaño et al., 2011). The main soil types are Mollic Vertisols

(Hypereutric), Luvic/Vertic Phaeozems (Pachic), and Luvic Phaeozems (Abruptic/Oxyaquic) (Alliaume et al., 2013).

The south of Uruguay comprises 350 ha of greenhouse crops, where tomato is the main crop (DIEA-MGAP, 2017). Typical greenhouses are "open greenhouses" made of wooden posts covered with transparent polyethylene plastic, where ventilation is manually controlled through opening and closing the plastic cover on the sides. Greenhouses typically comprise areas between 380 and 1000 m^2, and crops are cultivated in the soil (Fig. 3.1). Greenhouse tomato is produced in short (200 days or less) or long (more than 200 days) cycles. The typical short cycle in spring is transplanted in August or September and harvested until January or February (Berrueta et al., 2019). In this short cycle, greenhouse whitefly (*Trialeurodes vaporariourum* Westwood*,* Hemiptera: Aleyrodidae) and tomato leaf miner (*Tuta absoluta* (Meyrick)*,* Lepidoptera: Gelechiidae) are major pests that can reduce tomato yield (Berrueta et al., 2019). Occasional pests are thrips (*Frankliniella occidentalis* Pergande, and *F schultzei* (Trybom), Thysanoptera: Thripidae), aphids (*Macrosiphum euphorbiae* (Thomas) and *Aphis gossypii* Glover, Hemiptera: Aphididae), red spider mite (*Tetranychus urticae* Koch, Acari: Tetranychidae), tomato russet mite (*Aculops lycopersici* (Tryon), Acari: Eriophydae), stinkbug (*Nezara viridula* L., Hemiptera: Pentatomidae), and cucurbit beetle (*Diabrotica speciosa* (Germar), Coleoptera: Chrysomelidae) (Bentancourt & Scatoni, 2010).

We used a participatory research approach where farmers and technicians were closely involved in problem identification and execution of the research. Farmers and technicians expressed their interest to explore the potential of flowering plants in greenhouses to enhance beneficial arthropods during a workshop in December 2017. Field days were organised in farms that used sown flowers in greenhouses to discuss the management and experiences in 2018. During September 2019 and December 2020, preliminary results and adjustments of the experiment were discussed with farmers and technicians during two workshops, and farmers involved in the experiment had weekly interactions with the research team (see below).

3.2.2. Experimental design

The experiment was conducted at four organically certified and four conventionally managed farms in Canelones. The organic farms were certified and implemented agroecological management for more than five years. The conventional farms implemented biological control and integrated pest management (IPM) for at least three years (Table 3.1). The criteria for farm selection were: (i) tomato had been an important crop for more than five years; (ii) each farm comprised at least two greenhouses with short cycle spring tomato with similar size, soil type, surrounding vegetation, previous

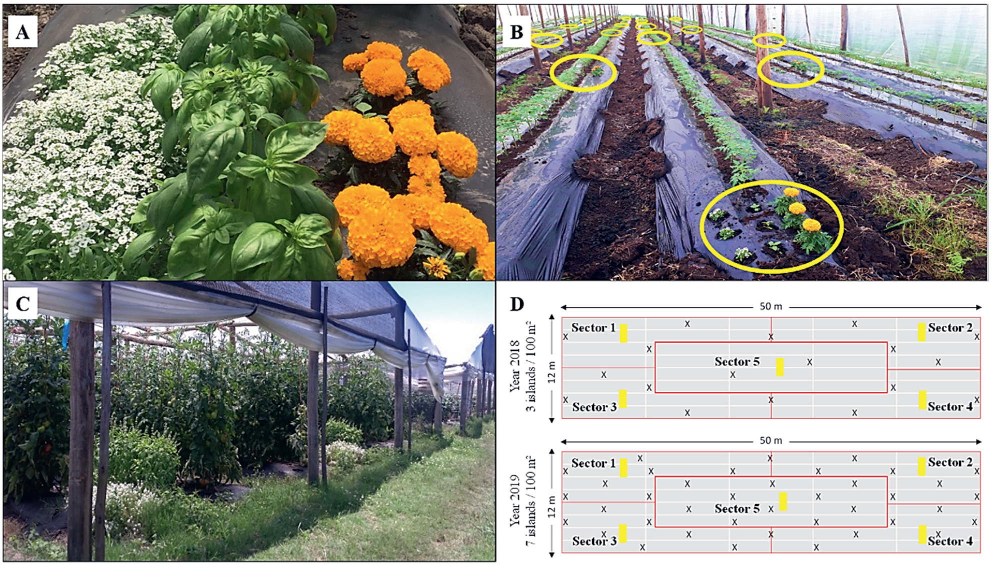


Fig. 3.1. Flower island composition with three plants of basil in the middle and three marigold and alyssum plants on each side (A), flower islands at ten days post-transplanting (B), flower islands located in the borders of the greenhouse at the onset of tomato harvest (C), schematic overview of a greenhouse of 600 m^2 divided into five sectors, with locations of yellow sticky traps (yellow quadrangles) and flower islands (crosses) in 2018 and 2019 (D).

crop, and management (tomato variety, planting date, plant density, soil and fertilisation management); (iii) farmers were willing to engage in the participatory research process. At each farm, we selected two paired greenhouses. In one randomly selected greenhouse, flower islands were established (treatment), while the other greenhouse did not receive flower islands (control). In total, sixteen greenhouses (2 greenhouses x 8 farms) were included. The experiment was conducted during two growing seasons: from October to January 2018-2019 ("Year 2018") and from October to January 2019-2020 ("Year 2019"). Year 2018 had more rain and a greater number of rainy days, less radiation and lower temperatures than 2019 (Appendix A3.1.).

The plant species selected for the flower islands were *Lobularia maritima* (L.) Desv. (alyssum, Brassicaceae), *Tagetes patula* L. (marigold, Asteraceae), and *Ocimum basilicum* L. (basil, Lamiaceae). These species were selected because (i) some organic farmers were already using these plant species; (ii) these plant species attract natural enemies without attracting potential pests or hosting tomato viruses (Ambrosino et al., 2006; Balzan & Wäckers, 2013; Jankowska, 2010; Lu et al., 2014; Song et al., 2010); (iii) the flowering periods coincide with the tomato crop cycle; and (iv) the plants were readily available from local nurseries.

Table 3.1. Overview of farms, type of management, resource endowment and greenhouses size.

Farm number	Type of management[1]	Farm size (ha)[2]	Mechanisation level[3]	Total labour (FTE)[4]	Family labour (proportion of Total labour)	Annual farm area vegetable crops (ha)	Greenhouse area vegetable crops (ha)	Irrigated area[5]	Average individual greenhouse size (m^2)
F1	Organic (since 1991)	26	5	9.1	0.22	5.8	0.77	3	750
F2	Organic (since 1995)	90	5	15.6	0.19	9.5	1.77	2	840
F3	Organic (since 1992)	27	4	12.2	0.30	9.0	0.40	2	700
F4	Organic (since 2014)	27	4	15.8	0.27	6.0	1.14	2	588
F5	Conventional (BC since 2015)	42	4	8.0	0.30	2.9	2.9	3	980
F6	Conventional (BC since 2016)	26	3	3.2	0.63	10.2	0.82	2	1050
F7	Conventional (BC since 2016)	2.2	3	3.1	1	0.7	0.34	3	396
F8	Conventional (BC since 2016)	9	3	2.9	1	0.5	0.48	3	480

[1] BC: biological control. In all cases, farmers used entomopathogenic fungus to control whitefly and used selective insecticides when possible.

[2] Farm size corresponded to the total area managed by the farmer.

[3] Scale 1 to 5: 1: no tractor or 1 tractor but no tractor sprayer, greenhouse sprayer, mulching machine, disc ridger, rotary tiller, cultivator; 2: 1 tractor and one implement mentioned in 1; 3: 1 tractor and 2 or more implements, or 2 tractors and 2 implements; 4: 2 tractors and more than two implements; 5: 3 or more tractors and 2 or more implements.

[4] Full-time equivalent (FTE). 1 FTE = 300 days of work and 8 hours per day = 2400 hours per year of labour.

[5] Scale 1 to 3: 1: less than 50% of the annual vegetable area under irrigation, 2: between 51 and 80% of the annual vegetable area under irrigation, 3: 100% of the annual vegetable area under irrigation.

Each flower island contained three basil, alyssum and marigold plants, for a total of nine plants (Fig. 3.1-A). The area of the flower island was approximately 1 m^2, with a distance of approximately 30 cm between plants. In the first year, we established three islands per 100 m^2 greenhouse, with a maximum distance of 8 m between islands and two islands on each greenhouse border (Fig. 3.1-B, C, D). After discussing first-year results with farmers and technicians, the number of islands in the second year was increased to seven islands per 100 m^2 greenhouse and three islands on each greenhouse border (Fig. 3.1-D).

3.2.3. Data collection

3.2.3.1. Crop and farm management and tomato yield

Farmers were interviewed to assess their farm and greenhouse management. During the study, the farmers kept records of the pesticide applications (product, dose, date) and other management practices in the greenhouses (soil tillage, fertilisation, irrigation, plant management). We recorded tomato plant density, tomato variety, planting and transplanting date, harvest period, and the preceding crop in the greenhouses. Crop yield was calculated from farmer records of weekly harvests. Soils were characterised through a description of the soil profile and soil analysis. Composite soil samples were taken from the top layer (0–20 cm). We determined soil organic carbon using the Walkley-Black method described by Nelson & Sommers (1996), extractable phosphorus (P, Bray & Kurtz, 1945), exchangeable potassium (K) (atomic absorption spectrophotometry following ammonium acetate 1M extraction at pH 7 (Isaac & Kerber, 1971), and nitrate content (colorimetry, Mulvaney, 1996). Leaf N concentration was assessed by the Kjeldahl method (Bremmer & Mulvaney, 1982) at the start of harvest in the second year on a sample of 15 randomly selected young fully-grown leaves in each greenhouse. Temperature and relative humidity in the greenhouse during the crop cycle were recorded in the second year with a Datalogger (MX2301) placed in the middle of each greenhouse at 2 m height. The percentage of ground cover of weeds in the pathways of the greenhouses was assessed using a ground cover estimation sheet (McNaught et al., 2008). The weed cover assessment was conducted at twenty random plots of 625 cm^2 (25 x 25 cm) in the pathways of each greenhouse at each sampling round during the first year and at the last four rounds in the second year. Weed cover was classified into three levels: low (less than 20% soil cover during the entire season), medium (between 20 and 50% soil cover in at least half the sampling rounds), and high (more than 50% in at least half the sampling rounds).

3.2.3.2. Surrounding vegetation

The vegetation around each greenhouse was mapped at two scales: within 3 m and within 150 m. Within 3 meters of the greenhouse border, we assessed (i) the type of vegetation (grass, grass and shrubs, bare soil); (ii) the average vegetation height (<20 cm, 20-50 cm, >50 cm); (iii) the number of plant species (<10, 10 to 20, >20); (iv) the identity of the two or three main plant species; and (v) the type of management or use (mowing, pathway, no management). We classified the area into 4 quality levels: Very low: ≥ 50% bare soil; Low: full vegetation cover with vegetation height < 20 cm and less than ten plant species; Medium: full vegetation cover with vegetation height ≥20 cm or more than ten plant species; and High: full vegetation cover with vegetation height ≥20 cm and more than ten plant species. In a 150 m radius around the greenhouse, we recorded the type of land use (field crops, vegetable greenhouse crops, pastures, and non-cultivated land) and the type of vegetation (crop species and semi-natural habitat type(s): pasture and/or shrubs and/or trees). The surroundings were classified into three levels of complexity: Low: >75% arable land and greenhouses; medium: 50-75% arable land and greenhouses; and high: <50% arable land and greenhouses.

3.2.3.3. Yellow sticky traps

The abundance of pests, natural enemies, and pollinators in the greenhouses was assessed using yellow sticky traps. Each greenhouse was divided into five sectors, and one sticky trap was placed in the middle of each sector (Fig. 3.1-D). The sticky traps (15 x 20 cm) had thirty-six quadrants (2 x 2 cm) on each side. Traps were placed above the tomato plants by attaching them to the beams of the greenhouse at approximately two meters height. In 2018, four 14-day sampling rounds were conducted from mid-November (starting dates: mid-November, early December, mid-December, and early January). In 2019, one earlier round was included (early November) for a total of five sampling rounds.

Upon collection, the traps were wrapped in plastic clingfilm and put in a freezer until processing. Eight of the thirty-six quadrants (32 cm^2) on one side of the sticky trap were inspected (one quadrant in each corner, two quadrants left from the centre and two quadrants right from the centre of the sticky trap). The arthropods in the eight quadrants were identified under a microscope to order, family or species level and divided into six functional groups: tomato pests, other phytophagous arthropods, predators, parasitoids, pollinators, and other arthropods. Natural enemies (NE) comprised predators and parasitoids. The group "other arthropods" consisted of arthropods that did not belong to any of the other functional groups or that we could not classify with certainty (e.g. Diptera and ants; Appendix A3.2.).

3.2.3.4. Pest infestation levels on tomato plants

In each sampling round, twenty tomato plants were randomly selected per greenhouse to visually assess whitefly abundance and tomato leaf miner injury. Whitefly adults were counted on the three top leaves of each plant. Tomato leaf miner injury was assessed by counting the number of tunnels on three leaves per plant, at the top, middle, and bottom stratum of plants, respectively. In addition to the sampling rounds described for sticky traps, in 2019 one extra late round of tomato plant assessment was included in mid-January, for a total of four rounds in 2018 and six rounds in 2019.

3.2.3.5. Visual observation of flower islands

We assessed flower visitation by arthropods during 15-minute observation periods, divided into 5 minutes per flowering plant species. Observations were made on one randomly selected flower island in each of the five sectors per sampling round in 2018 and three randomly selected islands per greenhouse per sampling round in 2019. Because many arthropods are sensitive to motion, the observer remained motionless during observation and did not cast a shadow on the flower island (Ambrosino et al., 2006). Sampling rounds coincided with yellow sticky traps rounds, for a total of four in 2018 and five in 2019. The arthropods were recorded per plant species, and we used the same arthropod groups as for the yellow sticky traps.

3.2.3.6. Suction sampling

Arthropods on the flowering plant species in 2018 and 2019 and tomato plants in 2019 were sampled using a handheld aspirator (PK-VC404, 80W) (Swart et al., 2017). Following the visual observation of flower islands, each flowering plant species and the three tomato plants nearest to each island were sampled for ten seconds. Arthropods were collected in bags and put in a freezer until processing. The arthropods were identified and classified in the same functional groups used for the yellow sticky traps.

3.2.3.7. Quality assessment of flower islands

Flower island quality was assessed by recording the number of plants per species and their development stage (vegetative or flowering). During each round, the quality of each sampled flower island was recorded. All islands in a greenhouse were assessed at harvest initiation and the end of the tomato cycle.

3.2.4. Data analysis

We conducted the analysis in four steps. First, the 16 greenhouses were grouped according to their crop and farm management practices, not considering management type. The following variables were included: the amount of organic, synthetic and total N, P, K inputs (kg per ha); the number of synthetic and organic insecticide applications, fungicide applications, and the total number of pesticide applications; biological and alternative products applications; soil organic carbon (percentage) and relative active soil organic matter (proportion); previous crop (tomato, other solanaceous, or other not solanaceous crops); the presence of other crops in the greenhouse (yes or no); weed cover (low, medium, high); vegetation in the 3 m radius (very low, low, medium, high) and the 150 m radius (low, medium, high); crop diversity in the 150 m radius and over the year (number of crops); plant density (plants m^{-2}), greenhouse size (m^2), nylon black mulch use (yes or no), and tomato variety type (hybrid, no hybrid). In total 27 variables were included. Factor analysis of mixed data (FAMD) was used to transform categorical variables into continuous principal components and combine and reduce the number of variables (Kassambara, 2017). Hierarchical cluster analysis on the first seven dimensions of the FAMD output was conducted (principal components, HCPC), which explained 88% of the variance. Clusters were defined according to the proportion of the total explained variability and agronomic criteria, and were characterised by the significant active variables used in the partition (Kassambara, 2017). The tomato yield among clusters was compared using the Kruskal-Wallis test.

Second, we assessed how the arthropod abundances per functional group on the yellow sticky traps, and whitefly abundance and leaf miner injury on tomato plants were influenced by the presence or absence of flower islands and the farm management type. We only used data from greenhouses of which 80% of the flower islands still contained at least two flowering plants per species at tomato harvest, resulting in the exclusion of data from farms F1 (organic) in 2018 and F4 (organic) and F5 (conventional) in 2019. We also excluded F6 (conventional) in 2018 because the tomato crops in the two greenhouses were subject to different pesticide application regimes. We used generalised linear models and principal component analysis (PCA) and analysed each year separately. For the generalised linear model analysis, response variables were the abundance of pests, other phytophagous arthropods, parasitoids, predators, natural enemies, pollinators, other arthropods, and total number of arthropods on the yellow sticky traps, number of adult whitefly individuals and number of leaf mines per tomato plant. Explanatory variables were management (organic or conventional), treatment (flowers or control), sampling round, and their two-way interactions. Arthropod abundances and tomato leaf miner injury were treated as count data, and we tested the Poisson, negative binomial, zero-inflated Poisson, and zero-inflated negative binomial error distributions. We selected the negative binomial error distribution for all response variables and both years because models with this error distribution had the lowest Akaike Information Criterion (AICc) value. Residual plots confirmed that the models met homogeneity of variance criteria (Zuur & Ieno, 2016; Zuur et al., 2010). We applied a model selection procedure using the dredge approach, which calculates all possible factor combinations and sorts the models according to the value of AICc. Then we used full model averaging in the cases where we had more than one model within an envelope of 2 delta AICc points (Burnham & Anderson, 2007; Feld et al., 2016; Grueber et al., 2011). For the PCA analysis, we used the summed number of arthropods of all sampling rounds for each functional group, whitefly individuals, and number of tomato leaf mines per tomato plant.

Third, we assessed whether tomato yield was related to management type and the presence or absence of flowers. We used linear models including yield as response variable, and year, management type, flower treatment and their two-way interactions as fixed effects. Residual plots confirmed that the models met homogeneity of variance criteria (Zuur & Ieno, 2016; Zuur et al., 2010). First, we performed the analysis excluding farms F1 and F6 in 2018, and F4 and F5 in 2019 (24 greenhouses). As the flower treatment was not significant, we performed an analysis with the full dataset (32 greenhouses; 2 years).

Fourth, we analysed the arthropod abundance data obtained by suction sampling and visual observation of the three flowering plant species. We used suction sampling data at the functional group level on marigold, alyssum, basil in 2018 and 2019, and tomato in 2019. For visual observations, we used data at the arthropod functional group level on marigold, alyssum and basil in both years. We used generalised linear models and PCA. In the generalised linear models, the response variables were the abundance of arthropods in each functional group. Pollinators in the suction sampling were discarded because the numbers were too low for a meaningful analysis. The explanatory variables were: farm management type (organic or conventional), plant species (marigold, alyssum and basil for both methods, including tomato in suction data in 2019), year, and round. Model selection and validation were conducted in a similar way as described for step 2. For all functional groups, a negative binomial error distribution was used. For the PCA analysis, we considered the cumulative number of arthropods per functional group (sum of all sampling rounds).

Data analyses were conducted using R 3.6.3 (2020-02-29). The R-packages "factoextra" (Kassambara & Mundt, 2020b) and "FactoMineR" (Le et al., 2008) were used for FAMD, HCPC and PCA analyses. The R-packages "MASS" (Venables & Ripley, 2002), "pscl" (Jackman, 2020) and "car" (Fox & Weisberg, 2019) were used for analyses with generalised linear models, and "MuMIn" (Barton, 2020) for model selection and averaging. The R-packages "lattice" (Sarkar, 2008), "ggplot2" (Wickham, 2016), "ggpubr" (Kassambara, 2020a) and "HH" (Heiberger, 2020) were used for data visualization.

3.3. Results

3.3.1. Characterisation of farm management types

The first partition of the HCPC analysis explained 31% of the total variability and resulted in two clusters coinciding with the two farm management types: one cluster included all the organically managed greenhouses, while the other included all the conventionally managed greenhouses (Table 3.2, Appendix A3.3). Organic management was characterised by a higher number of crops (ranging from 12 to 30 versus 1 to 5 in conventional, $p<0.001$) and higher soil organic carbon ($p<0.001$). Both management types used organic manure, but conventional farms combined it with synthetic fertilisers. Organic farms had lower organic and total N, P and K fertiliser input than conventional farms ($p<0.001$). Both farm management types had a similar total number of pesticide applications, but differed in the type of products used (Table 3.2, Appendix A3.3). Synthetic pesticides were not used in organic management, but the application of organic insecticides in organically managed greenhouses exceeded those of conventionally managed greenhouses ($p<0.05$). Organically managed greenhouses had a higher weed cover than conventional ones ($p<0.01$). Organically managed farms had high and medium vegetation quality in the 3 m area around greenhouses, while conventional farms had low and very low vegetation quality ($p<0.01$). Conventional farms had a higher proportion of high-quality vegetation within a 150 m radius, while organic farms had more medium quality vegetation ($p<0.05$, Table 3.2). Tomato crop yield was not significantly different between organically and conventionally managed greenhouses (Kruskal-Wallis tests $p=0.676$, Table 3.2).

3.3.2. Arthropod sampling in greenhouses and flower islands

Across the two years, 49,073 arthropods were captured on sticky traps in the 16 greenhouses (2018: 19,922; 2019: 29,151). While we captured a higher number of arthropods in 2019 than in 2018, the distribution of the arthropods across functional groups and the main pests, NE and pollinators, were roughly similar. Pests comprised 78% of the total number of arthropods, followed by NE (10%) and other arthropods (9%) (Table 3.3). Suction sampling of the flowering plants and tomato in the 16 greenhouses resulted in 9,804 arthropods, and 4,531 arthropods were recorded during visual observation of flowering plants (Table 3.3). Suction samples were dominated by "other arthropods" (62% of the individuals), pests (19%) and NE (11%, Table 3.3). In visual observations, "other arthropods" accounted for 39% of the individuals, followed by NE and pollinators in 2018 and NE and pests in 2019 (Table 3.3). The main pests, NE and pollinators, were the same in both years (Table 3.3). Detailed information can be found in Appendix A3.4.

3.3.3. Influence of flower islands and farm management

Organically managed tomato supported a significantly lower abundance of pests ($p<0.001$), lower population densities of greenhouse whitefly ($p<0.05$ to 0.001 depending on the round), and lower tomato leaf miner injury levels ($p<0.001$) than conventionally managed tomato, and this was consistent for 2018 and 2019, and for

Table 3.2. Characterisation of management across the 32 greenhouses and identification of clusters based on HPCP analysis. Two clusters were identified: one cluster included all greenhouses of conventional farms, while the other included all the organic ones. NA is not applicable. Statistically significant differences are indicated in bold, ns: not significant.

Indicator	Units	**Cluster 1: Conventional**					**Cluster 2: Organic**					p-value HCPC analysis
		Number	Average	S.D	Min	Max	Number	Average	S.D	Min	Max	
Yield[1]	kg/m^2	16	9.1	1.9	6.0	12.0	16	8.7	2.3	5.5	12.0	NA
Synthetic insecticide applications	Number of applications	16	**3.1**	**3.2**	**0**	**9**	16	**0**	**0**	**0**	**0**	**<0.001**
Organic insecticide applications	Number of applications	16	**0.1**	**0.3**	**0**	**1**	16	**3.0**	**4.0**	**0**	**10**	**<0.05**
Fungicide applications	Number of applications	16	2.7	2.8	0	9	16	2.9	4.0	0	10	ns
Total number of pesticide applications	Number of applications	16	4.3	2.7	1	9	16	3.6	3.9	0	10	ns
Biological and alternative applications [2]	Number of applications	16	4.1	3.3	0	10	16	3.6	5.0	0	15	ns
Soil organic carbon	%	16	**1.83**	**0.37**	**1.31**	**2.45**	16	**2.69**	**0.49**	**2.13**	**3.63**	**<0.001**
Relative active soil organic carbon [3]	Proportion	16	**0.41**	**0.24**	**0.15**	**0.95**	16	**0.71**	**0.19**	**0.49**	**1.16**	**<0.01**
N input-organic source	g/m^2	16	**10.0**	**3.8**	**6**	**19**	16	**6.3**	**3.4**	**3**	**10**	**<0.01**
P input-organic source	g/m^2	16	**9.4**	**5.4**	**3**	**22**	16	**4.3**	**2.6**	**2**	**8**	**<0.01**
K input-organic source	g/m^2	16	**41.4**	**23.7**	**8**	**93**	16	**22.8**	**13.3**	**10**	**43**	**<0.01**
N input – synthetic source	g/m^2	16	**2.3**	**2.4**	**0**	**6**	16	**0**	**0**	**0**	**0**	**<0.01**
P input – synthetic source	g/m^2	16	0	0	0	0	16	0	0	0	0	ns
K input – synthetic source	g/m^2	16	**12.3**	**16.9**	**0**	**40**	16	**0**	**0**	**0**	**0**	**<0.05**
N input – total	g/m^2	16	**12.0**	**3.8**	**9**	**21**	16	**6.3**	**3.4**	**3**	**10**	**<0.001**
P input – total	g/m^2	16	**9.4**	**5.4**	**3**	**22**	16	**4.3**	**2.6**	**2**	**8**	**<0.01**
K input – total	g/m^2	16	**53.5**	**24.9**	**18**	**96**	16	**22.8**	**13.3**	**10**	**43**	**<0.001**
NO3-soil at harvest initiation	ppm	8	236	106	116	376	8	181	81	96	314	NA
N-leaf at harvest initiation	%	8	2.8	0.2	2.5	3	8	2.6	0.6	1.8	3.6	NA
Average air temperature	ºC	8	22.5	1.7	20.0	26.0	8	22.7	1.6	19.7	25.4	NA
Average relative humidity	%	8	68.3	4.9	56.5	77.7	8	69.0	5.1	58.2	81.0	NA
Plant density	Number of plants / m^2	16	2.64	0.22	2.22	3.07	16	2.37	0.38	1.87	3.45	ns
Greenhouse size	m^2	16	686	314	320	1080	16	724	115	528	870	ns
Indicator	Units	Number	Median		Min	Max	Number	Median		Min	Max	
Number of crops in 150m radius	Number of crops	16	**2**		**1**	**5**	16	**19**		**12**	**30**	**<0.001**
Number of crops per year in the farm	Number of crops	16	**6**		**2**	**8**	16	**41**		**28**	**48**	**<0.001**
Indicator	Classes	Number	Number of cases per class				Number	Number of cases per class				
Vegetation quality in the 3 m radius [4]	High / Medium / Low /Very Low	16	**0 high, 2 medium, 6 low, 8 very low**				16	**6 high, 10 medium, 0 low, 0 very low**				**<0.001**
Proportion of uncultivated land 150 m radius[5]	High / Medium / Low	16	**9 high, 7 medium, 0 low**				16	**3 high, 12 medium, 1 low**				**<0.05**
Previous crop in the greenhouse	Tomato/Other Solanaceae/Other	16	5 tomato, 5 other Solanaceae, 6 other				16	6 tomato, 6 other Solanaceae, 4 other				ns
Diverse crops inside the greenhouse	Only tomato / Combined	16	**16 only tomato**				16	**9 only tomato, 7 combined**				**<0.05**
Weed cover inside greenhouse [6]	High / Medium / Low	16	**0 high, 8 medium, 8 low**				16	**8 high, 4 medium, 4 low**				**<0.01**
Nylon black mulch	Yes/ No	16	6 yes, 10 no				16	12 yes, 4 no				ns
Tomato variety [7]	Hybrid / Non-hybrid	16	16 hybrid				16	12 hybrid, 4 mixture hybrid-non-hybric				<0.1

[1] Estimated based on weekly records of the farmers. Not significantly different for organically and conventionally managed greenhouses (Kruskal-Wallis tests p=0.676). [2] Entomopathogenic fungus, milk and bicarbonate, vegetable oil. [3] Relative Active Soil Organic Carbon (RASOC) = ((Actual SOC – Min SOC)/(Max SOC – Min SOC)) * 100 (Dogliotti et al., 2014). [4] Vegetation quality in the 3 m radius: High: soil full covered, more than 20 sp and more than 10 sp., Medium: soil full covered, more than 20 cm or more than 10 sp, Low: soil full covered, less 20 cm high, less than 10 species, Very low: with 50% or more soil no covered. [5] Proportion of uncultivated land in 150 m radius: High: < 50% crop fields and greenhouses, Medium: 50-75% crop fields and greenhouses, Low: > 75% crop fields and greenhouses. [6] Weeds cover: High: more than 40% in at least half sampling rounds, Medium: between 10 and 40% in at least half sampling rounds, Low: less than 10% soil cover during all season. [7] Tomato genetic: Hybrid: Belfast, Eterei, Ichiban, Barteza, Santa Paula; Non-hybrid: farmer´s seeds of heirloom tomatoes

Table 3.3. Number of arthropods collected by three sampling methods, distribution among functional groups and main orders/families of dominant groups.

Method	Total number of arthropods	Distribution among the functional groups (%) and main order/family identified within each functional group (%)					
		Pests	Natural enemies (NE)		Pollinators	Other phytoph.	Other
			Parasitoids	Predators			
Sticky traps	49073	78 greenhouse whitefly (Hemiptera: *Aleyrodidae*, 80%) thrips (Thysanoptera: *Terebrantia*, 17%)	8 microhymenoptera (74%) longlegged flies (Diptera: *Dolichopodidae,* 8.5%)	2	3 houseflies (Diptera: *Muscidae,* 38%) wasps (Hymenoptera: *Vespidae*, 33%)	1	8
Suction sampling of flowering plants and tomato	9804	19 thrips (Thysanoptera: *Terebrantia*, 63%) aphids (23%)	6 microhymenoptera (51%) spiders (33%)	5	0	8	62
Visual observation of flowering plants	4531	17 stinkbugs (Hemiptera: *Pentatomidae*, 55%) thrips (Thysanoptera, 37%)	13 microhymenoptera (44%) hoverflies (Diptera: *Syrphidae,* 26%) spiders (8%)	14	9 houseflies (72%) wasps (17%)	8	39

yellow sticky trap data and observed pest infestation levels on tomato plants (Fig. 3.2-A and 3.2-C, Table 3.4). Pest populations, dominated by greenhouse whiteflies, increased exponentially in conventional farms, while in organic farms, populations only increased slightly or remained stable along crop cycle (Fig. 3.3, Appendix A3.5).

In 2018 the establishment of flower islands did not significantly influence the abundance of pests on sticky traps (Table 3.4, Fig. 3.2-B) or observed pest infestation levels on tomato plants (Fig. 3.2-B, Appendix A3.5.). Similarly, in 2019, greenhouse whitefly abundance assessed by visual observation and tomato leaf miner injury on tomato plants were not significantly influenced by the presence of flower islands (Appendix A3.5.). For sticky trap catches, however, there was a significant interaction between the farm management type and treatment in 2019 ($p<0.05$), indicating that pest abundance was lower in greenhouses with flowers on conventional farms but not on organic farms (Table 3.4, Fig. 3.2-D, Fig. 3.3). In the three conventional farms included in the analysis in 2019, the summed number of pests of all sampling rounds of the greenhouse with flowers was 18 ± 8% lower than the control greenhouse.

In both 2018 and 2019, NE abundance on yellow sticky traps was significantly higher in organically than in conventionally managed tomato ($p<0.001$ in 2018, $p<0.01$ in 2019) (Fig. 3.2-A and 3.2-C, Fig. 3.3, Table 3.4), both for parasitoids ($p<0.001$ in 2018, $p<0.01$ in 2019) and predators ($p<0.001$ in 2018, $p<0.05$ in 2019) (Fig. 3.2-A and 3.2-C, Appendix A3.5.). The presence of flower islands did not significantly influence NE abundance (Table 3.4, Fig. 3.3). NE abundance increased in rounds 3, 4 and 5 in 2018 and 2, 4 and 5 in 2019 for both management types and flower treatments (Table 3.4, Fig. 3.3).

Pollinator abundance on yellow sticky traps was not significantly influenced by management type or flower treatment in both years and showed an increase in sampling rounds 2 to 5 in 2019 (Table 3.4). The abundance of other phytophagous arthropods was not significantly influenced by any explanatory variable in 2018 and only by sampling round in 2019 (Appendix A3.5.). The abundance of other arthropods decreased during the crop cycle ($p<0.001$) and was lower on organic than conventional farms in 2019 ($p<0.05$, Appendix A3.5.).

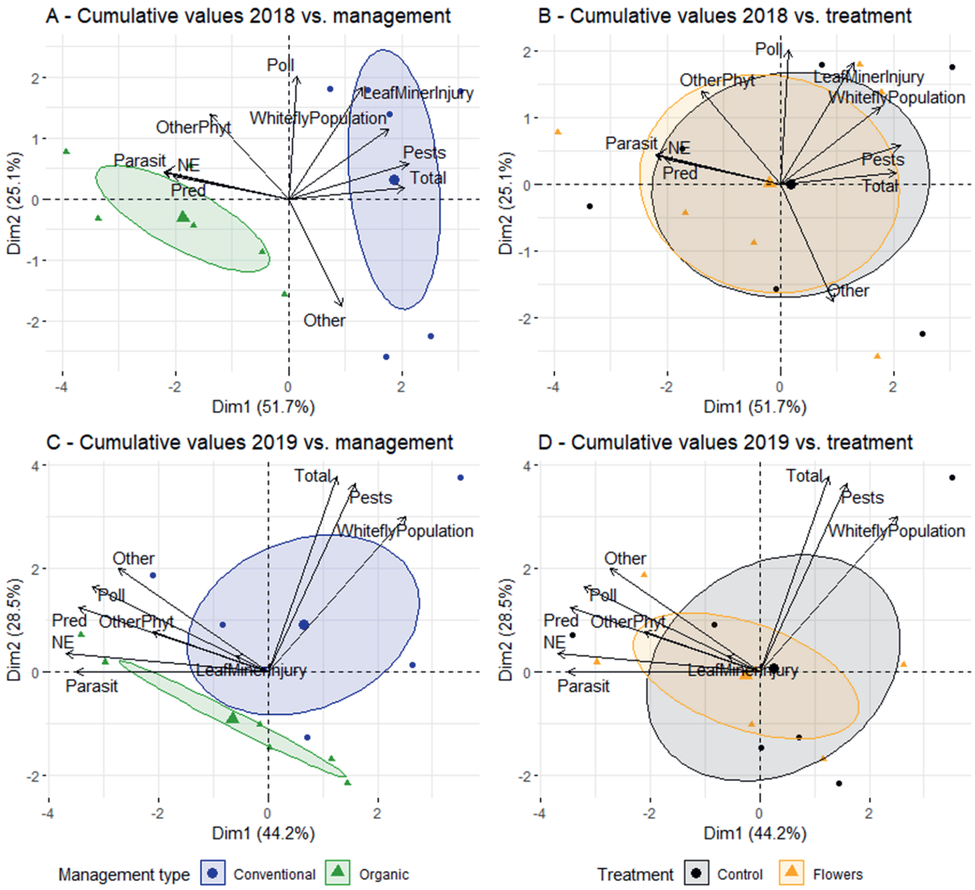


Fig. 3.2. Principal component analysis of total number of arthropods captured per greenhouse during the growing cycle in sticky traps: pests, parasitoids (Parasit), predators (Pred), natural enemies (NE), pollinators (Poll), other phytophagous (OtherPhyt), other arthropods (Other) and total whitefly population and tomato leaf miner injury in tomato plants. Separate analyses were conducted for 2018 (A and B) and 2019 (C and D). Management type (A, C) and flower treatment (B, D) are indicated with specific markers. For both years, N = 12 greenhouses, and the total variation explained by the first two principal components was in all cases more than 70%.

Tomato yield was not significantly influenced by management type (linear model p = 0.730; and cluster's comparison section 3.3.1), the presence or absence of flower islands (p = 1.000) or year (p = 0.931).

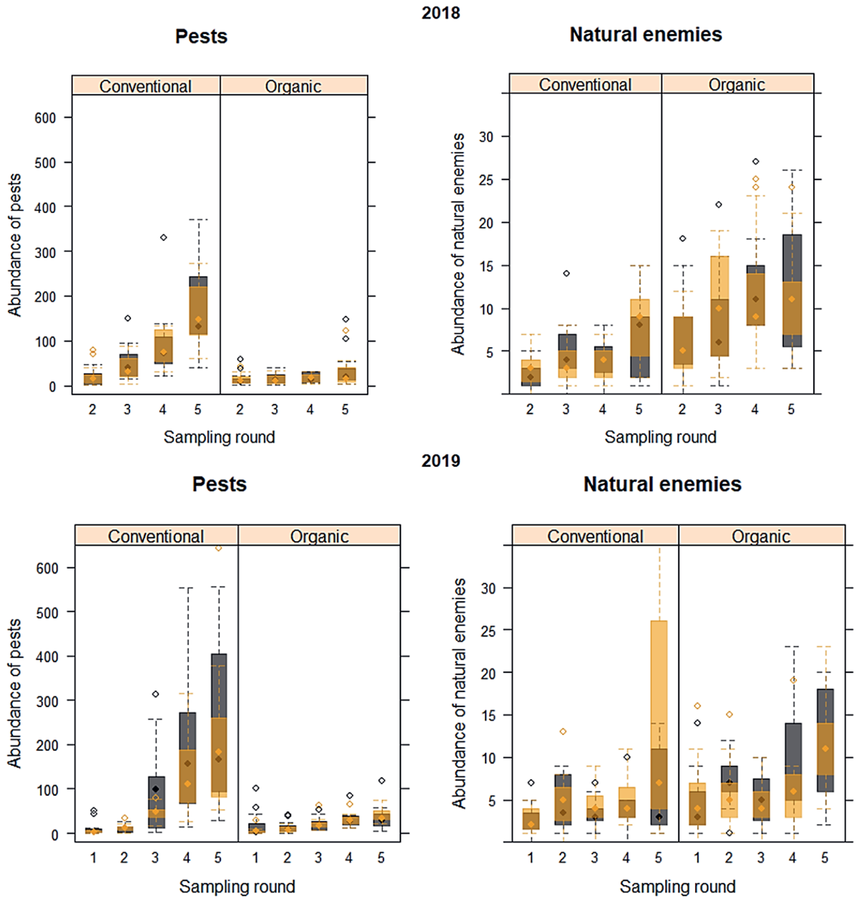


Fig. 3.3. Boxplots of the development of pest and natural enemies abundance in conventionally and organically grown tomatoes in greenhouses with (orange) and without flower islands (black) in 2018 (top) and 2019 (bottom). The Y-axis shows the abundance of pests or natural enemies on yellow sticky traps. Sampling rounds 1: early Nov, 2: mid-Nov, 3: early Dec, 4: mid-Dec, and 5: early Jan. Organically managed tomato had significantly lower pest abundance than conventional greenhouses from round 3 to 5 in 2018 and 2 to 5 in 2019 ($p<0.05$ to <0.001 depending on the round), and higher NE abundance ($p<0.001$ in 2018, $p<0.01$ in 2019). Conventionally managed tomato crops with flower islands in 2019 had a significantly lower pest abundance than without flower islands ($p<0.05$).

Table 3.4. Results of the model averaging procedure (based on ΔAICc < 2) to assess the effects of farm management type (conventional versus organic), presence or absence of flower islands, and sampling round on the abundance of pests, natural enemies (NE) and pollinators on yellow sticky traps, and greenhouse whitefly abundance and tomato leaf miner injury on tomato plants. All models included a negative binomial error distribution. NA is not applicable. A dash (/) indicates that the variable was not included in the final model. Estimates are shown, with the standard error between brackets and statistical significance in bold and with asterisks. * $p < 0.05$; ** $p < 0.01$; *** $p < 0.001$; ˙ $p < 0.1$.

Variable	2018					2019				
	Pests	NE	Pollinators	Whitefly	Leaf miner	Pests	NE	Pollinators	Whitefly	Leaf miner
Organic	-0.30 (0.20)	**0.95 (0.20)*****	-0.05 (0.10)	0.28 (0.49)	**-3.34(0.70)*****	**0.62 (0.23)****	**0.39 (0.13)****	-0.08 (0.12)	**-2.61 (1.17)***	**-2.98 (0.26)*****
Flowers	-0.02 (0.06)	0.04 (0.2)	-0.01 (0.06)	/	/	**-1.26 (0.24)*****	0.09 (0.13)	0.08 (0.12)	/	/
Round2	NA	NA	NA	NA	NA	0.23 (0.26)	**0.42 (0.14)****	**0.92 (0.21) *****	**2.41 (1.10)***	**-1.13 (0.51)***
Round3	**0.81 (0.19)*****	**0.62 (0.22)****	/	**1.75 (0.48)*****	-0.36 (0.00)	**2.14 (0.25)*****	0.18 (0.14)	**0.53 (0.21)***	**2.22 (0.97)***	1.14 (0.45)*
Round4	**1.48 (0.19)*****	**0.56 (0.22)***	/	**2.64 (0.48)*****	**1.68 (0.84)***	**2.90 (0.26)*****	**0.46 (0.14)*****	**0.48 (0.21)***	**3.35 (1.04)****	**1.08 (0.45)***
Round5	**2.14 (0.19)*****	**1.12 (0.21)*****	/	**3.80 (0.48)*****	**2.41 (0.83)****	**3.13 (0.25)*****	**1.09 (0.13)*****	**0.62 (0.21)***	**3.30 (0.99)*****	-0.20 (0.47)
Round6	NA	NA	NA	NA	NA	NA	NA	NA	**2.89 (0.68)*****	**2.33 (0.45)*****
Organic:Flowers	/	-0.00 (0.16)	/	/	/	**0.36 (0.17)***	-0.13 (0.19)	/	/	/
Flowers:Round2	NA	NA	NA	NA	NA	**1.13 (0.31)*****	/	/	/	/
Flowers:Round3	/	-0.09 (0.24)	/	/	/	**0.88 (0.30)****	/	/	/	/
Flowers:Round4	/	-0.12 (0.24)	/	/	/	**1.05 (0.30)*****	/	/	/	/
Flowers:Round5	/	-0.02 (0.23)	/	/	/	**1.30 (0.30)*****	/	/	/	/
Flowers:Round6	NA	NA	NA	NA	NA	NA	NA	NA	/	/
Organic:Round2	NA	NA	NA	NA	NA	**-0.65 (0.31)***	/	/	-1.74 (1.73)	/
Organic:Round3	**-0.83 (0.28)****	-0.20 (0.24)	/	**-1.68 (0.69)***	/	**-1.84 (0.30) *****	/	/	-1.22 (1.30)	/
Organic:Round4	**-1.30 (0.28)*****	0.18 (0.24)	/	**-2.98 (0.69)*****	/	**-2.31 (0.30) *****	/	/	-1.47 (1.50)	/
Organic:Round5	**-1.40 (0.27)*****	**-0.45 (0.23)˙**	/	**-3.11 (0.68)*****	/	**-2.44 (0.30) *****	/	/	-1.27 (1.34)	/
Organic:Round6	NA	NA		NA	NA	NA	NA	NA	-0.38 (0.79)	/
Number models averaged	2	2	3	1	1	2	3	4	2	1
AICc	2129.7	1356.5	982.5	451.6	146.2	2596.3	1598.5	1030.4	679.0	403.0

Model references: Management: conventional, Treatment: control, Round: 2 in 2018, 1 in 2019.

3.3.4. Influence of flowering plant species

Visual observations of arthropods on flowering plants indicated that organic farms had a higher abundance of arthropods visiting the flowering plants than conventional farms ($p<0.001$), including higher numbers of pests ($p<0.05$), predators ($p<0.05$), and other arthropods ($p<0.001$) (Table 3.5, Appendix A3.6.). Alyssum had a lower abundance of pests than basil and marigold ($p<0.001$, Table 3.5), a higher abundance of other phytophagous ($p<0.05$) and other arthropods ($p<0.001$, Fig. 3.4-A, Appendix A3.6.). Alyssum supported the highest abundance of NE ($p<0.001$), caused by a higher number of parasitoids than marigold ($p<0.001$) and a higher number of predators than basil and marigold ($p<0.001$) (Fig. 3.4-A, Table 3.5). Alyssum also had a higher abundance of pollinators than basil ($p<0.05$) and marigold ($p<0.001$, Fig. 3.4-A, Table 3.5).

There was a significant interaction between plant species and management type in the suction samples, indicating that the abundance of pests on conventionally managed tomato plants was higher than on alyssum, basil, and marigold. In contrast, in organically managed tomato, marigold had a higher abundance of pests than tomato and alyssum ($p<0.001$, Fig. 3.4-B, Table 3.5), which was mainly caused by the presence of thrips and aphids. In both farm types, basil had the lowest abundance of pests ($p<0.001$). Alyssum supported the highest abundance of NE ($p<0.001$), caused by a higher abundance of parasitoids than tomato, basil and marigold ($p<0.001$), and a higher abundance of predators than basil and tomato ($p<0.001$), irrespective of farm type (Fig. 3.4-B, Table 3.5).

Both visual observation and suction sampling of flowering plant species indicated that the abundance of pests ($p<0.001$), other phytophagous ($p<0.001$), parasitoids ($p<0.001$), predators ($p<0.001$), and other arthropods ($p<0.001$) was higher in 2019 than in 2018 (Table 3.5, Appendix A3.6.). The number of observed pollinators was significantly higher in 2018 than in 2019 ($p<0.001$). NE, other phytophagous and other arthropods increased during the sampling rounds, while the abundance of pests increased in rounds 3 and 4 ($p<0.01$) as assessed by suction sampling, but not by visual observation (Table 3.5, Appendix A3.6.).

3.4. Discussion

This study assessed the effect of introduced flowering plants and farm management (organic and conventional) on the abundance of pests, natural enemies, and pollinators in commercial greenhouse tomato crops in the south of Uruguay. We reported three key findings. First, organic farms had a lower abundance of pests and pest injury levels and

Table 3.5: Results of the model averaging procedure (based on ΔAICc < 2) to assess the effects of the plant species (PlantSp: marigold, alyssum and basil), farm management type (conventional and organic), year (2018 and 2019) and sampling round on the abundance of pests, natural enemies (NE), parasitoids, predators and pollinators assessed by suction sampling and visual observation. Suction sampling data also contain arthropod abundances on tomato. All models included a negative binomial error distribution. NA is not applicable. A dash (/) indicates that the variable was not included in the final model. Estimates are shown, with standard error between brackets and statistical significance in bold and asterisks: *p < 0.05; ** p < 0.01; *** p < 0.001; ˙ p < 0.1.

Variable	Suction sampling				Visual observation				
	Pests	NE	Parasitoids	Predators	Pests	NE	Parasitoids	Predators	Pollinators
Year2019	0.49 (0.12)***	1.21 (0.14)***	1.42 (0.20)***	1.03 (0.16)***	1.61 (0.16)**	1.65 (0.11)***	4.51 (0.40)***	0.83 (0.11)***	-0.89 (0.16)***
Organic	-0.38 (0.16)*	0.02 (0.07)	-0.01 (0.09)	0.11 (0.14)	0.30 (0.14)*	0.11 (0.09)	-0.01 (0.08)	0.23 (0.10)*	-0.05 (0.11)
Basil	-0.72 (0.17)***	-1.58 (0.16)***	-1.62 (0.22)***	-1.53 (0.20)***	1.00 (0.17)**	-0.51 (0.11)***	0.04 (0.17)	-0.86 (0.13)***	-0.36 (0.16)*
Marigold	-0.03 (0.16)	-0.63 (0.13)***	1.10 (0.20)***	-0.16 (0.14)	1.22 (0.18)**	-0.81 (0.12)***	-0.62 (0.18)***	-0.80 (0.13)***	-1.78 (0.26)***
Tomato	0.67 (0.19)***	-2.52 (0.23)***	-2.60 (0.31)***	-2.47 (0.32)***	NA	NA	NA	NA	NA
Round2	-0.45 (0.19)	0.42 (0.28)	0.74 (0.42)˙	0.14 (0.33)	-0.79 (0.26)**	1.14 (0.19)***	0.43 (0.27)***	1.36 (0.24)***	1.28 (0.48)**
Round3	0.48 (0.18)**	1.35 (0.25)***	1.77 (0.38)***	0.91 (0.28)**	-0.23 (0.24)	1.01 (0.19)***	0.96 (0.25)***	1.05 (0.24)***	1.41 (0.47)**
Round4	0.77 (17)***	1.49 (0.24)***	2.05 (0.67)***	1.02 (0.27)***	-0.02 (0.24)	1.36 (0.18)***	1.26 (0.24)***	1.35 (0.23)***	1.09 (0.48)*
Round5	0.32 (0.18)	1.84 (0.24)***	2.14 (0.38)***	1.57 (0.28)***	0.11 (0.25)	1.15 (0.19)***	1.47 (0.26)***	1.00 (0.25)***	1.69 (0.47)***
Organic:Basil	0.10 (0.25)	/	/	/	/	/	/		/
Organic:Marigold	0.46 (0.23)*	/	/	/	/	/	/		/
Organic:Tomato	-1.01 (0.27)***	/	/	/	NA	NA	NA		NA
Round:PlantSp	/	/	/	/	/	/	/		/
Management:Round	/	/	/	/	/	/	/		/
No. models averaged	1	2	2	2	1	2	2	1	2
AICc	2736.7	1773.7	1276.3	1216.2	1560.1	2018.9	1162.33	1579.2	1150.9

Model references: Year: 2018, Management: conventional, Plant species: Alyssum, Round: 1

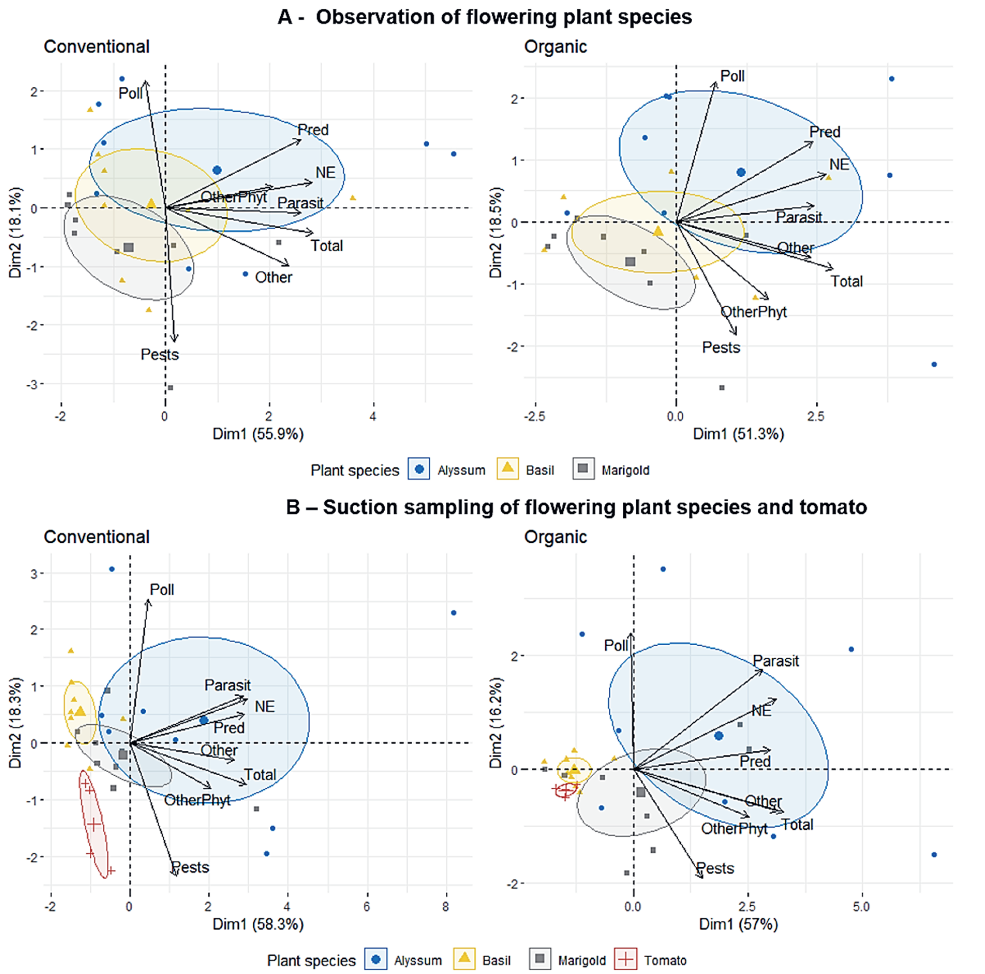


Fig. 3.4. Principal component analysis of total number of arthropods per functional group: pests, parasitoids (Parasit), predators (Pred), natural enemies (NE), pollinators (Poll), other phytophagous (OtherPhyt), other arthropods (Other). (A) Observed among flowering species (N = 56), and (B) captured with suction sampling among flowering species and tomato (N = 48) during the growing cycle according to management type. Plant species are indicated with specific markers. The total variation explained by the first two principal components in both analysis was more than 70%.

a higher abundance of natural enemies than conventional farms, resulting, on average, in a pest:NE ratio of 9 in organically and 38 in conventionally managed greenhouses. Moreover, while pests increased exponentially during the growing season in conventional farms, they remained constant or increased slightly in organic farms. Second, the effect of flowering plants on arthropods depended on the type of farm management. In conventional farms, tomato crops with flower islands had, on average, an 18% lower pest abundance during the growing season than the controls, while flower islands did not affect arthropod abundance in organic farms. This interaction was significant in the second year when we doubled the number of flower islands per greenhouse as compared to 2018. Third, alyssum, basil, and marigold had a lower proportion of pests and a higher proportion of NE than tomato plants. However, while tomato had a higher abundance of pests than the three introduced plant species in conventionally managed greenhouses, marigold had a higher abundance of pests than tomato in organically managed greenhouses. Alyssum had the lowest abundance and proportion of pests and the highest abundance and proportion of NE and pollinators.

Organic farms achieved tomato yield levels similar to conventional farms, but had a lower pest pressure and more natural enemies than conventional farms. The presence of NE early in the season when pests densities are still very low, as we found in organic greenhouses, is essential for the suppression of pests, in particular for greenhouse whitefly, the dominant pest, which has the potential for exponential population increase (Jaworski et al., 2019; van Lenteren et al., 1996). Moreover, in conventionally managed tomato more insecticides with lower selectivity and higher toxicity on natural enemies of the main pests of the crop were applied than in organic tomato (Appendix A3.3., Table A3.3.2), which can disrupt natural biological control and lead to secondary pest outbreaks (Janssen & van Rijn, 2021). Frequent insecticide applications can also trigger resistance development in pest populations, such that insecticides are no longer effective in controlling pests (Bommarco et al., 2011; van Lenteren, 2000). The patterns in pest and natural enemy populations in the conventionally managed greenhouses in our study were compatible with the patterns that can be expected from insecticide-mediated disruption of biocontrol and resistance development in pest populations. In addition, the conventional farms involved in this study were already in a transition process towards integrated pest management (IPM) for at least three years and had a substantially lower number of pesticide applications (4.3 on average) than the average of 11 applications in short cycle tomato in the south of Uruguay (Scarlato et al., 2022). Thus, the pest problems in conventional farms in this study may be relatively low as compared to the mainstream conventional farms based on the number of applications and may not reveal the full extent of the pesticide induced problems.

Besides pesticide use, organically and conventionally managed greenhouse tomato differed in many other aspects. The conventional farms applied IPM and substituted synthetic pesticides by less harmful products when possible (Deguine et al., 2021). The organic farms involved in this study applied agroecological management (Deguine et al., 2021; Nicholls et al., 2016), which influenced resource availability and host plant finding for herbivores in various ways (bottom-up effects). For instance, relatively high levels of crop diversity, vegetation quality around the greenhouses (Sarthou et al., 2014; Yang et al., 2021; Zehnder et al., 2007), and weed abundance and richness (Bretagnolle &

Gaba, 2015; Marshall et al., 2003; Ryelandt et al., 2017; Storkey & Neve, 2018) reduce the potential of herbivores to find host plants. Furthermore, high soil organic matter levels (Altieri et al., 2012; Magdoff & van Es, 2009), absence of synthetic fertilisers and lower levels of nutrient application reduce the host plant quality for herbivores and the associated potential for population increase (Hsu et al., 2009; Jauset et al., 2000; Stavisky et al., 2002). The absence of synthetic pesticides and crop and wild plant diversification also influenced the amount, diversity and proximity of natural enemies (top-down effects). While our experimental setup did not allow assessing the contribution of these various aspects to pest suppression in organically managed farms, they likely influenced the capacity for bottom-up and top-down pest suppression mechanisms (Bianchi, 2022). We hypothesise that the pest suppressive environment of the organic systems was created by various management practices that had been implemented simultaneously for more than five years, rather than by a single practice. Thus, quick fixes and “silver bullet” approaches have limited potential (Lewis et al., 1997), highlighting the need for a more holistic management approach to reduce the reliance on synthetic pesticides (Deguine et al., 2021; Lewis et al., 1997; Nicholls et al., 2016).

Our finding of a significant reduction of pest abundance by increasing floral resources in conventional management but not in organic management indicates that the potential of flowering plants to enhance biocontrol in open greenhouse tomato is moderated by farm management and landscape context (Balzan et al., 2016; Begg et al., 2017; Tscharntke et al., 2016, 2012). The "intermediate landscape-complexity hypothesis" proposed by Tscharntke et al. (2012) postulates that the efficacy of biodiversity-based management interventions depends on landscape complexity. Landscapes with a low complexity may be most responsive to these management practices, while for landscapes with an already high level of complexity the addition of more diversity will only have limited effect (Tscharntke et al., 2005; Tscharntke et al., 2012). Our results suggest that this hypothesis may also apply to the open greenhouses in our study region. While conventional farms had a higher proportion of non-cultivated land than organic farms in a 150 m radius around greenhouses (Table 3.2), organic farms had a higher crop diversity in this area, reflecting more diversified crop rotations, a higher vegetation quality in the 3 m adjacent to the greenhouses, and a higher weed cover in the greenhouse. Organic systems may therefore have a higher structural complexity within and outside the greenhouse than conventional systems, and the addition of flower resources may have contributed relatively little to the resources for natural enemies that were already present (i.e. resources reached saturation levels) (Tscharntke et al., 2012). In contrast, in conventional farms with low pesticides use, the addition of flower islands made a meaningful contribution to pest suppression, suggesting that these farm contexts reflect the responsive part of the "intermediate landscape-complexity hypothesis" curve.

The introduced flower islands significantly reduced pest abundance in the conventionally managed farms after increasing their number of islands in the second year. Pest abundance of greenhouses with flower islands decreased by on average 18% in comparison with greenhouses without flowers. The pest reduction was mainly caused by a decrease in the abundance of greenhouse whiteflies. We did not find a significant effect of flower islands on NE abundance. However, it is possible that the flower islands affected NE efficacy of pest control by providing resources that enhance NE activity (Lu et al., 2014). Indeed, we found that the flowering plants supported parasitoids and generalist predators, such as hoverfly larvae and spiders. A second explanation may be the release of volatile compounds by marigold that may deter whiteflies (Conboy et al., 2019). A third explanation could be that the placement of the yellow sticky traps at about 2 meters height above the tomato plants was effective in trapping greenhouse whitefly adults located at the top of the plants (Basso et al., 2001), but underestimated the abundance of NE. For instance, parasitoids may be more abundant in the middle of the plant where eggs and immature stages of whitefly are placed (Basso et al., 2001). Our study setup did not allow testing these potential mechanisms and therefore further research is needed to elucidate this paradox.

Many flowering plant species have been tested for their potential role in enhancing biological pest control (Arnó et al., 2018; Balzan, 2017; Kopta et al., 2012; Li et al., 2021; Parolin et al., 2012; Wäckers & van Rijn, 2012). We found differences between marigold, basil, and alyssum to support tomato pests, NE, and pollinators. The three plant species had a lower proportion of pests and a higher proportion of NE than tomato plants. However, while tomato had a higher abundance of pests than the three introduced plant species in conventionally managed greenhouses, marigold had a higher abundance of pests than tomato in organically managed greenhouses. Alyssum supported the highest number of NE and pollinators and relatively few pests, confirming previous research findings (Arnó et al., 2018; Pease & Zalom, 2010; Ribeiro & Gontijo, 2017). On the contrary, marigold supported a relatively high number of pests (mainly thrips and aphids), and relatively few NE and pollinators. Marigold has earlier been reported to perform less than other flowering species such as alyssum and *Fagopyrum esculentum* Moench (Arnó et al., 2018), *Anethum graveolens* L., *Calendula officinalis* L., *Centaurea cyanus* L., *Fagopyrum esculentum* L. and *Foeniculum vulgare* (Kopta et al., 2012), and *Cosmos bipinnatus* Cav. and *Borago officinalis* L. (Li et al., 2021). Nevertheless, marigold hosted a lower abundance of pests than tomato in conventionally managed greenhouses. In contrast, marigold had a higher abundance of pests than tomato on organic farms, potentially functioning as a reservoir of pests and/or as a trap crop (Srinivasan et al., 1994). The differences among flowering plants may be related to their flower morphology, floral resources, flowering intensity, flowering period, and presence of secondary metabolites or volatiles (Wäckers & van Rijn, 2012). Alyssum had the highest intensity and most extended flowering period, basil had flowering waves, and marigold had a relatively low number of flowers and had the lowest number of plants persisting in the greenhouses. Therefore, it is important to select the flowering species according to their morphological characteristics and attractiveness while considering the practical considerations in commercial open greenhouses.

The involvement of farmers and technicians during all the stages of the research was essential for ensuring that the research findings were relevant to farmers. The participatory methodology helped to shape and improve the research substantially. In particular, after the first year of research, in June 2019, a workshop was held to discuss the first year's results and adjust or improve the experiment for the second year. In this workshop, farmers proposed to double the flower island density, which improved pest suppression in conventionally managed tomato. The farmers also identified the need for more information to explain the management effects, which led to the inclusion of an additional early sampling round, the monitoring of temperature and relative humidity in the greenhouses, and the measurement of tomato leaf nitrogen content. Also, several ideas emerged for future management adjustments and follow-up research. For example, planting the islands earlier might provide resources for early NE colonisation of the greenhouses (Conboy et al., 2019; Jaworski et al., 2019). Moreover, flower islands inside the greenhouses could be complemented with perennial flower strips or islands at the outside borders (Arnó et al., 2018; Li et al., 2021). Finally, flowering plant species selection according to their attractiveness to NE and pests is important (Li et al., 2021; Wäckers & van Rijn, 2012). During the workshop, farmers expressed the need for more research-supported knowledge to enhance conservation biological control by managing the attractiveness of the surrounding natural vegetation and nearby crops (Bàrberi et al., 2010) and the resources provided by native plants (Landis et al., 2012). Therefore, the participatory method applied promoted synergies between the context-specific empirical knowledge of farmers and technicians and the scientific knowledge of researchers that improved the research design and allowed the identification of new questions for the research agenda.

3.5. Conclusions

Our study revealed that organically and conventionally managed tomatoes in open greenhouses comprise clearly different agroecosystems, which had profound effects on pest and natural enemy dynamics. The differences between organic and conventional management were not only reflected by the abundances of pests and natural enemies, but also by the arthropod responses to flower islands. While the introduction of sufficient flower islands resulted in a 18% reduction of pest abundance in IPM-conventionally managed tomato, it did not further reduce pest abundance in organic tomato systems based on agroecological management, which was already low. This indicates that the introduction of flowering plants has potential as a conservation biological control strategy in conventional systems with low pesticides use, and that organic systems based on agroecological management already benefit from effective levels of functional diversity to suppress pest populations without the addition of flowers. Despite the differences between the two systems, the tomato yield levels were comparable, highlighting that there is ample room to reduce synthetic insecticides without productivity loss in Uruguayan vegetable production (Scarlato et al., 2022). Furthermore, the gap in pest densities between conventional systems with flower resources and organic systems indicates that the addition of flower resources in conventional systems alone is not enough to effectively suppress pests, and that a more holistic approach is needed.

Acknowledgement
We thank the eight farmer families and the technicians involved in this research. We thank Red de Agroecología del Uruguay for its contribution in organizing the workshops. We thank MSc students Lisa Van der Graaf and Lotte Demmink for helping with data collection and processing. This work was supported by the National Research and Innovation Agency of Uruguay (grant no. POS_EXT_2016_1_134356), the National Institute of Agricultural Research of Uruguay, and the HortEco project funded by NWO-WOTRO (contract no. W 08.250.304).

Appendix 3

A3.1. Weather conditions during 2018 and 2019

Table A3.1.1. Solar radiation, average, maximum and minimum daily temperature, average wind speed, amount of rain and number of rainy days per half month during 2018 and 2019.

Year	Half month	Period	Solar radiation MJ/m^2/half month	Avg Temperature ºC	Max Temperature ºC	Min Temperature ºC	Avg Wind 2m/km /24hs	Cumulative rains mm	Number of days with rains	Number of days with more than 3mm rain
1	1st Sept	15/9/2018	220	13.8	19.5	9.2	181	1	2	0
1	2nd Sept	30/9/2018	212	16.9	22.6	12.4	172	113	7	6
1	1st Oct	15/10/2018	287	14.4	20.4	8.0	137	10	3	2
1	2nd Oct	31/10/2018	306	16.8	22.2	11.4	155	4	2	0
1	1st Nov	15/11/2018	315	19.5	25.6	14.0	167	48	7	4
1	2nd Nov	30/11/2018	330	19.2	25.0	13.7	189	37	8	4
1	1st Dec	15/12/2018	360	17.9	23.4	12.1	180	177	3	3
1	2nd Dec	31/12/2018	368	22.1	27.8	16.7	148	109	5	4
1	1st Jan	15/1/2019	293	22.1	26.9	17.2	115	130	9	7
1	2nd Jan	31/1/2019	357	23.5	29.1	18.5	142	54	4	3
		2018/2019	**3048**	**18.6**	**24.3**	**13.3**	**158.6**	**683**	**50**	**33**
2	1st Sept	15/9/2019	198	10.4	15.0	6.0	163	73	3	3
2	2nd Sept	30/9/2019	282	14.1	22.1	6.7	180	26	1	1
2	1st Oct	15/10/2019	205	14.6	19.0	9.8	189	249	8	5
2	2nd Oct	31/10/2019	290	16.5	21.2	11.6	165	17	6	1
2	1st Nov	15/11/2019	336	19.1	25.2	13.5	166	16	2	2
2	2nd Nov	30/11/2019	348	21.4	28.3	14.6	170	20	4	2
2	1st Dec	15/12/2019	382	20.4	27.1	13.1	172	25	3	2
2	2nd Dec	31/12/2019	365	22.7	29.6	16.8	197	53	7	4
2	1st Jan	15/1/2020	374	22.9	29.0	16.8	194	32	5	2
2	2nd Jan	31/1/2020	409	22.4	29.3	15.8	175	3	1	1
		2019/2019	**3189**	**18.5**	**24.6**	**12.5**	**177.0**	**513**	**40**	**23**

Source of information: INIA Las Brujas Experimental Station. Canelones, Uruguay.

Table A3.1.2. Solar radiation, average, maximum and minimum daily temperature, average wind speed, amount of rain and number of rainy days per sample round for 2018 and 2019.

Year	Round	Dates	Solar radiation MJ/m2/round	Avg Temperature ºC	Max Temperature ºC	Min Temperature ºC	Avg Wind 2m/km /24hs	Cumulative rains mm	Number of days with rains	Number of days with more than 3mm rain
2018	Round 1	not done								
2019	Round 1	25/10-8/11	276	18.9	24.4	13.7	168	19	5	2
2018	Round 2	16/11-1/12	330	19.2	25.0	13.7	189	37	8	4
2019	Round 2	8-22/11	339	21.4	28.2	15.0	156	16	1	1
2018	Round 3	1/12-14/12	315	17.6	23.0	11.7	190	177	3	3
2019	Round 3	22/11-6/12	324	18.9	25.0	12.4	186	4	4	1
2018	Round 4	14/12-28/12	319	21.6	27.6	16.3	128	82	4	4
2019	Round 4	6-19/12	369	22.0	29.1	14.6	180	25	3	2
2018	Round 5	2/1-16/1	267	21.9	26.5	17.2	112	122	8	6
2019	Round 5	23/12-7/1	361	23.3	29.8	17.6	185	45	7	3

Source of information: INIA Las Brujas Experimental Station. Canelones, Uruguay.

A3.2. Definition of functional groups of arthropods

Table A3.2.1. Overview of functional groups of arthropods

Pests	**Other phytophagous**	**Parasitoids**
Greenhouse whitefly *Trialeurodes vaporariorum* (Hemiptera, Aleyrodidae) Aphids (Hemiptera, Aphidoidea) Thrips (Thysanoptera, Terebrantia) Cucurbit beetle *Diabrotica speciosa* (Coleoptera, Chrysomelidae) Stinkbugs (Hemiptera, Pentatomidae) Tomato leaf miner *Tuta absoluta* (Lepidoptera, Gelechiidae)	Hemiptera, Miridae Leafminer *Liriomyza huidobrensis* (Diptera, Agromyzidae) Leafhoppers (Hemiptera, Cicadellidae) Leaf beetles (Coleptera, Chrysomelidae) *Epilachna paenualata* (Coleoptera, Coccinellidae) Psyllids (Hemiptera, Psyllidae) Grasshopper (Orthoptera, Acridoidea) Leaf-footed bugs (Hemiptera, Coreidae) Caterpillar (Lepidoptera) Other Hemiptera	Hymenoptera, Microhymenopterans Hymenoptera, Parasitica

Predators	**Pollinators**	**Other**
Spiders (Arachnida, Araneae)	Bees (Hymenoptera, Apoidea)	Mites (Arachnida, Acari)
Ladybugs (Coleoptera, Coccinellidae)	Blow flies (Diptera, Calliphoridae)	Diptera others
Ground beetles (Coleoptera, Carabidae)	Houseflies (Diptera, Muscidae)	Coleoptera others
Long legged flies (Diptera, Dolichopoidae)	Lepidopterans	Springtails (Collembola)
Eriopis connexa (Coleoptera, Coccinellidae)	Dance flies (Diptera, Empididae)	Ants (Hymenoptera, Formicidae)
Tubulifera thrips (Thysanoptera, Tubulifera)	Wasps (Hymenoptera, Vespidae)	Psocoptera
Green lacewing (Neuroptera,Chrysopidae)		Cockroach (Blattodea)
Tupiocoris sp. (Hemiptera, Miridae)		Earwig (Dermaptera)
Hoverfly (Diptera, Syrphidae)		
Dragonfly (Odonata, Coenagrionidae)		
Jalysus sp. (Hemiptera, Berytidae)		
Orius sp. (Hemiptera, Anthocoridae)		
Rove beetles (Coleoptera, Staphylinidae)		
Predatory mites (Acari, Phytoseiidae; Red velvet mites, Acari, Trombidiidae)		

A3.3. Farm management characteristics

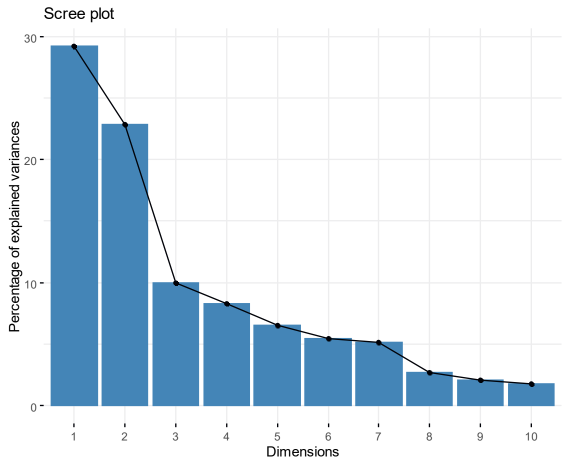


Fig. A3.3.1. Variance explained per dimension of the factor analysis of mixed data.

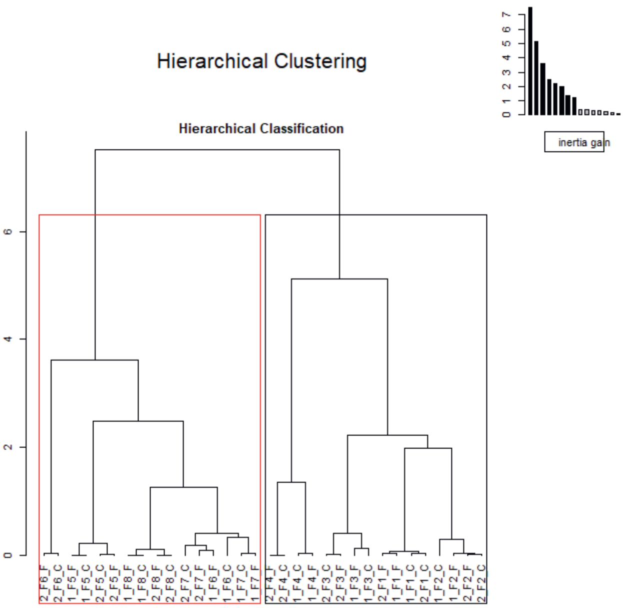


Fig. A3.3.2. Results of the HCPC analysis. The farms in the red box are conventional (left) and in the black box organic (right). Labels on the x-axis indicate year (1 or 2), farming system (F1 to F4 organic, F5 to F8 conventional) and treatment (F: flowers, C: control).

Table A3.3.1. Characterisation of management across the 16 greenhouses on 8 farms during 2018 and 2019. NA indicates "not applicable".

Indicator	Units	YEAR 2018 Farm (1 to 4 organic, 5 to 8 conventional) - Greenhouse (C: control, F: flowers)															
		1-C	1-F	2-C	2-F	3-C	3-F	4-C	4-F	5-C	5-F	6-C	6-F	7-C	7-F	8-C	8-F
Yield[1]	kg/m^2	9.8	10.2	11.2	11	6.8	7.1	5.8	6	10.9	11	6	6	9	9	10	10
Synthetic insecticide applications	Number of applications	0	0	0	0	0	0	0	0	2	2	8	1	5	5	1	1
Organic insecticide applications	Number of applications	0	0	1	1	0	0	10	10	0	0	0	0	0	0	1	1
Fungicide applications	Number of applications	1	2	1	1	0	0	10	10	3	3	4	3	1	1	3	3
Total number of pesticide applications	Number of applications	1	2	2	2	0	0	10	10	4	4	8	4	6	6	4	4
Biological and alternative applications [2]	Number of applications	2	2	15	15	0	0	4	4	1	1	1	2	10	10	6	6
Soil organic carbon	%	3.28	3.21	2.31	2.65	2.32	2.27	3.09	2.37	1.4	1.47	1.87	2.42	1.43	1.49	1.31	1.4
Relative active soil organic carbon [3]	Proportion	0.84	0.83	0.51	0.63	0.49	0.5	1.16	0.78	0.15	0.18	0.32	0.52	0.24	0.28	0.17	0.22
N input-organic source	g/m^2	9	9	3	3	3	3	10	10	8	8	9	9	10	10	10	10
P input-organic source	g/m^2	5	5	2	2	2	2	8	8	10	10	7	7	9	9	9	9
K input-organic source	g/m^2	24	24	10	10	17	17	43	43	40	40	28	28	45	45	45	45
N input – synthetic source	g/m^2	0	0	0	0	0	0	0	0	6	6	2	2	0	0	0	0
P input – synthetic source	g/m^2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
K input – synthetic source	g/m^2	0	0	0	0	0	0	0	0	40	40	4	4	0	0	0	0
N input – total	g/m^2	9	9	3	3	3	3	10	10	14	14	11	11	10	10	10	10
P input – total	g/m^2	5	5	2	2	2	2	8	8	10	10	7	7	9	9	9	9
K input – total	g/m^2	24	24	10	10	17	17	43	43	80	80	32	32	45	45	45	45
NO3-soil at harvest initiation	ppm	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
N-leaf at harvest initiation	%	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
Average air temperature	°C	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
Average relative humidity	%	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
Plant density	Number of plants / m^2	2.34	2.45	2.4	2.35	2.57	3.45	1.87	1.97	2.6	2.65	2.65	2.8	2.7	2.73	2.22	2.43
Greenhouse size	m^2	750	750	840	840	682	720	588	588	980	980	1050	1050	396	396	480	480
Indicator	**Units**																
Number of crops in 150m radius	Number of crops	16	16	24	24	20	20	15	12	1	1	3	2	4	4	2	2
Number of crops per year in the farm	Number of crops	28	28	48	48	35	35	47	47	2	2	6	6	8	8	6	6
Indicator	**Classes**																
Vegetation quality in the 3 m radius [4]	High / Medium / Low / Very Low	high	high	high	high	med	med	med	med	very low	very low	low	low	med	low	very low	very low
Proportion of uncultivated land in 150 m radius [5]	High / Medium / Low	med	med	low	med	high	med	med	med	med	med	med	high	med	high	high	high
Previous crop in the greenhouse	1:Tomato, 2: Other Solanaceae, 3: Other	2	2	1	1	3	3	3	3	2	2	2	1	1	1	1	1
Diverse crops inside the greenhouse	1: Only tomato, 2: Combined	1	1	1	1	1	2	2	2	1	1	1	1	1	1	1	1
Weed cover inside greenhouse [6]	High / Medium / Low	low	low	med	med	high	high	high	high	low	low	med	med	med	med	low	low
Nylon black mulch	Yes/ No	yes	yes	yes	yes	no	no	yes	yes	yes	yes	yes	yes	no	no	no	no
Tomato variety [7]	1: Hybrid, 2: Non-hybrid, 3: mixture	1	1	1	1	3	3	3	3	1	1	1	1	1	1	1	1

[1] Estimated based on weekly records of the farmers. [2] Entomopathogenic fungus, milk and bicarbonate, vegetable oil.
[3] Relative Active Soil Organic Carbon (RASOC) = ((Actual SOC – Min SOC)/(Max SOC – Min SOC)) * 100 (Dogliotti et al., 2014).
[4] Vegetation quality in the 3 m radius: High: soil full covered, more than 20 sp and more than 10 sp., Medium: soil full covered, more than 20 cm or more than 10 sp, Low: soil full covered, less 20 cm high, less than 10 species, Very low: with 50% or more soil no covered.
[5] Proportion of uncultivated land in 150 m radius: High: < 50% crop fields and greenhouses, Medium: 50-75% crop fields and greenhouses, Low: > 75% crop fields and greenhouses.
[6] Weeds cover: High: more than 40% in at least half sampling rounds, Medium: between 10 and 40% in at least half sampling rounds, Low: less than 10% soil cover during all season.
[7] Tomato genetic: Hybrid: Belfast, Eterei, Ichiban, Barteza, Santa Paula; Non-hybrid: farmer´s seeds of heirloom tomatoes

Table A3.3.1 (cont.). Characterisation of management across the 16 greenhouses on 8 farms during 2018 and 2019. NA indicates "not applicable".

Indicator	Units	YEAR 2019 Farm (1 to 4 organic, 5 to 8 conventional) - Greenhouse (C: control, F: flowers)															
		1-C	1-F	2-C	2-F	3-C	3-F	4-C	4-F	5-C	5-F	6-C	6-F	7-C	7-F	8-C	8-F
Yield[1]	kg/m²	10	10.5	12	12	8	8	5.5	5.7	11.5	12	7	7.2	7.8	8	10.2	10
Synthetic insecticide applications	Number of applications	0	0	0	0	0	0	0	0	3	3	9	9	0	0	0	0
Organic insecticide applications	Number of applications	3	3	1	1	0	0	9	9	0	0	0	0	0	0	0	0
Fungicide applications	Number of applications	2	2	0	0	0	0	9	9	0	0	9	9	1	1	1	1
Total number of pesticide applications	Number of applications	5	5	1	1	0	0	9	9	3	3	9	9	1	1	1	1
Biological and alternative applications [2]	Number of applications	1	1	7	7	0	0	0	0	3	0	0	0	4	4	7	7
Soil organic carbon	%	3.63	3.46	2.55	2.53	2.63	2.39	2.13	2.18	2.1	1.8	2.08	2.05	1.94	2.45	2.17	1.87
Relative active soil organic carbon [3]	Proportion	0.97	0.91	0.59	0.59	0.67	0.58	0.66	0.68	0.51	0.3	0.41	0.39	0.53	0.82	0.66	0.95
N input-organic source	g/m²	9	9	3	3	3	3	10	10	6	6	19	19	8	8	10	10
P input-organic source	g/m²	5	5	2	2	2	2	8	8	5	6	22	22	3	3	9	9
K input-organic source	g/m²	24	24	10	10	11	11	43	43	27	27	93	93	8	8	45	45
N input – synthetic source	g/m²	0	0	0	0	0	0	0	0	6	6	2	2	2	2	0	0
P input – synthetic source	g/m²	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
K input – synthetic source	g/m²	0	0	0	0	0	0	0	0	40	40	4	4	10	10	0	0
N input – total	g/m²	9	9	3	3	3	3	10	10	11	11	21	21	9	9	10	10
P input – total	g/m²	5	5	2	2	2	2	8	8	6	6	22	22	3	3	9	9
K input – total	g/m²	24	24	10	10	11	11	43	43	67	67	96	96	18	18	45	45
NO3-soil at harvest initiation	ppm	258	177	96	314	220	118	102	97	316	267	149	116	192	118	376	356
N-leaf at harvest initiation	%	3.14	3.59	2.86	2.88	2.26	2.37	1.86	1.79	2.95	2.76	2.82	2.95	2.78	2.5	3	2.9
Average air temperature	°C	22.4	22.9	23.0	22.8	23.3	22.6	22.3	22.2	22.6	22.1	22.9	22.8	22.0	22.3	22.7	22.5
Average relative humidity	%	70.9	66.7	65.5	67.2	75.1	73.8	65.8	66.6	67.3	70.6	67.5	67.5	68.2	67.9	69.0	68.5
Plant density	Number of plants / m²	2.13	2.07	1.61	2.46	2.52	2.63	2.03	20.3	2.79	2.83	2.54	2.32	3.07	2.89	2.52	2.56
Greenhouse size	m²	800	800	870	870	698	732	528	528	800	800	1080	1080	320	320	384	384
Indicator	**Units**																
Number of crops in 150m radius	Number of crops	16	16	30	30	18	18	30	30	1	1	2	2	5	5	5	5
Number of crops per year on the farm	Number of crops	28	28	48	48	35	35	47	47	2	2	6	6	8	8	6	6
Indicator	**Classes**																
Vegetation quality in the 3 m radius [4]	High / Medium / Low / Very Low	high	med	high	high	med	med	med	med	very low	very low	low	low	med	low	very low	very low
Proportion of uncultivated land in 150 m radius [5]	High / Medium / Low	med	med	high	med	high	med	med	med	high	high	med	med	med	high	high	high
Previous crop in the greenhouse	1:Tomato, 2: Other Solanaceae, 3: Other	2	2	1	1	1	1	2	2	2	2	2	3	3	1	1	1
Diverse crops inside the greenhouse	1: Only tomato, 2: Combined	1	1	1	1	2	2	2	2	1	1	1	1	1	1	1	1
Weed cover inside greenhouse [6]	High / Medium / Low	low	low	med	med	high	high	high	high	low	low	med	med	med	med	low	low
Nylon black mulch	Yes/ No	yes	yes	yes	yes	no	no	yes	yes	no	no	yes	yes	no	no	no	no
Tomato variety [7]	1: Hybrid, 2: Non-hybrid, 3: mixture	1	1	1	1	1	3	3	3	1	1	1	1	1	1	1	1

[1] Estimated based on weekly records of the farmers. [2] Entomopathogenic fungus, milk and bicarbonate, vegetable oil.
[3] Relative Active Soil Organic Carbon (RASOC) = ((Actual SOC – Min SOC)/(Max SOC – Min SOC)) * 100 (Dogliotti et al., 2014).
[4] Vegetation quality in the 3 m radius: High: soil full covered, more than 20 sp and more than 10 sp., Medium: soil full covered, more than 20 cm or more than 10 sp, Low: soil full covered, less 20 cm high, less than 10 species, Very low: with 50% or more soil no covered.
[5] Proportion of uncultivated land in 150 m radius: High: < 50% crop fields and greenhouses, Medium: 50-75% crop fields and greenhouses, Low: > 75% crop fields and greenhouses.
[6] Weeds cover: High: more than 40% in at least half sampling rounds, Medium: between 10 and 40% in at least half sampling rounds, Low: less than 10% soil cover during all season.
[7] Tomato genetic: Hybrid: Belfast, Eterei, Ichiban, Barteza, Santa Paula; Non-hybrid: farmer´s seeds of heirloom tomatoes

Table A3.3.2. Insecticides, fungicides and biological or alternative products used per farm (Farms 1 to 4 have organic management, and farms 5 to 8 conventional management). Active ingredient and commercial name are indicated. Greenhouses with and without flowers per farm received the same products.

Conventional	Type		Toxicity on natural enemies	Conventional farms	Organic farms
Abamectin (Abatop)	insecticide	Synthetic	High[1], Very high[2]	6, 7, 8	
Acetamiprid (Minalán)	insecticide	Synthetic	High[1], Very high[1,2,4]	6	
Chlorfenapyr (Clorfenac)	insecticide	Synthetic	Intermediate-Very high[2,4]	6, 7	
Clorpirifos (Lorsban)	insecticide	Synthetic	Very high[1,2]	7	
Flutriafol + imidacloprid (Impact)	insecticide	Synthetic	Low[1,2], Very high[4]	6	
Spinosad (Tracer)	insecticide	Synthetic	High[1,2,5], Very high[1,4]	5	
Spiromesifen (Oberon)	insecticide	Synthetic	Low[1,2,4]	5	
Spirotetramat (Movento)	insecticide	Synthetic	Low[1], Intermediate[2]	6	
Thiocyclam (Evisect)	insecticide	Synthetic	High, Very high[1,2]	6	
Azoxystrobin (Amistar, Quadris)	fungicide	Synthetic	Intermediate[1,2]	6, 8	
Carbendazim (Carbendazim)	fungicide	Synthetic	Low[2], Very high[1]	7	
Ciprodinil + Fludioxinil (Switch)	fungicide	Synthetic	Low[2], Very high[1]	7, 8	
Chlorothalonil (Braconil)	fungicide	Synthetic	Intermediate[1]	5	
Difenoconazole (Score)	fungicide	Synthetic	Low[1,2]	6	
Flutriafol (Flutec)	fungicide	Synthetic	Low[1,2]	6	
Isopyrazam + Azoxystrobin (Reflect)	fungicide	Synthetic	Intermediate[1]	5, 6	
Pyraclostrobin (Bellis)	fungicide	Synthetic	Low[1]	6, 8	
Copper (Biocobre, Biorend Cobre)	fungicide	Mineral	Low[1], High[1,2]	6, 7	4
Sulphur	fungicide/acaricide	Mineral	Intermediate-Very high[1,2]	6, 7, 8	1, 4
Limonene (Protek)	insecticide	Organic	ND		4
Matrine (Baicen)	insecticide	Organic	Intermediate[3]		1, 4
Quitosan (Biorrot)	fungicide	Organic	ND		2
Spinosad (Entrust)	insecticide	Organic	High[1,2,5], Very high[1,4]		2
Bacillus thuringiensis (Bactur)	entomopathogenic fungus	Microbial	Low[2,4,5]	7, 8	2
Beauveria bassiana (Los Arenales)	entomopathogenic fungus	Microbial	High[5]	6, 7, 8	
Effective microorganisms (EM)	Other	Microbial	ND	7, 8	1, 2
Isaria javanica (Crebio)	entomopathogenic fungus	Microbial	ND	5, 6, 7, 8	1
Trichoderma spp.	Fungus (fungus diseases)	Microbial	ND	7, 8	
Milk + bicarbonate	Other	Other	ND	7, 8	1, 2
Mineral oil	other (insecticide)	Other	Low[1,2], High[1]	7, 8	2

Scale: Low: <25% mortality, Intermediate: 25-50% mortality, High: 50-75% mortality, Very high: >75% mortality.

Toxicity based on: [1]Biobest https://www.biobestgroup.com/es/manual-de-efectos-secundarios and [2]Koppert https://efectos-secundarios.koppert.es considering the target natural enemies: *Encarsia formosa*, *Eretmocerus* spp, and *Orius* spp., [3]Kordestani et al. (2022, https://doi.org/10.1093/jee/toab267) and [4]Kim et al. (2018, http://dx.doi.org/10.1016/j.aspen.2017.10.015) assessing on *Orius spp.*, and [5]Barrera et al. (2013, *Acta biol. Colomb.* 18(2):265-270) assessing on *Encarsia formosa*. ND: no data available.

A3.4. Farm management characteristics

Table A3.4.1. Number of arthropods collected on yellow sticky traps per functional group, management type (organic and conventional) and year (2018 and 2019).

Species/order	2018 Conventional	Organic	SubTotal	2019 Conventional	Organic	SubTotal	Total
Tomato pests							
Greenhouse whitefly *Trialeurodes vaporariorum* (Hemiptera, Aleyrodidae)	10240	2511	12751	16645	1116	17761	30512
Aphid (Hemiptera, Aphidoidea)	41	72	113	73	326	399	512
Thrips (Thysanoptera, Terebrantia)	790	910	1700	2122	2660	4782	6482
Cucurbit beetle *Diabrotica speciosa* (Coleoptera, Chrysomelidae)	83	132	215	84	244	328	543
Stinkbug (Hemiptera, Pentatomidae)	2	1	3	1	6	7	10
Tomato leaf miner *Tuta absoluta* (Lepidoptera, Gelechiidae)	0	0	0	1	0	1	1
Sub-total pests	11156	3626	14782	18926	4352	23278	38060
Other phytophagus							
Hemiptera, Miridae	3	2	5	19	17	36	41
Leafminer *Liriomyza huidobrensis* (Diptera, Agromyzidae)	31	44	75	9	14	23	98
Leafhopper (Hemiptera, Cicadellidae)	28	34	62	33	41	74	136
Leaf beetle (Coleoptera, Chrysomellidae)	42	35	77	41	28	69	146
Hemiptera	3	5	8	27	11	38	46
Epilachna_paenualata (Coleoptera, Coccinellidae)	0	4	4	0	4	4	8
Psyllid (Hemiptera, Psyllidae)	0	0	0	60	33	93	93
Sub-total other phytophagus	107	124	231	189	148	337	568
Parasitoids							
Microhymenoptera	946	1060	2006	612	959	1571	3577
Parasitic wasp	81	21	102	119	128	247	349
Sub-total parasitoids	1027	1081	2108	731	1087	1818	3926
Predators							
Spider (Arachnida, Araneae)	21	34	55	26	32	58	113
Ladybug (Coleoptera, Coccinellidae)	32	41	73	32	47	79	152
Ground beetle (Coleoptera, Carabidae)	6	12	18	14	25	39	57
Long-legged fly (Diptera, Dolichopoidae)	45	70	115	128	168	296	411
Eriopis_connexa (Coleoptera, Coccinellidae)	0	1	1	2	0	2	3
Tubulifera thrips (Thysanoptera, Tubulifera)	4	16	20	3	0	3	23
Green lacewing (Neuroptera, Chrysopidae)	1	0	1	0	0	0	1
Tupiocoris sp. (Hemiptera, Miridae)	18	77	95	34	29	63	158
Hoverfly (Diptera, Syrphidae)	19	19	38	8	13	21	59
Dragonfly (Odonata: Coenagrionidae)	3	1	4	5	1	6	10
Jalysus sp. (Hemiptera, Berytidae)	0	0	0	1	0	1	1
Orius sp. (Hemiptera, Anthocoridae)	0	0	0	1	0	1	1
Rove beetle (Coleptera, Staphylinidae)	0	0	0	2	0	2	2
Sub-total predators	149	271	420	256	315	571	991
Pollinators							
Bee (Hymenoptera, Apoidea)	5	5	10	9	28	37	47
Blow fly (Diptera, Calliphoridae)	10	6	16	20	48	68	84
Houseflie (Diptera, Muscidae)	242	174	416	67	55	122	538
Lepidoptera	1	1	2	0	2	2	4
Dance fly (Diptera, Empididae)	53	65	118	39	54	93	211
Wasp (Hymenoptera, Vespoidea)	130	48	178	162	118	280	458
Sub-total pollinators	441	299	740	297	305	602	1342
Other arthropods							
Mite (Arachnida, Acari)	10	5	15	7	16	23	38
Diptera other	971	542	1513	1461	868	2329	3842
Coleoptera other	16	24	40	50	53	103	143
Springtail (Collembola)	1	0	1	3	44	47	48
Ant (Hymenoptera, Formicidae)	0	5	5	0	0	0	5
Psocoptera	20	31	51	0	2	2	53
Cockroach (Blatodea)	5	11	16	24	17	41	57
Sub-total other arthropods	1023	618	1641	1545	1000	2545	4186
Total	13903	6019	**19922**	21944	7207	**29151**	**49073**

Table A3.4.2. Number of arthropods per functional group in suction samples of marigold, basil, alyssum and tomato plants.

Species/order	2018 number	%	2019 number	%	Both years number	%
Tomato pests						
Greenhouse whitefly *Trialeurodes vaporariorum* (Hemiptera, Aleyrodidae)	9		31		40	
Aphid (Hemiptera, Aphidoidea)	189		239		428	
Thrips (Thysanoptera, Terebrantia)	525		632		1157	
Cucurbit beetle *Diabrotica speciosa* (Coleoptera, Chrysomelidae)	6		4		10	
Stinkbug (Hemiptera, Pentatomidae)	49		156		205	
Tomato leaf miner *Tuta absoluta* (Lepidoptera, Gelechiidae)	2		5		7	
Sub-total pests	780	27	1067	15	1847	19
Other phytophagus						
Hemiptera, Miridae	64		306		370	
Leafhopper (Hemiptera, Cicadellidae)	18		26		44	
Leaf beetle (Coleoptera, Chrysomellidae)	9		0		9	
Hemiptera	9		365		374	
Epilachna paenualata (Coleoptera, Coccinellidae)	0		0		0	
Gryllidae	1		0		1	
Agromyzidae	3		2		5	
Sub-total other phytophagus	104	4	699	10	803	8
Parasitoids						
Microhymenoptera	146		373		519	
ParasiticWasp	1		27		28	
Sub-total parasitoids	147	5	400	6	547	6
Predators					0	
Spider (Arachnida, Araneae)	124		214		338	
Ladybug (Coleoptera, Coccinellidae)	3		6		9	
Ground beetle (Coleoptera, Carabidae)	19		2		21	
Long-legged fly (Diptera, Dolichopoidae)	0		34		34	
Eriopis_connexa (Coleoptera, Coccinellidae)	6		14		20	
Tubulifera thrips (Thysanoptera, Tubulifera)	0		0		0	
Green lacewing (Neuroptera, Chrysopidae)	0		1		1	
Tupiocoris sp. (Hemiptera, Miridae)	5		6		11	
Hoverfly (Diptera, Syrphidae)	4		5		9	
Dragonfly (Odonata: Coenagrionidae)	0		0		0	
Orius sp. (Hemiptera, Anthocoridae)	5		15		20	
Sub-total predators	166	6	297	4	463	5
Pollinators						
Bee (Hymenoptera, Apoidea)	0		0		0	
Blow fly (Diptera, Calliphoridae)	0		0		0	
Housefly (Diptera, Muscidae)	3		2		5	
Lepidopterans	0		0		0	
Wasp (Hymenoptera, Vespoidea)	4		2		6	
Dance flly (Diptera, Empididae)	23		3		26	
Sub-total pollinators	30	1	7	0	37	0
Other arthropods						
Mite (Arachnida, Acari)	316		491		807	
Diptera other	289		516		805	
Coleoptera other	27		201		228	
Ant (Hymenoptera, Formicidae)	235		698		933	
Springtails (Collembola)	775		2450		3225	
Isopoda	14		92		106	
Psocoptera	2		0		2	
Earwig (Dermaptera)	1		0		1	
Sub-total other arthropods	1659	57	4448	64	6107	62
Total	2886	100	6918	100	9804	100

Table A3.4.3. Number of arthropods on marigold, basil and alyssum assessed by visual observation.

	2018		2019		Both years	
Species/order	number	%	number	%	number	%
Tomato pests						
Greenhouse whitefly *Trialeurodes vaporariorum* (Hemiptera, Aleyrodidae)	7		18		25	
Aphid (Hemiptera, Aphidoidea)	0		6		6	
Thrips (Thysanoptera, Terebrantia)	0		283		283	
Cucurbit beetle *Diabrotica speciosa* (Coleoptera, Chrysomelidae)	15		12		27	
Stinkbug (Hemiptera, Pentatomidae)	86		332		418	
Tomato leaf miner *Tuta absoluta* (Lepidoptera, Gelechiidae)	1		0		1	
Sub-total pests	*109*	11	651	18	760	17
Other phytophagus						
Hemiptera, Miridae	0		72		72	
Leafhopper (Hemiptera, Cicadellidae)	6		20		26	
Leaf beetle (Coleoptera, Chrysomellidae)	2		0		2	
Hemiptera	0		219		219	
Grasshopper (Orthoptera, Acridoidea)	6		7		13	
Hemiptera, Coreidae	1		0		1	
Caterpillar (Lepidopterans)	11		22		33	
Sub-total other phytophagus	26	3	340	10	366	8
Parasitoids						
Microhymenoptera	7		531		538	
Parasitic wasp	0		46		46	
Sub-total parasitoids	7	1	577	16	584	13
Predators						
Spider (Arachnida, Araneae)	27		77		104	
Ladybug (Coleoptera, Coccinellidae)	3		61		64	
Ground beetle (Coleoptera, Carabidae)	1		0		1	
Long-legged fly (Diptera, Dolichopoidae)	5		5		10	
Eriopis_connexa (Coleoptera, Coccinellidae)	13		21		34	
Green lacewing (Neuroptera, Chrysopidae)	0		2		2	
Tupiocoris sp. (Hemiptera, Miridae)	0		23		23	
Hoverfly (Diptera, Syrphidae)	158		168		326	
Predatory mite (Acari, Phytoseiidae; Red velvet mites, Acari, Trombidiidae)	0		89		89	
Sub-total predators	207	22	446	12	653	14
Pollinators						
Bee (Hymenoptera, Apoidea)	4		8		12	
Blow fly (Diptera, Calliphoridae)	11		14		25	
Housefly (Diptera, Muscidae)	228		50		278	
Lepidopterans	0		4		4	
Wasp (Hymenoptera, Vespoidea)	38		29		67	
Sub-total pollinators	281	29	105	3	386	9
Other arthropods						
Mite (Arachnida, Acari)	11		7		18	
Diptera other	1		586		587	
Coleoptera other	16		122		138	
Ant (Hymenoptera, Formicidae)	296		743		1039	
Sub-total other arthropods	324	34	1458	41	1782	39
Total	954	100	3577	100	4531	100

A3.5. Overview of number of arthropods per functional group collected on sticky traps and visual assessment of pest infestation levels on tomato plants.

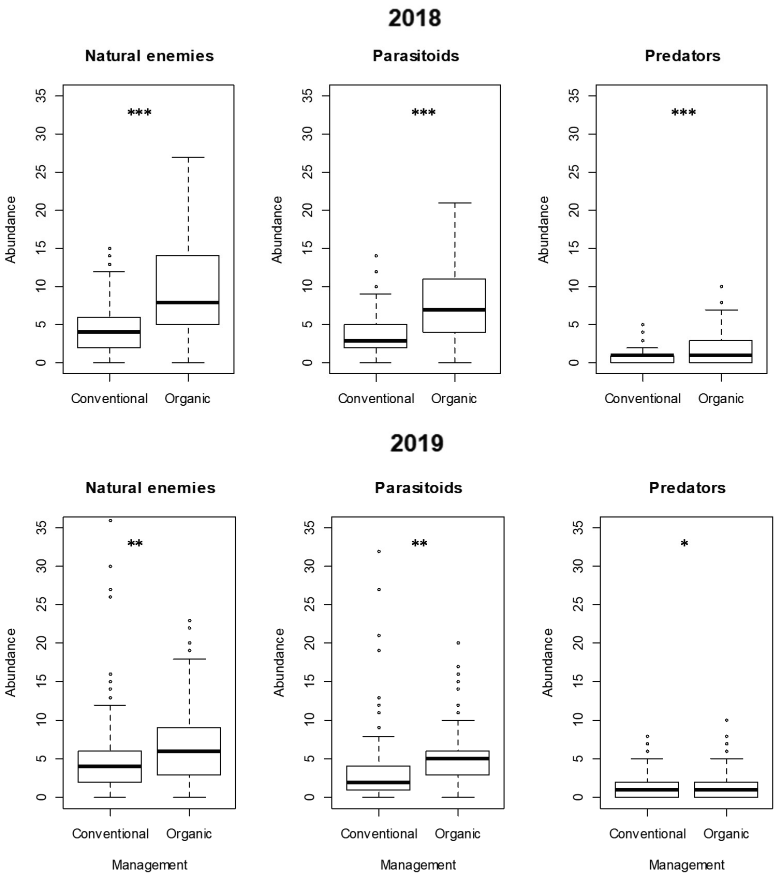


Fig A3.5.1. Boxplots of abundance of natural enemies, parasitoids and predators in conventionally and organically grown tomato in 2018 (top) and 2019 (bottom). The Y-axis shows the abundance of natural enemies, parasitoids or predators on yellow sticky traps. Statistical significance between management types: * $p < 0.05$; ** $p < 0.01$; *** $p < 0.001$.

Table A3.5.1. Results of the model averaging procedure (based on ΔAICc < 2) to assess the effects of farm management type (conventional versus organic), presence or absence of flower islands, and sampling round on the abundance of total, other phytophagous and other arthropods on yellow sticky traps. All models included a negative binomial error distribution. NA is not applicable. A dash (/) indicates that the variable was not included in the final model. Estimates are shown with statistical significance in bold and asterisks. * p < 0.05; ** p < 0.01; *** p < 0.001; ˙ p < 0.1.

Variable	2018			2019		
	Other phytophagous	Other arthropods	Total	Other phytophagous	Other arthropods	Total
Organic	0.148	**-1.130*** **	**-0.295***	-0.005	**-0.493***	-0.145
Flowers	0.237	-0.015	-0.0222	-0.019	0.009	**-0.425** **
Round2	NA	NA	NA	**0.801***	**-0.257˙**	0.050
Round3	/	**-0.668** **	**0.427*** **	**0.640˙**	**-0.742*** **	**1.239*** **
Round4	/	**-1.104*** **	**0.941*** **	**1.257*** **	**-1.044*** **	**1.909*** **
Round5	/	**-1.431*** **	**1.561*** **	**1.204*** **	**-0.941*** **	**2.317*** **
Organic:Flowers	0.039	/	/	/	/	**0.298***
Flowers:Round2	NA	NA	NA	/	/	0.075
Flowers:Round3	/	/	/	/	/	0.033
Flowers:Round4	/	/	/	/	/	0.044
Flowers:Round5	/	/	/	/	/	0.157
Organic:Round2	NA	NA	NA	/	0.062	0.016
Organic:Round3	/	**0.627˙**	**-0.341˙**	/	0.121	**-0.989*** **
Organic:Round4	/	**0.840***	**-0.711*** **	/	0.154	**-1.377*** **
Organic:Round5	/	**1.045** **	**-1.032*** **	/	0.131	**-1.590*** **
Number models averaged	5	2	2	3	3	2
AICc	535	1285	2201	745	1714	2829

Model references: Management: conventional, Treatment: control, Round: 2 in 2018, 1 in 2019.

Table A3.5.2. Results of the model averaging procedure (based on ΔAICc < 2) to assess the effects of farm management type (conventional versus organic), presence or absence of flower islands, and sampling round on greenhouse whitefly population on tomato plants and count of tomato leaf miner injuries. All models included a negative binomial error distribution. NA is not applicable. A dash (/) indicates that the variable was not included in the final model. Estimates are shown with statistical significance in bold and asterisks. * p < 0.05; ** p < 0.01; *** p < 0.001; ˙ p < 0.1.

Variable	2018		2019	
	Whitefly	Leaf miner	Whitefly	Leaf miner
Organic	0.283	**-3.343*** **	**-2.605***	**-2.375*** **
Flowers	/	/	/	/
Round2	NA	NA	**2.410***	**-1.126***
Round3	**1.745*** **	-0.360	**2.221***	**1.141***
Round4	**2.641*** **	**1.682***	**3.345** **	**1.083***
Round5	**3.798*** **	**2.412** **	**3.302*** **	-0.201
Round6	NA	NA	**2.894*** **	**2.330*** **
Organic:Flowers	/	/	/	/
Flowers:Round2	NA	NA	/	/
Flowers:Round3	/	/	/	/
Flowers:Round4	/	/	/	/
Flowers:Round5	/	/	/	/
Flowers:Round6	NA	/	/	/
Organic:Round2	NA	/	-1.739	/
Organic:Round3	**-1.682***	/	-1.216	/
Organic:Round4	**-2.978*** **	/	-1.472	/
Organic:Round5	**-3.111*** **	/	-1.269	/
Organic:Round6	NA	/	-0.383	/
Number models averaged	1	1	2	1
AICc	447	144	679	401

Model references: Management: conventional, Treatment: control, Round: 2 in 2018, 1 in 2019.

3

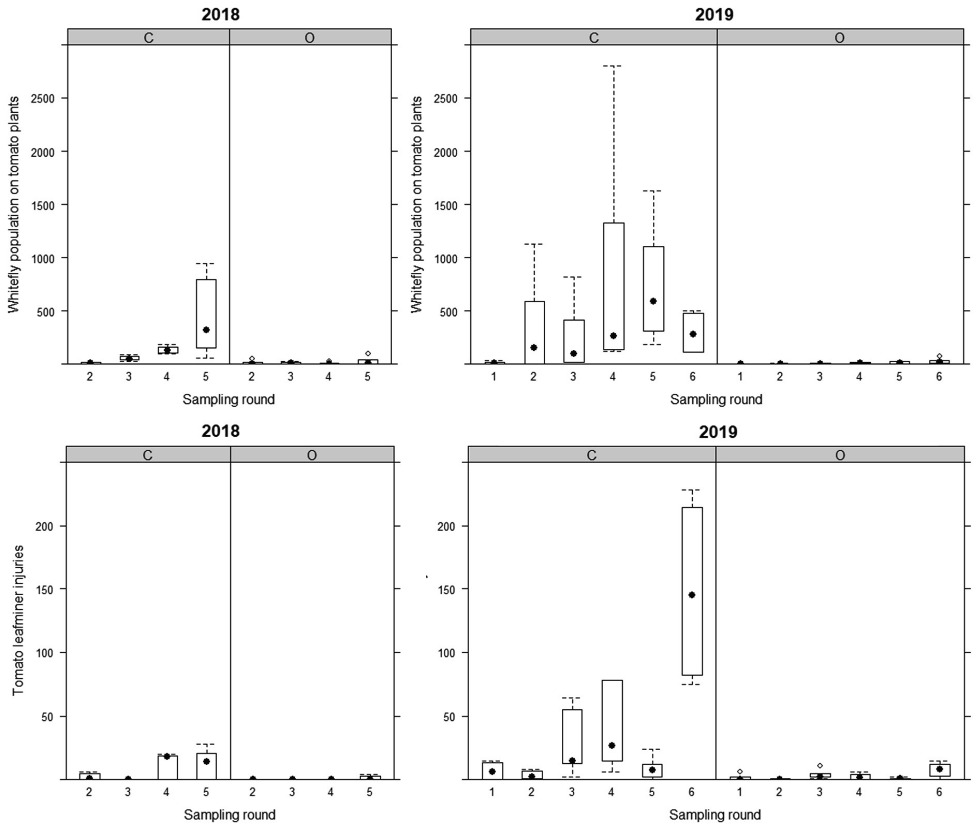


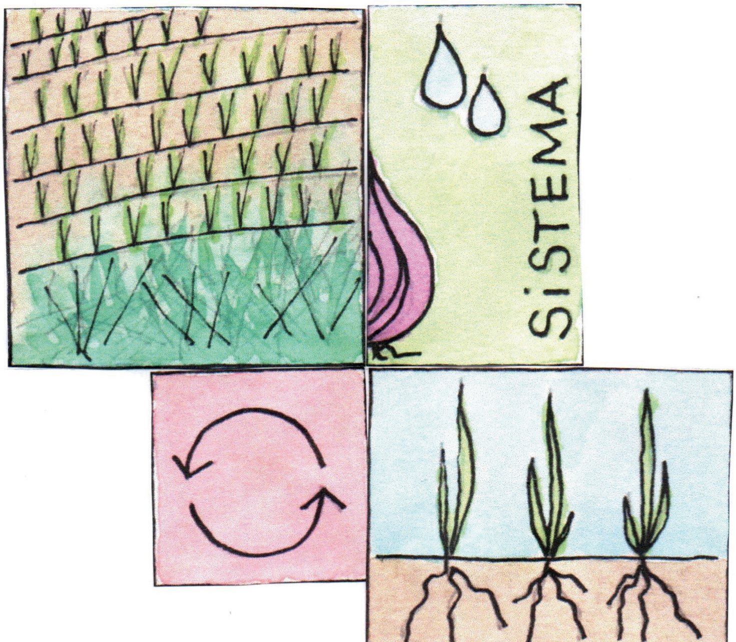
Fig. A3.5.2. Boxplots of greenhouse whitefly population on tomato plants and count of tomato leaf miner injuries per farm management type (C: conventional and O: organic) in 2018 and 2019. Greenhouse whitefly abundance and tomato leaf miner injuries are based on visual observations on 20 tomato plants per greenhouse. Rounds: 1: early Nov, 2: mid-Nov, 3: early Dec, 4: mid-Dec, 5: early Jan, and 6: mid-Jan.

A3.6. Overview of number of arthropods per functional group obtained by suction sampling and visual observation of flowering plant species.

Table A3.6.1. Results of the model averaging procedure (based on ΔAICc < 2) to assess the effects of the plant species (PlantSp: marigold, alyssum and basil), farm management type (conventional and organic), year (2018 and 2019) and sampling round on the abundance of other phytophagous, other arthropods and total arthropods assessed by suction sampling and visual observation. Suction sampling data also contain arthropod abundances on tomato. All models included a negative binomial error distribution. NA is not applicable. A dash (/) indicates that the variable was not included in the final model. Estimates are shown with statistical significance in bold and asterisks. * $p < 0.05$; ** $p < 0.01$; *** $p < 0.001$; · $p < 0.1$.

Variable	Suction sampling			Visual observation		
	Other phytophagous	Other arthropods	Total	Other phytophagous	Other arthropods	Total
Year2019	**2.386*** **	**0.924*** **	**0.914*** **	**2.518*** **	**1.420*** **	**1.270*** **
Organic	-0.016	**0.506*** **	**0.298** **	0.245	**0.651*** **	**0.362*** **
Basil	-0.760	**-2.057*** **	**-1.585*** **	**-0.532·**	**-1.842*** **	**-1.035*** **
Marigold	-0.396	**-0.522*** **	**-0.639***	-0.491	**-0.976** **	**-0.531** **
Tomato	-1.157	**-2.956*** **	**-0.931*** **	NA	NA	NA
Round2	**1.516***	-0.193	-0.113	**1.996*** **	**-0.503·**	0.001
Round3	**2.899*** **	0.211	**0.540***	**2.914*** **	**-0.730** **	-0.107
Round4	**2.633*** **	**0.518*** **	**0.628*** **	**2.973*** **	**-0.768** **	0.036
Round5	**2.753*** **	**0.364***	0.371·	**3.392*** **	**-0.652***	0.118
Organic: Basil	/	**0.711** **	0.271	-0.110	0.341	-0.016
Organic: Marigold	/	-0.259	-0.143	-0.187	**-0.489***	-0.125
Organic: Tomato	/	-0.286	**-1.290*** **	NA	NA	NA
Basil:Round2	-1.410	/	-0.030	/	**1.150** **	**0.538***
Marigold:Round2	-7.365	/	0.108	/	0.487	0.028
Tomato:Round2	-2.185	/	-0.138	NA		
Basil:Round3	-1.646	/	-0.266	/	**1.461*** **	**0.954*** **
Marigold:Round3	-6.281	/	-0.037	/	**0.919***	0.280
Tomato:Round3	-2.137	/	-0.452	NA	NA	NA
Basil:Round4	-1.265	/	0.010	/	**1.816*** **	**0.972*** **
Marigold:Round4	1.980	/	0.239	/	**1.289*** **	**0.393·**
Tomato:Round4	-1.980	/	-0.125	NA	NA	NA
Basil:Round5	-1.469	/	0.185	/	**1.594*** **	**1.082*** **
Marigold:Round5	2.513	/	0.419	/	0.625	-0.043
Tomato:Round5	-2.164	/	-0.075	NA	NA	NA
Management:Round	/	/	/	/	/	/
Number of models averaged	3	1	2	3	1	1
AICc	1366	3460	4139	929	2378	3143

Model references: Year: 2018, Management: conventional, Plant species: Alyssum, Round: 1.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Chapter 4

Development of a reduced tillage system for onion without agrochemicals: promising but challenges remain

This chapter is under revision as:

Scarlato, M.; Rieppi, M.; Alliaume, F.; Illarze, G.; Bajsa, N.; Bertoni, P.; Bianchi, F.J.J.A.; Echeverriborda, G.; Galván, G.; García de Souza, M.; Gilsanz, J.C.; González Barrios, P.; Dieste, J.P.; Trasante, T.; Rossing, W.A.H.; Dogliotti, S. Development of a reduced tillage system for onion without agrochemicals: promising but challenges remain.

Abstract

Cover crops with reduced tillage technology (CC-RT) can foster soil health and functioning, a crucial agroecological principle in any transition strategy to more sustainable agricultural systems. However, CC-RT commonly strongly relies on herbicides and synthetic fertilisers, and vegetable crop yields are variable and often low. We assessed the effects of two tillage systems (RT and conventional tillage) and the application of native effective microorganisms (NEM) on onion crop growth and development, yield, N-status, weed pressure, and soil physico-chemical and biological quality after a summer cover crop, without using herbicides or synthetic fertilisers. Using a participatory research strategy, we conducted a two-year experiment at an experimental station and a one-year trial on two commercial farms. Onion yields were generally low (between 10 and 16 Mg ha^{-1}), but lower in 2019 than in 2020, and lower in RT than in CT in 2020. The relative low yields in 2019 and RT were associated with poor crop growth and development, and leaf-N concentrations below the critical threshold in the early stages of crop development. Soil bulk density was not limiting crop growth in any treatment. Soil mineral N was lower in 2019 than in 2020 and did not significantly differ between treatments, while the NH4:NO3 ratio was higher in 2019 than in 2020 and higher in RT than in CT. Soil biological activity was higher in RT than in CT. Although the crop residue soil cover in the early stages of the onion crop in RT was more than 50%, RT had a higher weed pressure than CT, which was reversed later in the growing season. The NEM application did not significantly affect most crop, weed and soil variables. In conclusion, a reduced tillage system for onion without agrochemicals within reach, but further research is needed to manage weeds and soil N supply dynamics to make CC-RT feasible under organic management.

Keywords: conservation agriculture, crop system, agroecology, organic production, weeds, nitrogen

4.1. Introduction

Maintaining soil health and functioning is fundamental for reaching global sustainability goals (Kraamwinkel et al., 2021; Lehmann et al., 2020) and is a crucial agroecological principle in any transition strategy to more sustainable agricultural systems (Hoffland et al., 2020; Nicholls et al., 2016; Wezel et al., 2020). Soil health and functioning can be fostered by using wide crop rotations, limiting the proportion of root and tuber crops, using pasture, cover crops, green manure and organic amendments (Alliaume et al., 2013; Dogliotti et al., 2014; King & Blesh, 2018), reducing pesticide use (Hussain et al., 2009; Rose et al., 2016), and implementing erosion control practices (Alliaume et al., 2013; Dogliotti et al., 2014). However, these practices may not suffice to maintain or improve soil health in specific contexts. For example, maintaining soil organic carbon (SOC) levels in vegetable systems on soils with a high SOC level may require unrealistically high input levels of organic matter (Alliaume et al., 2013). In addition, three to four years of pastures do not always fit in small vegetable-based crop rotations systems, which are driven to rotations prone to erosion (García De Souza et al., 2011). Therefore, a broader set of management practices is needed to maintain soil health and functioning in vegetable systems.

The use of cover crops (CC) combined with reduced tillage (RT) is a promising practice that can minimize soil erosion (Alliaume et al., 2014), increase and maintain high SOC levels (Haddaway et al., 2017; Li et al., 2020), increase water infiltration (Alliaume et al., 2014), enhance biological activity and biological control (Navarro-Miró et al., 2022; Tamburini et al., 2016), reduce N leaching (Jokela & Nair, 2016; Zhang et al., 2020) and reduce CO_2 emissions (Abdalla et al., 2013; Boeckx et al. 2011). However, CC-RT management often results in variable and low crop yields, and farmers face technical difficulties implementing this system (Alliaume et al., 2014; Erenstein, 2002; Jokela & Nair, 2016; Navarro-Miró et al., 2022; Peigné et al., 2007). Thus, while promising, CC-RT needs to be further developed to become a practically feasible management option.

The implementation of CC-RT will influence the crop system as a whole, affecting the top-soil temperature, water and soil organic matter dynamics, and nutrient supply (Alliaume et al., 2014; Cook et al., 2006; Jokela & Nair, 2016; Peigné et al., 2007; Tittarelli et al., 2018). Therefore, the CC-RT systems must be tailored to the site-specific conditions to bridge the yield gap compared to conventional tillage systems. Moreover, most CC-RT systems strongly rely on herbicides to terminate the cover crop and to control weeds, and on synthetic N-fertilisers to ensure crop N-uptake at initial crop development stages (Antichi et al., 2022; Carr et al., 2013; Farooq & Siddique, 2015). Therefore, implementing CC-RT poses additional challenges in no or low agrochemical input systems (Casagrande et al., 2016; Peigné et al., 2007; Vollmer et al., 2010; Carr et al., 2013).

Organic agricultural systems strongly rely on mechanical practices for weed control and cover crop termination. The effectiveness of CC-RT and its residues to control weeds is erratic, and reducing tillage intensity is seen as a bottleneck (Carr et al., 2013; Casagrande et al., 2016; Mandal et al., 2021; Peigné et al., 2015). Additionally, crop nutrition in organic systems mainly relies on organic matter management. Since the time and amount of N release from organic amendments and soil organic matter is difficult to predict (Geisseler et al., 2022; Hodge et al., 2000; Masunga et al., 2016), matching N supply and crop demand under organic CC-RT management is challenging. The decomposition of the cover crop residues may result in N immobilization, depending on the cover crop biomass and C:N ratio (Hodge et al., 2000; Mooshammer et al., 2014; Masunga et al., 2016). An early termination of the cover crop and the incorporation of legume species in the cover crop may lower the C:N ratio, and thus the N-immobilization risk (Ranells & Wagger, 1996). Manipulation of the structure and functions of the microbiota through microbial inoculants could stimulate soil organic matter mineralization and promote nutrient availability for the crop (Terrazas et al., 2016). The application of effective microorganisms (Alarcon et al., 2020; Higa & Wididana, 1991; Morocho & Mora, 2019; Singh et al., 2011), particularly when combined with organic amendments (Khaliq et al., 2006), may promote this effect. However, strategies that reduce N immobilization risk or increase N mineralization may decrease soil cover and weed suppression, indicating a trade-off between soil cover and N supply.

Onion is one of the main vegetable crops in the world (FAO, 2021). Onion is highly susceptible to weed competition (Hewson & Roberts, 1973; van Heemst, 1985). Onion has a shallow, sparse, and low-density root system (Geisseler et al., 2022) and responds strongly to nitrogen availability (Brewster & Butler, 1989; Geisseler et al., 2022). However, overwinter-onion canopy growth and development occur during cool weather when biological activity, and the associated N availability, may be low (Luce et al., 2011). Therefore, conventional onion production systems heavily rely on herbicides and synthetic fertilisers, whereas onion organic systems on mechanical tillage and large labour requirement for weeding. Consequently, onion cultivation is associated with high soil erosion and nutrient leaching risk. Developing CC-RT systems for onions without agrochemical inputs could significantly reduce agrochemical use and soil erosion. However, the onion´s sensitivity to weed competition and N availability makes it difficult to develop such systems.

We conducted a two-year study to assess the effects of the tillage system (reduced tillage vs conventional tillage) and the application of native effective microorganisms (presence vs absence) on onion production after a summer cover crop, without using herbicides or synthetic fertilisers. We conducted experiments at an experimental station field and at two commercial farms using a participatory research approach where treatments and management were co-designed with the farmers. This paper reports on onion crop growth and development, onion yield, N-status, and weed pressure as main response variables, as well as soil physical, chemical and biological properties as supporting variables to comprehensively understand the crop system performance.

4.2. Materials and methods

4.2.1. Study area and research approach

The study was conducted in Canelones Department, south Uruguay, where most vegetable production of the country is concentrated (34º21'S to 34º57'S – 55º40'W to 56º40'W). The climate is humid subtropical, with an average mean temperature of 17 °C (average minimum: 11 °C, average maximum: 23 °C) and light frosts between May and September. Mean annual precipitation is 1200 mm, evenly distributed throughout the year, but with significant variation between years (Castaño et al., 2011). The main soil types in Canelones are Mollic Vertisols (Hypereutric), Luvic/Vertic Phaeozems (Pachic), and Luvic Phaeozems (Abruptic/Oxyaquic) (Alliaume et al., 2013).

The study comprised a two-year experiment at the Centro Regional Sur Experimental Station (CRS) of the Faculty of Agronomy, Universidad de la República (see section 4.2.3) and two simplified experiments on an organic and a conventional commercial farms in the second year (see section 4.2.4, Appendix A4.1). We used an interdisciplinary and participatory approach where a project support group of around 30 people, including farmers, technical advisers, and researchers participated from the beginning of the study to monitor, assess, and define the operational and tactical management of the experiments. The project support group met in a first workshop in 2017, two field days and workshops in 2019, two workshops and field days in 2020, and a final workshop in 2021 to discuss the results and implications of the research findings. In addition, the farmers of the two commercial farms had weekly interactions with the research team.

4.2.2. Design criteria and analytical framework

During the starting workshop in December 2017, participants expressed their interest and discussed their difficulties implementing CC-RT. Organic onion production was highlighted as particularly challenging in terms of cover crop, weed, and nitrogen management. Therefore, onion was selected for the study of a CC-RT system without herbicides and synthetic fertiliser inputs, and the experiences and suggestions of the workshop participants to overcome challenges were used to inform the experimental treatments. The mutually agreed design criteria for effective CC-RT systems were: (i) high biomass production and fast soil cover development of the cover crop; (ii) use of cover crop species with low risk of becoming a weed; (iii) termination of the cover crop should be possible without herbicides; and (iv) the cover crop should have a C:N ratio below 30 to reduce the risk of nitrogen immobilization (Hodge et al., 2000; Mooshammer et al., 2014). Participants also expressed interest in the potential of local biological inputs, such as native effective micro-organisms (NEM) or effective micro-organisms (EM) to increase soil organic matter mineralization and crop nitrogen availability (Higa & Wididana, 1991; Olle & Williams, 2013).

Since the tillage system and the use of NEM influence different components of the CC-onion cropping system, we assessed key response variables related to the crop, the weeds, and the soil to capture the relationships between these components (Fig. 4.1). Specifically, we assessed crop system outcomes in terms of crop growth and development, crop yield, crop N status, and weed pressure. We also assessed soil chemical, physical, and biological properties, as well as cover crop and residue soil cover to understand the underlying causes of these outcomes. This analytical framework guided the discussion at each workshop.

4.2.3. CRS on-station experiment

4.2.3.1. Treatments and experimental design

The experiment was arranged in a randomised complete block design with four replications using a split-plot treatment design. The whole plot factor was tillage (reduced (RT) and conventional (CT)), and the split-plot factor was NEM application (present+ or absent-), resulting in a total of four treatments (RT/NEM-, RT/NEM+, CT/NEM-, CT/NEM+). The experimental field was 1760 m^2, where each split-plots of 67.5 m^2 consisted of three contiguous raised beds, which were 1.5 m apart and 15 m long (Appendix A4.1). The experimental design was the same in both years, so each split-plot consistently received the same treatment in the two years.

4.2.3.2. Soil characterisation

The soil at the experimental site is a Mollic Vertisol (Hypereutric) (IUSS Working Group WRB, 2006), with particle size distribution in the upper soil layer of 10% sand, 42% silt and 48% clay. It had 2.55% SOC in both years, 1.8 and 1.7 meq of K, and 192 and 162 ppm P-Bray 1 in 2019 and 2020, respectively. Bulk density was 0.89 and 0.84 Mg ha^{-1} in 2019 and 2020, respectively. Neither in 2019 nor in 2020 significant differences were detected between the split-plots in SOC, soil nutrient content and bulk density before the application of treatments ($p>0.1$).

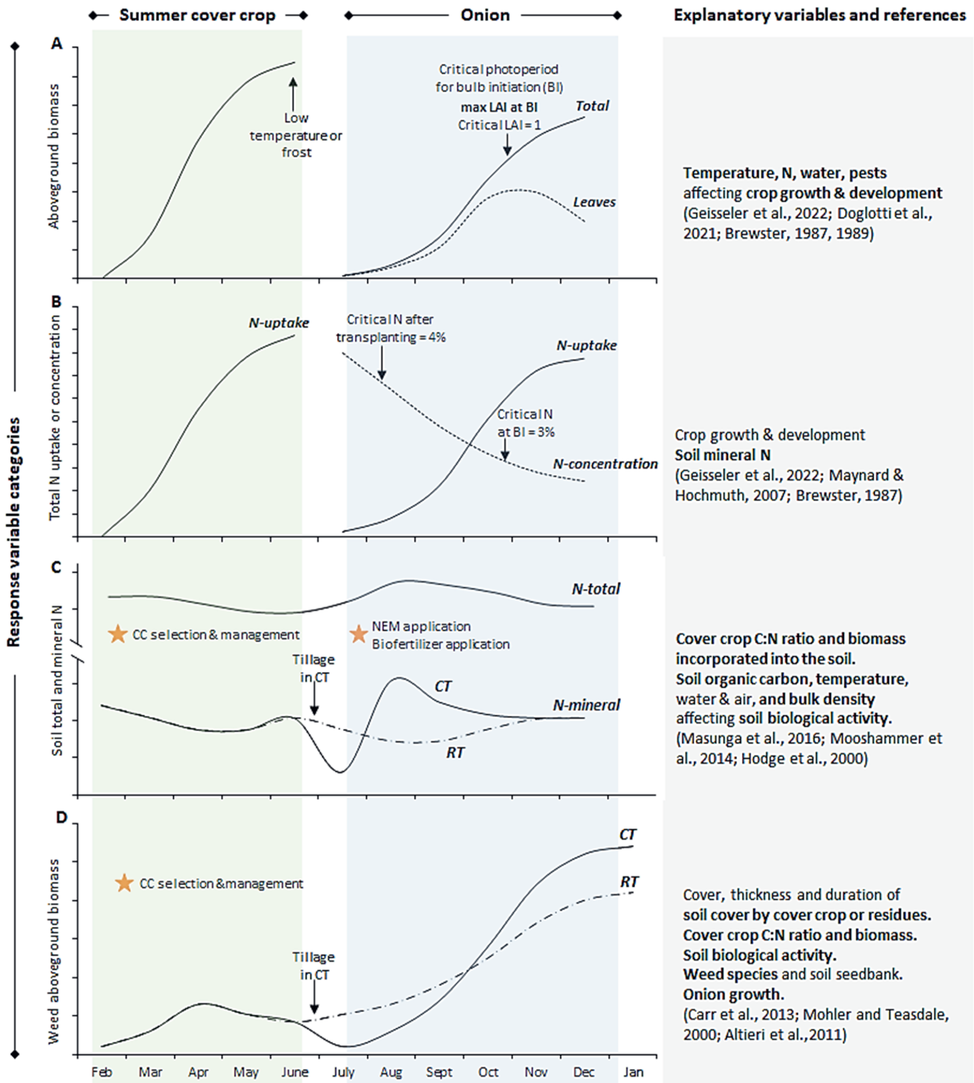

Fig. 4.1. Conceptual representation of the hypothesised trends along the year of the four response variable categories of the cover crop (CC) - onion cycle (left) and the explanatory variables that may explain the crop system performance (right). Main response variable categories: cover crop and onion aboveground biomass (A), crop nitrogen status (B), soil nitrogen (C), and weed pressure (D). Variables in bold letters correspond to the variables assessed. Orange stars correspond to the strategies to avoid N deficiencies and problematic weed pressure during the onion crop. BI is bulb initiation; solid lines indicate conventional tillage (CT); dashed lines indicate reduced tillage (RT).

4.2.3.3. Soil and crop management

A sequence of a summer cover crop consisting of foxtail millet (*Setaria italica)* and cowpea (*Vigna unguiculata*) followed by an onion crop was established during two subsequent years (2019-2020, Appendix A4.1). The cover crop was sown in raised beds at the end of the summer (22 Feb 2019, 11 March 2020) and finished its growing cycle due to low temperatures in the first half of June 2019 and at the end of May 2020 (Appendix A4.4). The sowing density of cowpea was 20 kg ha^{-1}, while foxtail millet was sown at 30 kg ha^{-1} in 2019 and 50 kg ha^{-1} in 2020. Intermediate-day length onion varieties were used: Pantanoso del Sauce-CRS in 2019 and PxR-CRS (Pananoso del Sauce variant) in 2020. Onion seedlings (aged 92 days) were transplanted by hand into raised beds on 6 and 4 August and harvested on 20 and 16 December 2019 and 2020, respectively. Plant density was 214,000 plants ha^{-1} arranged in three rows per bed, with a 20 cm distance between rows and from the edge of the raised-beds.

The experimental area was tilled annually during summer (January and February) before installing the cover crop. Soil management at the end of the cover crop and before transplanting onion in the CT treatment consisted of two passes of a chisel and a disc ridger during June and July, one pass of a rotavator with bed forming, and a furrow opener before transplanting. The RT treatment consisted of mechanical crushing of the cover crop with an inverted tooth harrow, followed by one pass with a furrow opener before transplanting in 2019, and two passes with a furrow opener starting four days before transplanting in 2020 (detailed information in Appendix A4.2). The NEM treatments consisted of immersion of the onion seedlings roots for two hours in a solution with 10% NEM before transplanting, plus ten soil applications of a NEM solution from transplanting in 2019, and ten soil applications from one week before transplanting to bulb initiation in 2020 (70 L ha^{-1}, dilution 10%). The NEM solution was obtained from a local company and was physico-chemically and microbiologically analysed before use (Appendix A4.3).

Before sowing the cover crop, chicken manure was applied and incorporated into the soil (11 and 14 Mg DM ha^{-1} in 2019 and 2020, respectively, Appendix A4.1), resulting in an estimated N supply from chicken manure of 112 and 168 kg N ha^{-1} (Appendix A4.2). Throughout the growing season of onion, an organic-N fertiliser (commercial name Mixamin, 7.2 g L^{-1}) was applied. In 2019 involved seven soil applications at a dose of 12.5 L ha^{-1}, and six foliar applications at 900 cc ha^{-1}, totaling 7 kg N ha^{-1} during the growing season. In 2020, compost-tea (1.3 g L^{-1}) was also applied, applying nine soil applications of organic-N fertiliser at a dose of 12.5 L ha^{-1} and compost-tea at 8 L ha^{-1}, totaling 9 kg N ha^{-1} in the growing season. Water was provided through drip irrigation at transplanting and during the onion growing season, based on daily visual monitoring of the field and the potential crop evapotranspiration (Allen, 2006). Pest and disease management for downy mildew caused by *Peronospora destructor* and *Sminthurus viridi*s consisted of six fungicide applications and one insecticide application in 2019, and five foliar applications of *Trichoderma sp.*, four fungicide, and one insecticide application in 2020 (detailed information in Appendix A4.2). Leaf-cutter ants were controlled with granular insecticide bait (Fipronil). Weed control at onion transplanting involved soil tillage in the CT treatments and manual weeding in the RT treatments. During the onion growing cycle, weeds were removed manually after weed pressure assessments. In 2019 three weedings were conducted in both tillage treatments, and in 2020 three weedings were conducted in CT and four in RT.

4.2.3.4. Data collection

Cover crop biomass and quality, soil cover and weed pressure

The aboveground biomass and cover crop quality were assessed on 5 June 2019 and 25 May 2020 when plants started to senesce because of low temperatures. The aboveground biomass was estimated by harvesting quadrants of 0.36 m^2 in three random replicates per plot. Cover crop species and weeds were separated, dried at 60ºC for 48 h, and weighted to evaluate the biomass proportion of each cover crop species and weeds. The carbon content of the samples was evaluated by oxidation with K_2CrO_7 in H_2SO_4 at 150°C for 30 minutes, followed by colourimetric determination (Mebius, 1960), and N concentration was assessed using the Kjeldahl method (Bremmer & Mulvaney, 1982). No significant differences in cover crop biomass and composition were detected between split-plots in either 2018 or 2019 ($p>0.1$).

The proportions of bare soil, cover crop cover, weed cover, and onion cover were estimated by sampling every 5 cm along a 1.6 m-transect using a pin micro-relief meter and recording the type of cover in three replicates per plot. Cover crop residue cover was assessed on three 1-m transects on the soil surface per plot. Measurements were taken at sowing and at the end of the cover crop, before onion transplanting, 30 and 60 days after transplanting, at BI, and before onion harvest in both years.

Weed aboveground biomass (g DM m^{-2}) and dominant weed species were assessed in three randomly selected 0.36 m^2 squares per plot at the end of the cover crop, before transplanting, at 20 and 50 days after transplanting, at BI, and before onion harvest. After collection, weed plants were dried at 60°C for 48 h to measure weed aboveground biomass.

Onion crop yield, growth and development, and foliar nitrogen

Onion crop yield was measured in each plot by harvesting all the plants in 8 m of bed in the central bed of the plot where no destructive sampling took place. Harvested onions were left to dry under sheltered, ambient conditions for one month. Then, leaves, false stems, and roots were removed, and total bulb yield, marketable yields (Mg ha^{-1}), number of bulbs, and average bulb size (g) were measured. Total yield comprised all bulbs, while marketable yield only included bulbs greater than 4 cm in diameter.

Onion growth, development, and leaf nitrogen status were measured by determining bulbing ratio, bulb initiation (BI), aboveground biomass, number of leaves per plant, leaf area index (LAI), and leaf nitrogen concentration and content. Bulbing ratio, calculated as the ratio between the diameter of the bulb and the diameter of the false stem, was assessed in ten randomly selected plants per plot at 30, 60, 90, and 100 days after transplanting and at harvest. BI date was defined as the date when the bulbing ratio of 50% of the plants exceeded 2 (Brewster et al., 1987). Onion aboveground biomass and the number of leaves per plant were measured though destructive sampling of ten randomly selected plants per plot at transplanting, 30 and 60 days after transplanting, BI, and harvest. After dividing the plants into leaves, false-stems, and bulbs all components were dried at 60°C for 48 h and weighed. LAI (m^2 of leaves m^{-2} of soil) was assessed at BI, as this index is a great determinant of crop yield (Dogliotti et al., 2021). LAI was estimated based on the leaf dry matter per plant, plant density, and the specific leaf area (SLA, cm^2 g^{-1}, Fang et al., 2019). SLA was estimated by sampling twelve circular fragments of the middle part of fully developed onion leaves of ten randomly selected plants per plot with a 16 mm diameter punch. Leaf nitrogen concentration (%) was measured using the Kjeldahl method (Bremmer & Mulvaney, 1982) on a composite sample of ten randomly selected active and completely developed leaves per plot at 30 and 60 days after transplanting, and at BI in both years, and at harvest in 2019. Total leaf nitrogen content (kg leaf-N per ha^{-1}) was estimated from leaf dry matter biomass, leaf N-concentration, and plant density.

In 2019 we observed differences in crop maturity at harvest. As a result, in 2020, we evaluated the proportion of green leaves and the percentage of collapsed foliage at harvest, indicative of bulb maturity (Brewster & Butler, 1989). The proportion of green leaves was assessed on ten randomly selected plants per plot using a four-level visual scale: 1: <40% green leaves, 2: 40-60%, 3: 60-80%, 4: >80 %. The percentage of collapsed foliage was calculated as the ratio of the number of plants with collapsed foliage and the total number of plants in the eight central meters of the middle bed per plot, which was also used to assess yield.

Soil physical, chemical and biological properties

Physical soil properties were measured in one composite sample per plot consisting of twenty subsamples of top soil (0-20 cm) taken at the beginning of the cover crop (March) and the end of the onion growing season (December) in 2019 and 2020. After drying the soil samples and passing them through a 2 mm sieve, the following analyses were made: soil pH (1:2.5 soil:water and soil:KCl ratio), soil texture (Forsythe 1975), SOC (Nelson & Sommers, 1996), available P (Bray & Kurtz, 1945), and exchangeable K (Isaac & Kerber, 1971). The relative active soil organic carbon (RASOC) was estimated according to Dogliotti et al. (2014). The bulk density of the top soil was estimated by taking undisturbed samples at 7–10 cm depth using three metal rings per plot (5 cm wide and 3 cm tall, Blake & Hartge, 1986) at cover crop sowing, onion transplanting, BI (only in 2019) and harvest in both years. Soil temperature was measured with three Pendant MX2201 sensors per plot, located at 5, 15 and 25 cm depth, and measurements were taken every 15 minutes from transplanting to onion harvest. Temperature recordings were summarised as daily averages and were assigned to the early (1 to 15 September), mid (15 to 31 October), and late onion seasons (1 to 15 December) for both years.

Chemical soil properties were measured in one composite sample per plot consisting of ten subsamples of top soil (0-20 cm) taken before onion transplanting, at 20, 50 and 70 days after transplanting, at BI, and before harvest in 2019 and 2020. Soil NO_3 and NH_4 (colourimetric analysis, Doane & Horwáth, 2003; Rhine et al., 1998) and soil mineral N (calculated by adding NO_3 and NH_4) were determined in each sample. In 2019 soil respiration (Kandeler, 1996) and potentially mineralisable nitrogen (PMN) were assessed in each soil sample, while in 2020, these determinations were was done only for the samples taken before transplanting and at BI. In 2019, the potential nitrification activity of ammonia oxidizers (PNA) (Rudisill et al., 2016), urease and dehydrogenase enzyme activity (Kandeler, 1996b; Von Mersi & Schinner, 1991) were assessed as well.

4.2.3.5. Statistical analysis

We analysed the effect of the tillage and NEM treatments on response variables using generalised linear mixed models. The response variables included: aboveground onion biomass, number of leaves, bulbing ratio, LAI at BI, total and marketable yield, bulb size, plant density and leaf-N concentration, cover crop aboveground biomass, cover crop C:N ratio, proportion of bare soil, and soil cover by the cover crop and residues, weed cover, weed aboveground biomass, soil mineral nitrogen, NH_4:NO_3 ratio, soil respiration, PMN, SOC, soil bulk density, and soil temperature. In 2019 we also assessed the effect of the treatments on PNA, urease and dehydrogenase enzyme activity, and in 2020 the proportion of green leaves and the percentage of foliage collapse at harvest. The explanatory variables were tillage (RT or CT, whole plot factor), NEM application (presence or absence, split-plots factor), year (2019 and 2020), sampling date when the variables had repeated measures, and their two-way interactions. The random effects were tillage and block interaction as whole plot error (1|Block:Tillage), the NEM, tillage, and block interaction as pooled error (1|Block:Tillage:NEM) in which we included the date when repeated measures in time were modelled (1|Block:Tillage:NEM:DateNumber). We first evaluated models with "Year" (2019 or 2020) as a fixed effect. When interactions with "Year" were significant, separate analyses were conducted for 2019 and 2020. We used Gaussian or gamma error distributions for continuous variables and Poisson or negative binomial error distributions for count and proportion data (Appendix A4.5). For response variables with many zeros, correction were included in the model. Generalised linear mixed models were developed using the glmmTMB R-package (Brooks et al., 2017). Model residuals were checked using the DHARMa package in R (Hartig, 2022). For significant effects, least square means were adjusted and Tukey test for multiple comparisons was performed using the lsmeans R-package (Lenth, 2016). The R-packages "ggplot2" (Wickham, 2016), "ggpubr" (Kassambara, 2020a), and “scales” (Wickham & Seidel, 2019) were used for data visualization.

4.2.4. On-farm experiments

In 2020, two simplified experiments were conducted on two commercial farms approximately 25 km from the CRS Experimental Station. The farmers were participating in the support group of the project. Farm 1 comprised a conventionally managed system in which soil-improving practices had been applied for more than fifteen years (including crop rotation, green manures, and four-year lucerne). Farm 2 had been a certified organic farm for five years. Onion was the main crop for more than ten years in both farms. The soil type is similar to CRS (Mollic Vertisols, Hypereutric), with relatively high organic matter and no soil-borne disease background. The farms had lower levels of organic matter than CRS (Farm 1: 3.1%, Farm 2: 3.9%) and a similar topsoil bulk density (0.86). Detailed soil information is presented in Appendix A4.2). On each farm, SOC, soil nutrients level and bulk density, cover crop biomass and quality were similar across treatments at the start of the experiment ($p>0.1$).

The treatments were discussed during a workshop and with each farmer in 2019. The experiment on Farm 1 consisted of two trials. The first trial focused on conventional tillage with synthetic fertiliser (CT/SF) and NEM treatment. Three pseudoreplicate plots were placed within the same row to evaluate soil and crop performance. The second trial focused on reduced tillage with chicken manure (RT/CkM) management. The trial consisted of three blocks, which were split in two plots randomly assigned to a NEM treatment (present+ or absent-). Thus, there were three treatments (CT/SF/NEM+, RT/CkM/NEM+, RT/CkM/NEM-) with three pseudoreplicates per treatment on Farm 1 (Appendix A4.6). The experiment on Farm 2 also consisted of two trials. Each trial was defined by the tillage system (RT and CT) and consisted of three blocks, whereby blocks were split into plots that were randomly assigned to a NEM treatment (present+ or absent-). Thus, there were four treatments (RT/NEM-, RT/NEM+, CT/NEM-, CT/NEM+) with three pseudoreplicates per treatment on Farm 2 (Appendix A4.6). The variables assessed were similar to CRS except for soil temperature, which was only monitored in one RT and one CT plot per farm.

Crop sequences, cover crop species, and onion seedlings were similar to those at CRS. The on-farm experiments were managed according to farmers' practice, except for pre-defined nutrient management for each treatment and weed management, where herbicides were not allowed. The research team exclusively did the weeding (Appendix A4.6). Due to heavy rain, soil tillage in CT on Farm 2 was postponed, and transplanting took place 13 days later than on Farm 1 and the CRS. Moreover, Farm 2 had a water deficit after transplanting, and leafcutter ants caused severe plant damage in one of the three replicates.

4.3. Results

4.3.1. CRS on-station experiment

4.3.1.1. Cover crop biomass, quality, and soil cover

Cover crop aboveground dry biomass in 2019 was 4.4 ± 1.1 Mg ha^{-1} and had C:N ratio of 31 ± 3. At cover crop termination, foxtail millet was in a late development stage (starting seed maturation), and foxtail millet, cowpea, and weeds comprised 71%, 32%, and 7% of the biomass, respectively. In 2020, cover crop biomass was 7.1 ± 1.7 Mg ha^{-1} and its C:N ratio was 21 ± 3. At the milky ripe development stage, foxtail millet constituted 94% of the biomass, and weeds constituted the remaining 6%. The drought in the summer of 2020 prevented the establishment of cowpea.

The soil coverage reached by the cover crop exceeded 80% in both years, and the area of bare soil was less than 15% (Fig. 4.2-A, B). In both years, RT had less than 20% of bare soil during the onion cycle. In 2019, CT had 70% of bare soil until the end of September, which decreased to 25% close to harvest, and in 2020 CT had 30% of bare soil until the end of September and decreased to below 15% bare soil close to harvest. Soil residue cover during the onion cycle in RT was more than double that in CT ($p < 0.001$, Fig. 4.2-C, D). NEM application did not significantly affect soil cover ($p > 0.05$).

4.3.1.2. Onion yield and yield components

Total onion yield was affected differently by tillage each year (significant interaction $p<0.01$). In 2019 there was no significant difference between tillage treatments on total yield (10.6 ± 3.7 Mg ha^{-1}), while in 2020, RT had a lower total yield (10.3 ± 1.8 Mg ha^{-1}) than CT (15.3 ± 1.9 Mg ha^{-1}, $p<0.001$). Total yield was not significantly affected by NEM. Marketable yield showed a significant interaction between year and tillage ($p< 0.05$) and between tillage and NEM ($p < 0.05$). In 2019, the marketable yields of CT and RT were comparable without NEM (around 7.5 Mg ha^{-1}), while with NEM, CT had a higher marketable yield than RT (11.2 ± 5.6 vs. 7.5 ± 3.1 Mg ha^{-1}). In 2020, CT had a higher marketable yield than RT (14.7 ± 2.0 vs. 9.4 ± 3.2 Mg ha^{-1}, $p<0.001$) and NEM did not significantly influence commercial onion yield. The differences in total and marketable yields were explained by differences in bulb size and not by the number of bulbs per ha (Table 4.1).

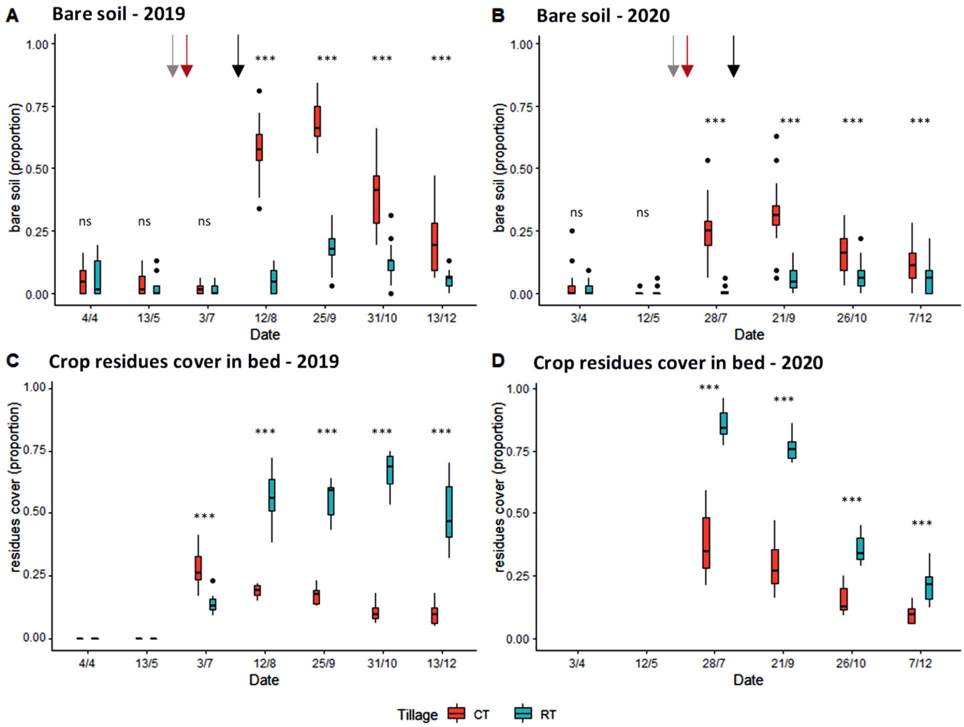

Fig 4.2. Proportion of bare soil (top) and crop residues cover in the raised beds (bottom) during 2019 (left) and 2020 (right) for conventional tillage (CT, red) and reduced tillage (RT, green) during the cover crop and onion growing period. The grey arrow indicates the end of the cover crop cycle due to low temperatures, the red arrow indicates the start of tillage in the CT treatment, and the black arrow indicates onion transplanting. Asterisks indicate significant differences between tillage treatments per sampling date: *$p < 0.05$; ** $p < 0.01$; *** $p < 0.001$, ns: non-significant. NEM application did not significantly influence vegetation cover.

Table 4.1. Total and commercial onion yield, bulb size, plant density, and leaf area index at bulb initiation (LAI at BI) per treatment for the two experimental years at the CRS station.

Year	Tillage	NEM application[1]	Total yield (Mg ha^{-1})	Marketable yield (Mg ha^{-1})	Average bulb fresh weight (g)	Plant density at harvest (plants m^{-2})	LAI at BI (m^2 leaf m^{-2})
2019	Conventional	No	10.5 ± 5.0 a	8.8 ± 6.2 b	53 ± 26 b	20 ± 2 a	0.56 ± 0.25 a
		Yes	12.2 ± 5.0 a	11.2 ± 5.6 a	61 ± 25 a	20 ± 2 a	0.53 ± 0.15 a
	Reduced	No	10.0 ± 3.0 a	8.3 ± 3.7 b	47 ± 10 b	21 ± 4 a	0.55 ± 0.13 a
		Yes	9.5 ± 2.5 a	7.5 ± 3.1 b	41 ± 10 b	23 ± 2 a	0.54 ± 0.15 a
2020	Conventional	No	15.3 ± 1.5 a	14.7 ± 1.5 a	89 ± 4 a	17 ± 2 a	1.02 ± 0.22 a
		Yes	15.2 ± 2.5 a	14.7 ± 2.7 a	87 ± 20 a	18 ± 2 a	1.13 ± 0.34 a
	Reduced	No	11.4 ± 1.1 b	10.5 ± 1.2 b	61 ± 9 b	19 ± 3 a	0.90 ± 0.18 b
		Yes	9.3 ± 1.8 b	8.4 ± 2.0 b	55 ± 7 b	17 ± 2 a	0.75 ± 0.15 b

[1] Native effective microorganisms. Different letters indicate significant differences among treatments within a year ($p < 0.05$).

4.3.1.3. Onion growth and development

LAI at BI was greater in 2020 than in 2019 ($p<0.001$), and there was a significant interaction between year and tillage ($p<0.01$, Table 4.1). In 2019, no significant differences among treatments were found, and the average LAI was 0.54 ± 0.16 m^2 leaf m^{-2}. In 2020, RT had lower LAI at BI than CT (0.83 ± 0.18 vs. 1.1 ± 0.3 m^2 leaf m^{-2}, $p<0.05$). LAI differences between treatments at BI were related to plant size and not to plant density, which was consistent among treatments ($p>0.1$). Differences in plant size at BI were explained by differences in plant aboveground biomass and not by the number of leaves per plant (Fig. 4.3). There was no significant effect of NEM on LAI.

Aboveground onion biomass in 2020 was higher than in 2019 ($p<0.001$), and there was a significant interaction between year and tillage ($p<0.05$). The growth rate after day 45 was higher in 2020 than in 2019 (Fig. 4.3-A and B). In 2019, CT had higher aboveground onion biomass than RT at two months after transplanting and at BI ($p<0.001$), and in 2020 from two months after transplanting to harvest ($p<0.001$). In 2019, there was no significant effect of NEM on aboveground onion biomass. In 2020, there was an interaction between NEM and date ($p<0.01$). One month after transplanting, onions receiving NEM had a higher biomass than those without NEM ($p<0.05$), but two months after transplanting, onions without NEM had a higher biomass than onions that received NEM ($p<0.05$, Fig. 4.3-A, and B).

Although onions in the CT and RT treatments had a similar crop development in terms of number of leaves per plant at BI and at harvest in both years, CT showed a greater number of leaves in the initial two-month period after transplanting than RT ($p<0.05$ and <0.001 depending on the date and year, Fig. 4.3-C and D). The bulbing ratio of RT was lower than that of CT at BI in both years ($p<0.001$ in 2019 and $p<0.05$ in 2020, Fig. 4.3-E and F), indicating a delay in crop development. Moreover, in 2020 RT had a higher proportion of green leaves ($p<0.05$) and a lower percentage of collapsed foliage at harvest than CT ($p<0.05$, Appendix A4.7), indicating that the onion crop in RT was in an earlier development stage at harvest than in CT.

N concentration in the onion leaves was influenced by tillage and NEM treatments. In 2019, there was a significant interaction between tillage and date ($p<0.001$). One month after transplanting, the leaf-N concentration in RT onion was lower than in CT onion (2.18 % in RT vs 2.95% in CT, $p<0.001$), but two months after transplanting, this difference was reversed (2.82% in RT vs 2.47% in CT, $p<0.001$, Fig. 4.3-G and H). One month after transplanting in 2019, RT/NEM+ had a lower leaf-N concentration than RT/NEM- ($p<0.05$, Fig. 4.3-G). In 2020, RT onion had a 20 to 25% lower leaf N-concentration than CT until BI ($p<0.01$, Fig. 4.3-H), and NEM had no significant effect on onion leaf N-concentration. In 2019, the leaf-N content of RT was lower than that of CT from one month after transplanting until BI and in 2020 from two months after transplanting (Appendix A4.7).

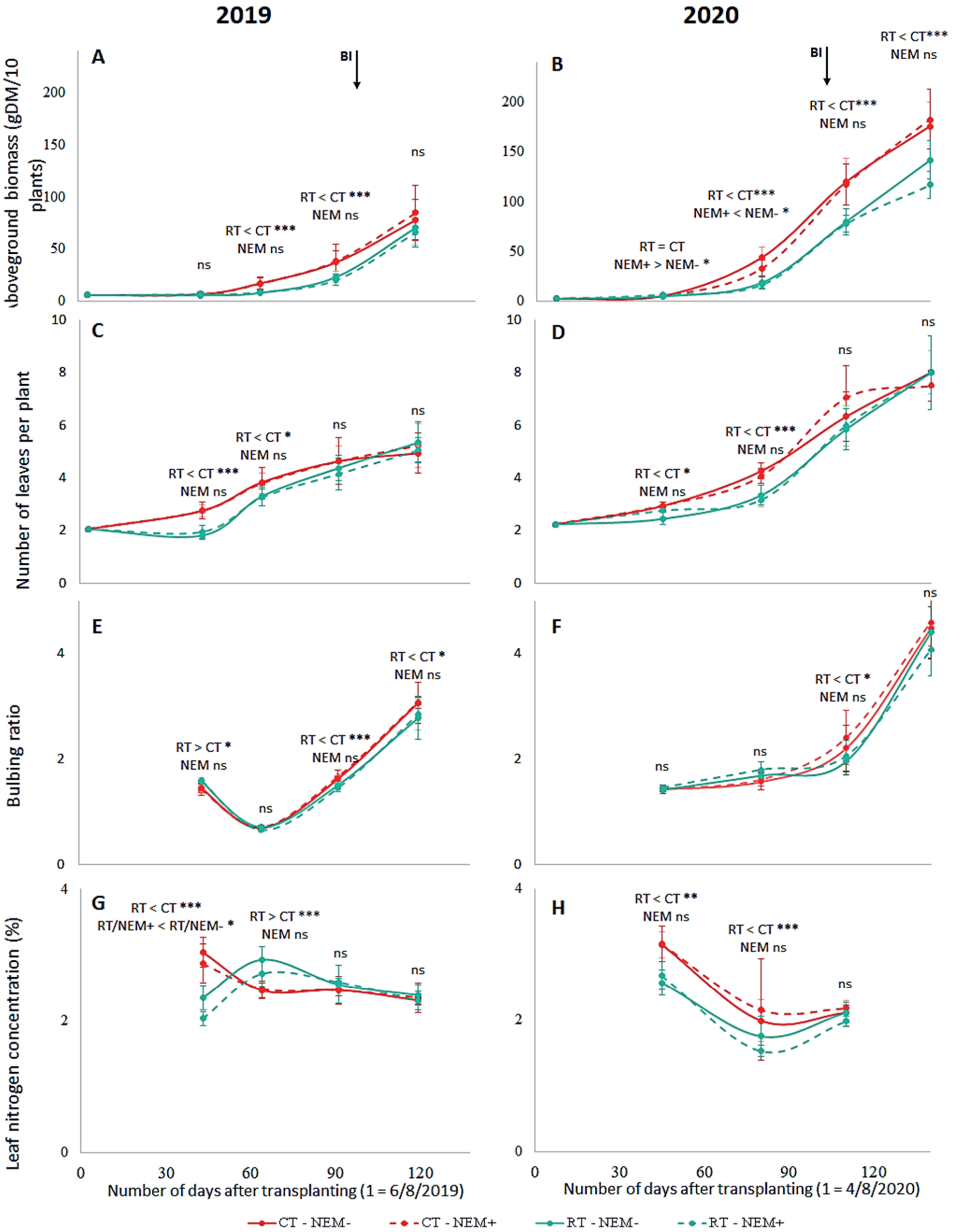

Fig 4.3. Aboveground biomass, number of leaves per plant, bulbing ratio, and leaf nitrogen concentration of onion during the 2019 (left) and 2020 (right) growing seasons for conventional tillage (CT, red) and reduced tillage (RT, green) without NEM (solid) and with NEM (dashed). Black arrows indicate bulb initiation. Asterisks indicate significant differences between treatments per sampling date: *p < 0.05; ** p < 0.01; *** p < 0.001, ns: non-significant.

4.3.1.4. Weed pressure

During the cover crop cycle, weed soil cover was always lower than 15% and was often virtually absent. However, after cover crop senescence and before weeding in RT or tillage in CT (in July), weed soil cover increased to more than 25% (Fig. 4.4-A and B). During the onion cycle in both years, weed biomass and weed cover showed a significant interaction between sampling date and tillage system, showing that RT had a higher weed pressure than CT at the beginning but not in the second half of the onion cycle. Weed biomass and soil covered by weeds at transplanting were higher in RT than in CT (Fig. 4.4). From transplanting to two or three months after transplanting, RT still had higher weed biomass and soil coverage than CT despite manual weeding applied to both tillage systems (Fig. 4.4). After that, weed variables did not differ between RT and CT, except at BI in 2019 when weed biomass was higher in CT than in RT ($p<0.05$).

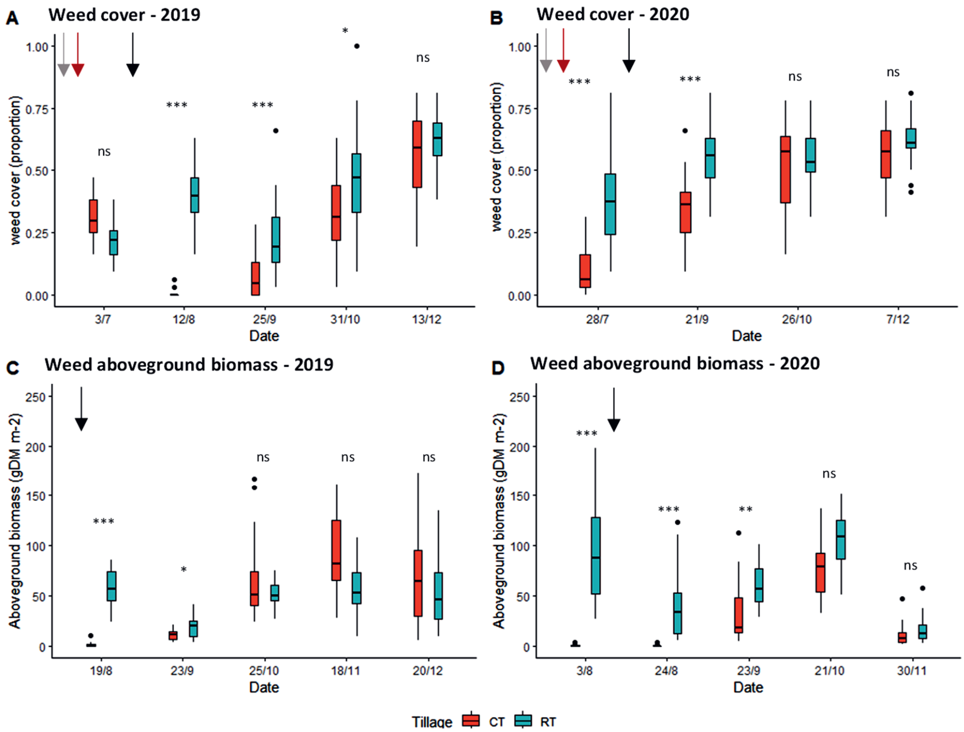

Fig. 4.4. Proportion of soil covered by weeds (top) and weed aboveground biomass (bottom) during the onion cycle in 2019 (left) and 2020 (right) for conventional tillage (CT, red) and reduced tillage (RT, green). The grey arrow indicates the end of the cycle of the cover crop, the red arrow indicates the starting of tillage in the CT treatment, and the black arrow indicates onion transplanting. Sampling dates of weed biomass (19/8/2019 and 3/8/2020) and proportion of weed cover assessments (12/8/2019 and 28/7/2020) were performed after soil tillage in the CT treatment and before the first manual weeding in the RT. Asterisks indicate significant differences between tillage treatments per sampling date: *$p < 0.05$; ** $p < 0.01$; *** $p < 0.001$, ns: non-significant. There was not significant effect of NEM application treatment.

In 2019, three weeding events for CT and RT were carried out, requiring 740 h human labour ha^{-1} during the onion cycle. In 2020, RT required four weeding interventions and 1390 h ha^{-1}, while CT required three weeding interventions and 620 h ha^{-1}.

In 2019, the main weed species were *Stachys arvensis* (Lamiaceae), *Bowlesia incana* (Apiaceae) and *Echinochloa crus-galli* (Poaceae). In 2020, the main weed species were *Stachys arvensis* (Lamiacea), *Stellaria media* (Caryophyllaceae), *Digitaria sanguinalis* (Poaceae) and *Bowlesia incana* (Apiaceae) (Appendix A4.8).

4.3.1.5. Soil physical, chemical, and biological properties

The RT treatment had lower bulk density values than CT (0.898 vs 0.961 g cm^{-3}, $p<0.01$, Appendix A4.9). Soil temperature showed season-specific responses to the tillage treatment each year ($p<0.01$). In 2019, soil temperatures were 2°C and 1°C lower than in 2020 in early and mid-season, respectively ($p<0.001$, Appendix A4.9). In 2019, RT had 0.5°C lower mean, minimum, and maximum soil temperatures at 5 cm depth than CT at late season ($p<0.05$), while in 2020, RT had 0.5°C lower temperatures than CT at 5 cm ($p<0.05$) and 10 cm depth in early season ($p<0.01$, Appendix A4.9).

The soil organic carbon stock was not significantly influenced by tillage, NEM application, or sampling date during the two-year experiment (Appendix A4.9). RT tended to have higher respiration rates than CT in both years and all sampling dates ($p=0.056$, Appendix A4.9) and higher PMN only at BI in 2019 ($p<0.05$, Appendix A4.9). In 2019, PNA at transplanting and BI were higher in RT than in CT ($p<0.01$), RT also had higher urease enzyme activity than CT ($p<0.05$) and a tendency to have higher dehydrogenase enzymes activity at transplanting than CT ($p<0.1$, Appendix A4.9). No significant effect of NEM on the assessed biological parameters was identified.

The level of soil mineral nitrogen at each sampling date in 2019 was around to be five times lower than in 2020 ($p<0.001$, Fig. 4.5-A and B), and the NH_4:NO_3 ratio in 2019 was more than double as in 2020 ($p<0.001$, Fig. 4.5-C and D). The tillage and NEM treatments did not significantly influence the total mineral nitrogen in both years. Still, in 2020 the tillage treatment affected the levels of NH_4 and NO_3 and, therefore, the NH_4:NO_3 ratio. In 2019, total mineral nitrogen peaked after transplanting (19 ppm) and remained around 11 ppm until harvest (Fig. 4.5-A). Soil-NH_4 increased, and soil-NO_3 decreased after transplanting, but the NH_4:NO_3 ratio was always higher than 1 during the onion cycle (Fig. 4.5-C). In 2020, total mineral nitrogen peaked after transplanting (100 ppm) and oscillated around 62 ppm until harvest (Fig. 4.5-B). NH_4:NO_3 ratio was higher in RT than in CT ($p<0.001$) (Fig. 4.5-D), explained by higher NO_3 in CT than RT or higher NH_4 in RT than CT, depending on the sampling date (Appendix A4.9). NEM treatment had no significant effect on soil N variables.

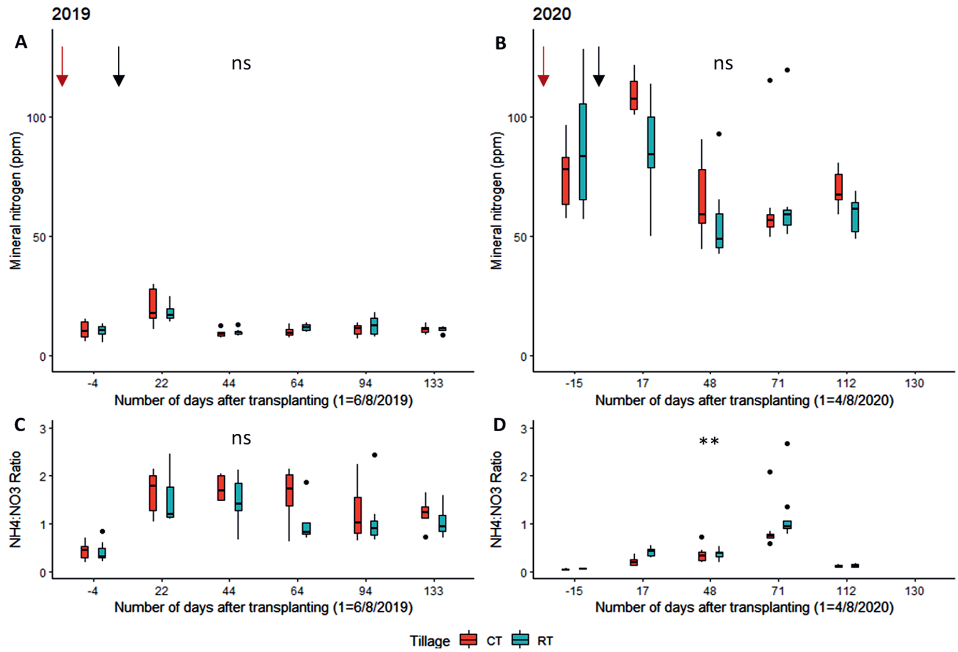

Fig. 4.5. Soil mineral nitrogen (top) and NH_4:NO_3 ratio (bottom) during the onion cycle in 2019 (left) and 2020 (right) for conventional tillage (CT, red) and reduced tillage (RT, green). The red arrow indicates tillage in the CT treatment, and the black arrow indicates onion transplanting. Asterisks indicate a significant difference between tillage treatments each year: *$p < 0.05$; ** $p < 0.01$; *** $p < 0.001$, ns: non-significant. NEM application had no significant effect on soil mineral nitrogen or the NH_4:NO_3 ratio.

4

4.3.2. Comparison between CRS and on-farm experiments

The on-farm experiments confirmed some of the findings from the CRS experiment (Table 4.2): i. leaf-N content in early stages of the onion crop and LAI at BI were lower for RT than for CT; ii. RT resulted in a delay in bulbing ratio and crop maturity; iii. soil mineral nitrogen did not differ among treatments, but RT had a higher NH_4:NO_3 ratio than CT; iv. soil biological activity tended to be higher in RT than in CT; v. weed biomass, weed soil cover in the early stages of the onion crop, and weeding workload were higher in RT than in CT; vi. soil cover by cover crop residues was higher in RT than CT during the entire cycle. However, there were also contrasting findings in the on-farm and CRS experiments (Table 4.2): i. RT had a higher bulk density than CT on both farms, while this was the other way around in the CRS on-station experiment; ii. on Farm 1, soil mineral N in the CT/SF treatment was more than double the levels of the RT, and more than all treatments on Farm 2 and CRS; iii. on Farm 1, yield of CT/SF was comparable to RT/CkM/NEM- and LAI levels were higher than in the other locations; iv. Farm 1 had a lower weed pressure compared to CRS and Farm 2. Results of commercial farms are presented in Appendix A4.10.

Table 4.2. Summary of results on the cover crop (CC), soil cover, onion yield, onion crop growth and development, weed pressure and soil properties at the CRS Experimental Station in 2019 and 2020, and the two commercial farms in 2020. For each variable, significant differences among treatments are indicated (RT: reduced tillage, CT: conventional tillage; NEM+: with NEM, NEM-: without NEM), and NS indicates non-significant relationships. Mean values and (standard deviations) are shown.

	Location and year	CRS 2019	CRS 2020	Farm 1 2020	Farm 2 2020[1]
	Treatments	RT/NEM+, RT/NEM-, CT/NEM+, CT/NEM-	RT/NEM+, RT/NEM-, CT/NEM+, CT/NEM-	RT/CkM/NEM+, RT/CkM/NEM-, CT/SF/NEM+ [1]	RT/NEM+, RT/NEM-, CT/NEM+, CT/NEM-
SOC and Cover crop	Soil organic carbon (%)	2.55 NS	2.55 NS	1.80 NS	2.26 NS
	RASOC [2]	0.62 NS	0.62 NS	0.35 NS	0.52 NS
	CC Biomass (Mg ha^{-1})	4.4 (1.1) NS	7.1 (1.7) NS	3.9 (0.3) NS	4.3 (0.5) NS
	CC C:N ratio	31 ± 3 NS	21 (3) NS	15 (1) NS	26 (1) NS
	Developmental stage at termination	Mature grains	Milky ripe grains	Anthesis	Milky ripe & mature grains
Soil cover	Bare soil at BI [3] (%)	RT < CT 12 (7) vs. 39 (14)	RT < CT 7 (6) vs. 16 (8)	RT/CkM < CT/SF 9 (6) vs. 39 (12)	RT < CT 24 (7) vs. 58 (11)
	Residues cover in bed at BI [3] (%)	RT > CT 67 (8) vs. 10 (4)	RT > CT 36 (6) vs. 15 (6)	RT/CkM > CT/SF 69 (13) vs. 7 (1)	RT > CT 43 (9) vs. 10 (3)
Yield and crop growth and development	Total yield (Mg ha^{-1})	NS 10.6 (3.7)	RT < CT 10.3 (1.8) vs. 15.3 (1.9)	RT/CkM/NEM+ < other two 14.0 (1.5) vs. 15.9 (1.6)	RT < CT 2.9 (1.0) vs. 6.2 (1.0)
	Marketable yield (Mg ha^{-1})	RT & CT/NEM- < CT/NEM+ 8.2 (4.1) vs. 11.2 (5.6)	RT < CT 9.4 (3.2) vs. 14.7 (2.0)	RT/CkM/NEM+ < other two 13.0 (1.7) vs. 15.2 (1.7)	RT < CT 1.7 (1.1) vs. 5.2 (1.1)
	LAI at BI [3] (m^2 leaf m^{-2})	NS 0.54 (0.16)	RT < CT 0.83 (0.18) vs. 1.1 (0.3)	RT/CkM < CT/SF 1.1 (0.1) vs. 1.4 (0.1)	RT < CT 0.3 (0.1) vs. 0.4 (0.1)
	Leaf-N after transplanting (%)	RT/NEM+ < RT/NEM- < CT 2.0 (0.1) vs. 2.3 (0.2) vs. 3.0 (0.3)	RT < CT 2.6 (0.2) vs. 3.2 (0.2)	NS 2.8 (0.2)	NS 2.7 (0.3)
	Leaf-N at BI [3] (%)	NS 2.6 (0.2)	RT < CT 2.1 (0.1) vs. 2.1 (0.1)	RT/CkM < CT/SF 2.3 (0.2) vs. 2.7 (0.1)	NS 2.1 (0.1)
	Bulbing ratio at BI [3]	RT < CT 1.5 (0.2) vs. 1.8 (0.2)	RT < CT 2.0 (0.3) vs. 2.3 (0.5)	RT/CkM < CT/SF 2.5 (0.5) vs. 2.9 (0.5)	NS 2.4 (0.5)
	Foliage collapse at harvest (%)	Not assessed	RT < CT 4 (2) vs. 8 (4)	RT/CkM < CT/SF 8 (1) vs. 14 (2)	Not assessed
	Green leaf at harvest (%)	Not assessed	RT > CT 83 (7) vs. 70 (15)	RT/CkM > CT/SF 77 (5) vs. 50 (26)	Not assessed

[1] In Farm 1: CkM: chicken manure, SF: synthetic fertiliser. [2] Relative Active Soil Organic Carbon (RASOC) = ((Actual SOC – Min SOC)/(Max SOC – Min SOC)) * 100 (Dogliotti et al., 2014). [3] BI: bulb initiation.

Table 4.2 (cont). Summary of results on the cover crop (CC), soil cover, onion yield, onion crop growth and development, weed pressure and soil properties at the CRS Experimental Station in 2019 and 2020, and the two commercial farms in 2020. For each variable, significant differences among treatments are indicated (RT: reduced tillage, CT: conventional tillage; NEM+: with NEM, NEM-: without NEM), and NS indicates non-significant relationships. Mean values and (standard deviations) are shown.

	Location and year	CRS 2019	CRS 2020	Farm 1 2020	Farm 2 2020
	Treatments	RT/NEM+, RT/NEM-, CT/NEM+, CT/NEM-	RT/NEM+, RT/NEM-, CT/NEM+, CT/NEM-	RT/CkM/NEM+, RT/CkM/NEM-, CT/SF/NEM+ [1]	RT/NEM+, RT/NEM-, CT/NEM+, CT/NEM-
Weed pressure	Weed biomass before treatments (g dm m^{-2})	NS 57 (19)	NS 95 (49)	NS 46 (36)	NS 167 (46)
	Weed biomass after transplanting (g dm m^{-2})	RT > CT 19 (10) vs. 11 (6)	RT > CT 38 (32) vs. 1 (1)	RT > CT 7 (7) vs. 1 (3)	RT > CT 19 (11) vs. 6 (8)
	Weed biomass at BI [3] (g dm m^{-2})	RT < CT 51 (13) vs. 62 (39)	NS 93 (30)	NS 11 (10)	RT > CT 34 (14) vs. 8 (10)
	Number and time (h ha^{-1}) of weeding interventions	NS Three 725 vs 750	RT > CT Four vs three 1390 vs 620	RT > CT Three vs two 480 vs 255	RT > CT Three 1170 vs 560
Soil chemical, physical and biological properties	Mineral N after transplanting	NS 19 (6)	NS 100 (20)	RT/CkM < CT/SF 85 (26) vs. 228 (40)	NS 60 (9)
	NH_4:NO_3 ratio after transplanting	NS 1.7 (0.6)	RT > CT 0.4 (0.1) vs. 0.2 (0.1)	NS 0.4 (0.1)	NS 0.5 (0.3)
	Mineral N at BI [3]	NS 12 (3)	NS 64 (21)	RT/CkM < CT/SF 53 (10) vs. 305 (78)	NS 49 (9)
	NH_4:NO_3 ratio at BI [3]	NS 1.2 (0.6)	RT > CT 1.2 (0.6) vs. 0.9 (0.5)	RT/CkM > CT/SF 0.3 (0.1) vs. 0.1 (0.0)	NS 0.1 (0.0)
	Respiration at BI [3] mg C-CO2 kg^{-1}	RT > CT 5.3 (1.3) vs. 4.6 (1)	RT > CT 5.3 (1) vs. 4.6 (1)	RT/CkM > CT/SF 35.1 (10.2) vs. 21.7 (3.4)	NS 32.0 (7.0)
	Potentially mineralizable N at BI [3] mg N. g^{-1} d^{-1}	RT > CT 8.3 (1.7) vs. 6.3 (1.5)	NS 6.1 (1.2)	RT/CkM > CT/SF 4.4 (0.2) vs. 3.1 (1.6)	NS 5.7 (1.1)
	Bulk density before harvest g cm^3	RT < CT 0.98 (0.15) vs. 1.06 (0.14)	RT < CT 0.89 (0.08) vs. 0.94 (0.11)	RT/CkM > CT/SF 0.97 (0.07) vs. 0.88 (0.02)	RT > CT 1.00 (0.11) vs. 0.94 (0.08)
	Mean temperature 5 cm depth [4] ºC	RT < CT at late season 23.6 vs. 24.1	RT < CT at early season 14.5 vs. 15.0	RT < CT at late season 22.5 vs. 23.0	RT < CT at late season 24 vs. 25.5

[1] In Farm 1: CkM: chicken manure, SF: synthetic fertiliser. [3] BI: bulb initiation. [4] Early season: 1 to 15 September, Late season: 1 to 15 December.

4

4.4. Discussion

In this study, we assessed the effect of CC-RT vs CC-CT in combination with NEM application on the performance of onion crops, N status, and weed pressure, without the application of herbicides or synthetic fertilisers on locations in the south of Uruguay. We report four key findings. First, onion growth and yields were generally low compared to the average (26 Mg ha^{-1}) and attainable yields (45 Mg ha^{-1}) for the region (Dogliotti et al., 2021); yields were lower in 2019 than in 2020, and lower in RT than in CT. Low yields were associated with relatively low leaf-N concentrations in the early stages of crop development, and these were lower in 2019 than in 2020 and lower in RT than CT. Second, soil mineral N was lower in 2019 than in 2020 and did not significantly differ between treatments, while the NH4:NO3 ratio was higher in 2019 than in 2020 and higher in RT than in CT. Soil physical properties were not limiting crop growth in any treatment, and biological activity was higher in RT than in CT. Third, although RT resulted in high soil and crop residue cover, it resulted in higher weed pressure in the early crop stages than CT, which was reversed at later stages. Both RT and CT required manual weeding during the onion cycle, but the workload was higher in RT than in CT. Fourth, the NEM application did not significantly affect most crop, weeds, and soil variables.

4.4.1. Effect of tillage on onion growth, development and yield

All treatments in both years had relatively low yields compared to the average yield (26 Mg ha^{-1}) and attainable yield (45 Mg ha^{-1}) for the region (Dogliotti et al., 2021). These low yields were related to low crop growth rates before BI, evidenced by LAI levels at BI from 0.53 to 1.13 m^2 leaf m^{-2}, while at least a LAI of 1 or 2 m^2 leaf m^{-2} are needed to achieve the average and attainable yield, respectively (Dogliotti et al., 2021). CT treatments in 2020 had a LAI at BI above 1 m^2 leaf m^{-2}, but the total yield was still lower than the regional average, suggesting that the crop growth rate after BI was also low. The low crop growth rate before BI can be explained by the observed leaf-N concentrations below the critical threshold of 4% at an early crop stage (Brewster et al., 1987; Geisseler et al., 2022; Maynard & Hochmuth, 2007), which were lower in 2019 than in 2020 and lower in RT than CT. Nitrogen deficiency reduces gross assimilation, growth rates, and leaf area expansion (Geisseler et al., 2022; Brewster & Butler, 1989). Moreover, in line with our results, N shortage during early stages also has a negative effect on crop development, lowering leaf initiation rate and bulb formation (Brewster & Butler, 1989). Thus, N deficiencies may explain the low yield levels of the CRS experiment in both years and the better onion performance in 2020 than in 2019. However, the better crop performance in the CRS on-station experiment in 2020 than in

2019 could also be partially explained by the earlier appearance and higher incidence and severity of downy mildew in 2019 than in 2020 (Appendix A4.7).

In 2020, RT yielded 32% lower onion yield than CT in the CRS on-station experiment. The lower leaf-N concentration observed in RT before BI might have reduced crop growth (expressed as crop biomass, LAI, bulb size at harvest) and delayed crop development (in terms of the number of leaves, bulbing ratio, and maturity at harvest), explaining the lower yield. A promising result was that in 2020 in CRS and on Farm 1, RT reached LAI levels close to 1, which could have allowed yield levels of around 25 Mg ha^{-1} (Dogliotti et al., 2021). However, these LAI levels did not translate to a high yield in RT, most likely because the crop was harvested prematurely since its development was delayed compared to the CT treatment. The RT onions could have continued to grow for at least one or two more weeks, and in this period the yield could have been further increased. Therefore, our onion yields in RT are conservative and higher yields can be expected in more optimised RT systems.

4.4.2. Effect of tillage on soil physical, chemical, and biological activity

Unfavourable soil physical conditions may limit the effectiveness of RT (Carr et al., 2013; Peigné et al., 2007). The lower bulk density in RT than in CT at the CRS experiment suggests that a relatively high SOC and RASOC levels allows the soil structure and porosity to be maintained despite not being tilled. In contrast, intensive soil tillage, such as in CT, increases macro porosity in the short term but deteriorates soil structure and increases SOC mineralization, which in the mid-to-long term results in more compaction (Weil & Brady, 2016). The two commercial farms showed a contrasting pattern compared to the CRS by having soil bulk densities in the RT treatment that were higher than for CT. This finding may be related to the lower SOC and RASOC level of the soils at the farms than at the CRS, which may point to a lower soil physical quality or resilience (Hoffland et al., 2020), and highlights the need for good soil quality for the effective implementation of RT.

Nevertheless, on both farms, the soil bulk density was below 1.1 g cm^{-3} and should not limit crop growth on this type of soil (USDA, 1999). In addition, farmers identified the "softness" of the soil as a positive and unexpected result of the experiment "*Contrary to what I expected to happen, the soil was not tight in the RT. It was softened and better than in the CT (...); beyond that, it is even a good result for the soil quality. It is also good because, for planting by hand, the soil has to be soft; otherwise, nobody will do it*".

RT had significantly lower soil temperatures at 5 and 15 cm depth than CT in the late season of 2019 and early season of 2020, which aligns with findings of Coolman & Hoyt

(2018) and Jokela & Nair (2016). These relatively low topsoil temperatures in RT can explain the delay in onion growth and development by a direct effect on the crop development rate (Lancaster et al., 1996) and by an indirect effect on the N availability for the crop via a reduction in root activity and N release by soil biota (Ciaccia et al., 2015).

Soil biological activity was greater in RT than in CT, which aligns with previous studies (Arboleya et al., 2012; Carr et al., 2013). The higher urease activity found in 2019 in RT compared to CT may point to a higher organic matter mineralization rate in RT than CT. The urease activity is a good index of soil quality as it is closely related to soil organic matter, N cycling, and the regulation of N supply to plants (Adetunji et al., 2017). However, the greater soil biological activity in RT than in CT may in the short term increase the competition for mineral N between soil microorganisms and the crop until a new dynamic equilibrium is reached (Hodge et al., 2000).

The soil mineral N in 2020 was higher than in 2019 at the CRS and did not differ significantly between RT and CT in both years. A combination of effects may explain the difference in mineral N between 2019 and 2020. First, the relatively low C:N ratio of the cover crop, the relatively early soil tillage, and the compost tea application in 2020 that may have reduced N immobilization by microorganisms and accelerated N mineralization (Hodge et al., 2000; Masunga et al., 2016; Mooshammer et al., 2014). Second, the higher precipitation in 2019 compared to 2020 may have increased N-leaching (Ciaccia et al., 2015). Third, the lower soil temperatures at early and mid-onion season in 2019 compared to 2020 may have reduced SOM mineralization (Luce et al., 2011). Fourth, the positive cumulative effect of the two years of chicken manure and cover crop in all the treatments hay have contributed to a higher N level in 2020 than 2019. The higher level of soil mineral N in 2020 increased N uptake by the onion crop, leading to higher LAI and aboveground biomass than in 2019, while maintaining levels of leaf N concentration similar to those in 2019 (Table 4.1; Fig 4.3). Nevertheless, soil N availability in 2020 was not enough to increase N uptake by the onion crop to non-limiting levels of leaf N content (Fig 4.3).

Tillage did not significantly influence soil mineral N levels, but RT negatively affected the onion leaf-N concentration before BI (Fig. 4.3). Possibly, the timing of the soil mineral N measurements done every 20 or 30 days were not effective in tracking the extremely dynamic soil mineral N pool (Hodge et al., 2000). Therefore, although our data do not allow us to confirm it, the N immobilization effect after the cover crop might have lasted longer in the RT than in CT, probably due to a more limiting soil mineral N availability (Terrazas et al., 2016). These results highlight the complexity involved in the strong dynamics of organic matter mineralization and nutrient availability (Geisseler et al., 2022; Hodge et al., 2000; Masunga et al., 2016), underlining the challenge of matching the supply and demand of N under organic CC-RT.

The NH_4:NO_3 ratio was higher in 2019 than in 2020, and RT had a higher NH_4:NO_3 ratio than CT in 2020. The higher ratios in 2019 than in 2020 may be associated with the high precipitation levels in 2019 (Appendix A4.4) that may have increased NO_3 leaching and decreased biological conversion of ammonium to nitrate due to reduced soil aeration. The higher ratio in RT than CT for 2020 has also been reported by Wacker et al. (2022), and may be related to a higher soil moisture in RT than in CT (Alliaume et al., 2017) and different-sized soil aggregates that affected microhabitat conditions (temperature, water, gas and nutrient dynamic) and thus, microbial activity (Puerta et al., 2019). Nevertheless, although the NH_4:NO_3 ratio affects plant growth and onion prefers high NH_4 at transplanting and a low NH_4:NO_3 ratio during the rest of the cycle, the values found were within the range of 1:3 and 3:1 reported for good onion crop performance (Abbès et al., 1995; Gamiely et al., 1991).

On Farm 1, synthetic fertiliser (urea) was applied in CT/SF like for most onion farms in the region (Scarlato et al., 2022), resulting in three to six times higher soil mineral N in CT/SF than in RT, mainly in the form of NO_3. However, onion yields of the RT/CkM/NEM- and CT/SF treatments were comparable (Table 4.2 and Appendix A4.10). High mineral N, particularly high NO_3 conditions, indicate inefficiencies and pose an environmental risk because of N-leaching (Terrazas et al., 2016) and N_20 emission (Butterbach-Bahl et al., 2013). The results of Farm 1 evidence the environmental risk of the current most common management in the region based on CT and synthetic fertilisers. At the same time, it highlights the positive contribution that CC-RT, in combination with organic amendments, may have to reduce this environmental risk.

4.4.3. Effect of cover crop and tillage on weed pressure and soil cover

The cover crop tested of foxtail millet and cowpea resulted in an aboveground biomass of 4 to 7 Mg DM ha^{-1} and more than 80% of soil cover following a growing period of less than 4 months during end of summer and autumn, which can be considered a good performance for the study region, and can reduce soil erosion and increase soil organic matter (Alliaume et al., 2013; García De Souza et al., 2011; Gilsanz, 2012). The cover crop was naturally terminated by low temperatures in June, around one and a half months before onion transplanting, which provided sufficient time to prepare the onion transplanting while eliminating the need for herbicide applications to terminate the cover crop. Farmers appreciated this unexpected outcome: *"I am not completely sure if I am going to continue trying the reduced tillage technology yet, but I am sure that I will continue using this cover crop in the system. It has a great performance, I do not need* *to use the herbicide and it is easy to manage before installing the onion* (…) *in general, it is not easy to include a cover crop in summer and before onion, because you need the land in summer for other crops and in general is difficult to prepare the soil in autumn. But this option has shown that it is a very good and viable one.”*

Despite the good cover crop performance, the cover crop biomass and residue cover in the RT system did not result in a lower weed pressure than in CT. RT had a higher weed pressure in the early stages of the crop than CT, as weeds in CT were removed by tillage before transplanting. Although this pattern was reversed at later crop development stages, and both RT and CT required weeding, RT required more interventions and work. The difference in aboveground weed biomass between RT and CT was significant until 45-60 days after transplanting. The relatively high weed cover in RT has likely caused increased competition for N with the onion crop in the early stages of crop development.

While previous studies found that a mulch biomass of around 5 Mg ha^{-1} can effectively suppress weeds (Altieri et al., 2011; Leavitt et al., 2011), these studies focused on winter cover crops followed by summer crops (tomato, beans, sweet pepper, zucchini), which are competitive with weeds. Other studies showed that at least 8 Mg ha^{-1} of mulch biomass and a mulch thickness of 10 cm were needed to effectively suppress weeds (Teasdale & Mohler, 2000). Although we achieved between 4 and 7 Mg cover crop DM ha^{-1}, onion is highly susceptible to weed competition during all its growing cycle (Hewson & Roberts, 1973; van Heemst, 1985). Mulch can provide good early-season weed suppression, but it generally cannot suppress weeds throughout the season (Teasdale, 1996) and is not effective in the suppression of perennial weed species that are well-established (Carr et al., 2013). The differences in weed pressure between CRS and Farm 1 underline the relevance of the seed bank on the feasibility of CC-RT technology. In situations of high weed pressure, such as in the case in the experiments at the CRS and Farm 2, holistic and long-term strategies have to be considered beforehand to reduce soil weed seed bank, such as crop rotation with winter and summer green manure and pastures, mechanical weeding, and false sow beds (Chikowo et al., 2009; Portela, 2008). The CC-RT technology could be complemented by adding external residues to increase the mulch thickness and the duration of soil cover (Teasdale & Mohler, 2000). The cover crop species selection and/or management could also be improved to achieve higher biomass, for example by using highly productive C4 species and an extended growing season, but care is needed to trade-offs between N-immobilization and cover crop biomass. Finally, other mechanisms of weed suppression, such as the use of cover crops with allelopathic and inhibitory compounds, could be included (Shirgapure & Ghosh, 2020).

4.4.4. Effect of NEM on onion crop system

NEM application had no significant effect in any of the variables related to soil properties and a few related to crop performance. We expected that NEM would enhance the mineralization of organic materials and the associated nutrients availability for the crop (Higa et al., 2011). In contrast, NEM application in the RT system in 2019 at the CRS resulted a significantly lower leaf nitrogen concentration 40 days after transplanting, and on Farm 1 led to significantly lower total and commercial onion yields than RT without NEM application. These unexpected findings may be explained by competition for N between plants and microorganisms (Hodge et al., 2000). Supporting this hypothesis, most studies that reported positive response of EM on yield where obtained when EM application was carried out in combination with farmyard manure or mineral NPK (Olle & Williams, 2013). Although organic manure was applied, this was done before sowing the cover crop, approximately 180 days before onion transplanting. This may have created top soil conditions with relatively low mineral N and high C levels because of the extended period with soil cover with cover crop biomass and the cover crop root systems in the top soil. In this environment, RT gave rise to a higher soil microbial activity that may have momentarily increased N immobilization. NEM application may have therefore enhanced N immobilization and reduced N availability for the onion crops.

4.4.5. Lessons learned and future steps

The CC-RT system tested in this study was able to limit bare soil cover below 20% during the onion cycle, did not impose any constraints on soil bulk density for crop growth, and the good performance of the cover crop was achieved without using synthetic fertilisers and herbicides. However, the onion yields achieved during our study, their link to nitrogen deficiencies and high weed pressure in early stages, and the site-specific results evidence that further improvements are needed, such as those mentioned for reducing weed pressure (section 4.4.3). However, the main benefits of RT associated with cover crop are expected and should be assessed in the long term, especially regarding soil health. Those benefits will result from organic matter accumulation and greater microbial biomass and activity, positively influencing soil biological, chemical, and physical attributes (Carr et al., 2013; Lv et at., 2023; Garcia et al., 2005; Mercante et al., 2008). Consequently, to continue testing and improving the application of the RT technology, it is necessary to set up a long-term research platform, including different situations.

Long-term research approaches that seek to generate appropriate technological alternatives require working in application contexts and involving end-users (Doré et al., 1997; Doré et al., 2011; Milleville, 1993), in our case, farmers and technical advisers. In particular, when working on developing technologies that result from changes in how farmers understand and manage their systems, and modify several components of the system and their interactions. In this context, participatory approaches promote collective and inclusive reflection improving the learning processes of all actors involved and the relevance of the research focus (Cerf et al., 2012; Méndez et al., 2013; Rossing et al., 2021), as was evidenced in our study. The CRS experiment plan for the first year was modified according to new ideas that emerged from the workshop discussion. We defined the cover crop management prioritizing weed suppression effect over nutrient supply, we adjusted the initial plan concerning methods and timing of termination of the cover crop, how to apply the NEM, and. In the second year, four main modifications emerged from the workshop: increasing cover crop sowing density to improve soil cover and weed suppression, avoiding all synthetic pesticide applications to promote soil health and the effectiveness of the NEM application, starting NEM applications before transplanting of onion, and including biofertiliser to provide N.

During this participatory research, the analytical framework was essential for a systemic shared view of the research problem among participants (Fig. 4.1). The understanding that crop performance or weed pressure are emergent properties of the entire cropping system and that the treatments generate long-term effects helped all participants appreciate the study's value as a step towards a more agroecological way of farming. During the project and workshops we focused on the processes and mechanisms underlying onion crop performance, rather than testing a particular technology or individual practice (Carr et al., 2013). Quotes from participant interventions during the workshops and end-of-project interviews show the relevance of this approach *"It is all connected, if we increase the decomposition of the residues to have more nutrients, they will be gone faster, and we will have more weeds (...) we have to delay weed appearance as much as possible, for nitrogen, I think there are more tools we can use", "We still need to adjust the management better to reduce weeds, but having a good soil and adjusting the timing of fertilization a little more, the truth is that we could achieve good results with reduced tillage, we need more time in this research project", "It will take time for the soil to respond to this good management, it is medium to long term if we have been doing everything the other way around for dozens of years, we cannot ask for miracles. We will be in a better starting position for the second year and those that follow"*. We conclude that the participatory approach requires a high commitment and time investment of farmers and researchers, but that it is an effective way to develop management systems that rely on the complex interactions of agroecosystem components.

4.5. Conclusions

Here we pioneered a cover crop – reduced tillage (CC-RT) system for onion without use of agrochemicals in a participatory setting. While CC-RT kept less than 20% of bare soil during the onion cycle and did not impose any constraints on soil bulk density for crop growth, onion yields were approximately 50% lower than the regional average achieved by conventional crops in both tillage treatments and years, yield in 2020 was higher than 2019, and higher in CT than in RT in 2020. Limited soil N availability was most likely a key reason for the relatively low onion yields in the experiment, the difference in yield between 2019 and 2020, and between the onion yields in the RT and CT treatments. Although the summer cover crop had a high biomass production and provided good soil cover for at least three months, the effect of RT on weed control was limited in CRS and Farm 2. Weed control on Farm 1 was satisfactory, which was most likely associated with a lower weed seed bank, and it also maintained better soil cover than CT for most of the onion crop cycle. Further research to make the CC-RT technology feasible under organic management should be targeted towards effective ways to suppress weeds and soil N availability at the start of the growing season in RT systems.

Acknowledgements

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Appendix 4

A4.1. Overview of the research timeline and schematic representation of the split-plot experiment design in CRS

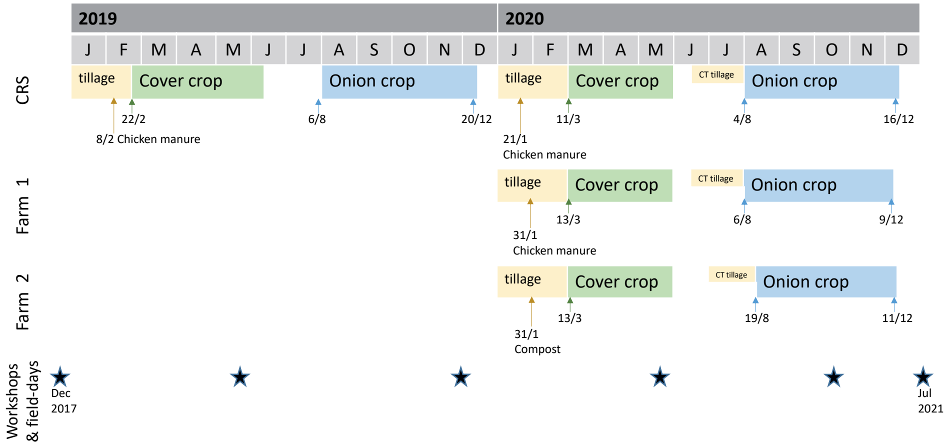

Fig A4.1.1. Timeline of the two-year experiment in CRS, the two commercial farms in the second year and the workshops and field-days with the support group.

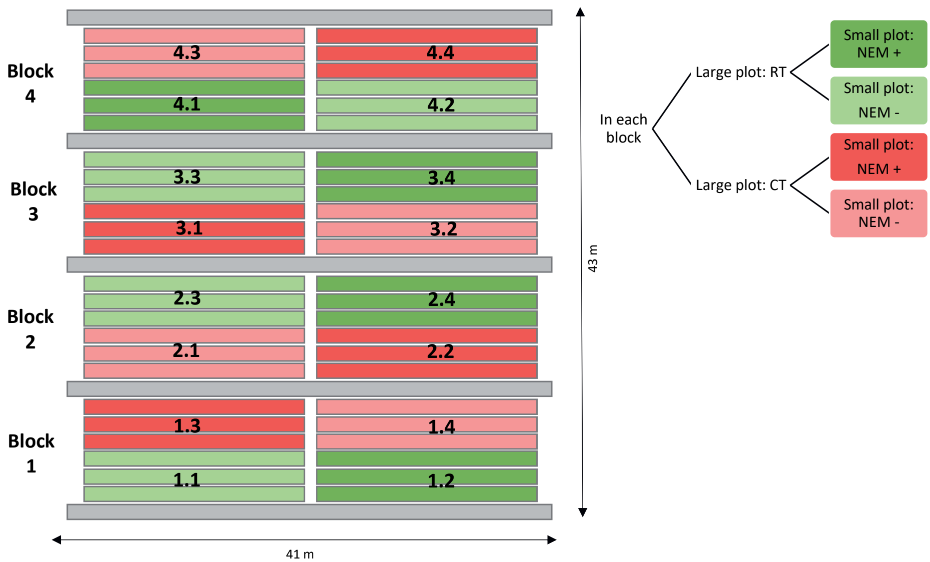

Fig. A4.1.2. Schematic representation of the split-plot experimental design at the experimental station. There were four blocks, the tillage system was the whole plot factor (green – RT; red - CT), and NEM applications was the subplot factor (colour intensity high for NEM+, low for NEM-).

A4.2. Soil, compost and compost tea characterisation, pesticide applications, organic amendment application and tillage sequence in CRS and the two farms

Table A4.2.1. Physic and chemical properties of top soil (0-20 cm depth) in CRS in 2019 and 2020, and in the two farms in 2020

Location	Year	pH	Organic Matter %	K (meq)	P (ppm)	Sand %	Silt %	Clay %	Bulk density	RASOC [1]
CRS	2019	6.60	4.40	1.80	192	10	42	48	0.89	0.62
CRS	2020	6.78	4.40	1.70	162	10	42	48	0.84	0.62
Farm 1	2020	7.40	3.10	1.63	105	12	49	39	0.86	0.35
Farm 2	2020	7.07	3.93	0.84	32	11	49	40	0.86	0.52

[1] Relative Active Soil Organic Carbon (RASOC) = ((Actual SOC – Min SOC)/(Max SOC – Min SOC)) * 100 (Dogliotti et al., 2014)

Table A4.2.2. Analysis of the chicken manure used in 2019 in CRS, and in 2020 in CRS and Farm 1

Year	Dry matter	Density	C	N	P	Ca	Mg	K	Na	Cu	Fe	Mn	Zn
	%	Kg DM L^{-1}	%	%	%	%	%	%	%	mg/kg	mg/kg	mg/kg	mg/kg
2019	59	0.359	24	1.89	1.6	4.0	0.9	2.2	0.6	56	3080	918	249
2020	73	0.292	30	2.53	1.3	1.9	0.7	2.4	0.7	43	1756	223	612

Table A4.2.3. Analysis of the compost used in 2020 in Farm 2.

Year	pH	Electric conductivity ds cm^{-1}	C:N ratio	N-total %	P ppm	K meq	Na meq
2020	7.4	4.1	13	1.2	572	17.1	6.3

Table A4.2.4. Compost tea analysis used in 2020 in CRS and the two commercial farms.

Year	pH	Electric conductivity ds cm^{-1}	N-total g L^{-1}	P g L^{-1}	K g L^{-1}	Na g L^{-1}
2020	6.7	16.6	1.3	0.3	3.0	1.0

Table A4.2.5. Pesticide applications in CRS in 2019 and 2020

Year	Active ingredient	Commercial name	Type of application	Purpose	Number of application	Dose (g a.i.ha^{-1})
2019	copper		foliar	downy mildeuw	3	340
	copper+mancozeb+metalaxyl	Ontrack	foliar	downy mildeuw	2	980
	copper+mancozeb+cymoxanil	Facym	foliar	downy mildeuw		1400
	azadirachtin	Neem oil	foliar	*Sminthurus viridis*	1	0.6
2020	*Trichoderma sp.*	*Trichoderma sp.*	foliar	downy mildeuw	5	
	copper	copper	foliar	downy mildeuw	4	340
	azadirachtin	Neem oil	foliar	*Sminthurus viridis*	1	0.6

Table A4.2.6. Soil tillage sequence in 2019 and 2020 according to conventional (CT) and reduced (RT) tillage

Year	Tillage treatment	Date	Tool
2019	CT	7 June	Chisel and disc ridger
		20 July	Chisel and disc ridger
		5 Aug	Rotovator with bed forming and furrow opener
	RT	5 Aug	Inverted tooth harrow and furrow opener
2020	CT	10 July	Chisel and disc ridger
		17 July	Chisel
		3 Aug	Rotovator with bed forming
		4 Aug	Furrow opener
	RT	31 July	Furrow opener
		3 Aug	Furrow opener

Table A4.2.7. Organic amendments and fertilizers applied per year and location and estimation of N mineral (Nmin) available for onion crop

Year	Location	Source	Nutrient application			N	Total N	Nmin first cycle[a]	Nmin residual[b]	Nmin total
			Number per year	L ha^{-1} year^{-1}	kg DM ha^{-1}	%	(kg ha^{-1})			
2019	CRS	Manure	1	40000	14340	1.89	271	112	0	112
2019	CRS	Mixamin	7soil,3foliar	91		7.2	6.6			6.6
2019	**CRS**	**Total**								**119**
2020	CRS	Manure	1	40000	11669	2.53	295	112	56	168
2020	CRS	Mixamin	9 soil	113		7.2	8.1			8.1
2020	CRS	compost tea	9 soil	72		1.3	1.0			1.0
2020	**CRS**	**Total**								**177**
2020	Farm 1	Manure	1	40000	11669	2.53	295	112	0	112
2020	Farm 1	Mixamin	8 soil	100		7.2	7.2			7.2
2020	Farm 1	compost tea	8 soil	64		1.3	0.8			0.8
2020	**Farm 1**	**Total**								**121**
2020	Farm 2	Compost	1	20000		1.19	238	79	0	79
2020	Farm 2	Mixamin	8 soil	100		7.2	7.2			7.2
2020	Farm 2	compost tea	8 soil	64		1.3	0.8			0.8
2020	**Farm 2**	**total**								**87**

[a] We assumed 50% of organic matter mineralization during the first year of application, and we assumed a 10/12 fraction during the CC and onion cycle. In the compost we assumed that 40% of the organic manure was mineralized during the first year and the same fraction 10 months in the total of 12 in the year.

[b] In case of previous organic amendment application, only in CRS 2020, we assumed a residual effect of 25% of mineralization of the organic matter incorporated in the previous year (2019).

A4.3. Native effective microorganisms (NEM) characterisation

The analysis of the NEM was carried out at the IIBCE lab, Uruguay. The number of culturable microorganisms of the groups: aerobic heterotrophic bacteria, lactic acid bacteria (lactobacilli), actinobacteria, yeasts and filamentous fungi was determined. The plate count technique was used. Samples were suspended in sterile 0.1% (w/v) sodium pyrophosphate. Serial dilutions were made in the same solution and seeded in Petri plates with the following semi-selective culture media:

- Trypticase Soy Agar (TSA) 1/10 with cycloheximide (100 g/mL) for heterotrophic bacteria.
- Lactobacilli MRS Agar (MRS) for lactic acid bacteria
- Malt Extract Agar (AM) 2 % pH 4.5 with chloramphenicol (100 g/mL) for yeasts and filamentous fungi
- Casein starch agar (CA) with cycloheximide (100 g/mL) for actinobacteria.

Plates were incubated at 25°C in darkness and aerobiosis, except for MRS which were incubated at 37°C and microaerobiosis. The number of characteristic colonies of each microbial group was determined after 3 days (fungi, yeasts and lactobacilli) or 7 days (heterotrophs and actinobacteria).

Table A4.3.1. Abundance of bacteria, yeasts, filamentous fungi, lactobacilli and actinobacteria on Native Effective Microorganisms (NEM) solution

Group	Abundance (c.f.u./mL)
Bacteria	8.8×10^7
Yeast	1.7×10^6
Filamentous fungi	$<1.0 \times 10^4$
Lactobacilli	2.9×10^8
Actinobacterias	1.8×10^3

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A4.4. Weather conditions

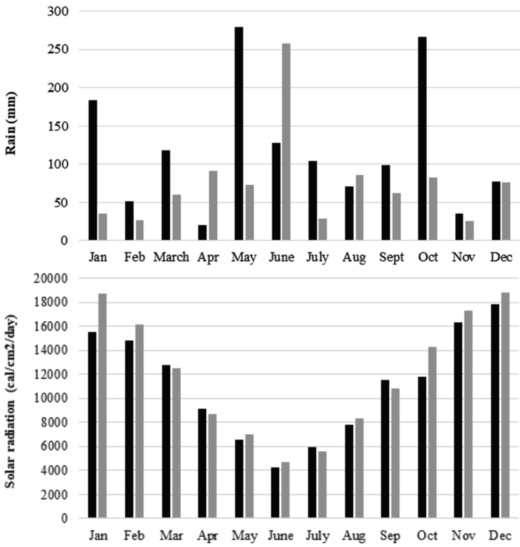

Fig. A4.4.1. Cumulative mm of rain (left) and solar radiation (right) per month in 2019 (grey) and 2020 (black). Data source: meteorological station of the INIA Las Brujas Experimental Station, located 12 km from CRS.

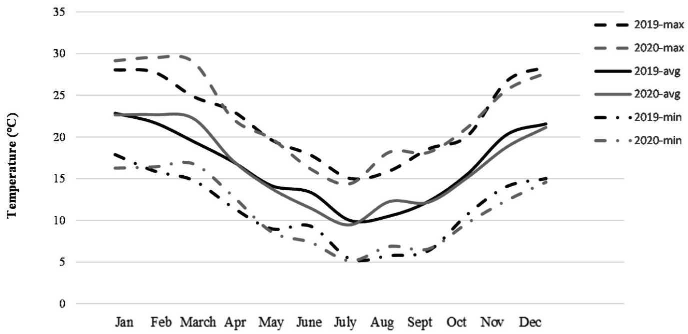

Fig. A4.4.2. Average, minimum and maximum air temperature in 2019 and 2020. Data source: meteorological station of the INIA Las Brujas Experimental Station, located 12 km from CRS.

Table A4.4.1. Number of days and dates of agrometeorological frosts in 2019 and 2020

Month	2019		2020	
	number	dates	number	dates
Jan	0		0	
Feb	0		0	
March	0		0	
April	0		0	
May	0		**3**	12, 13, 15
June	**2**	4, 6	**9**	3, 6, 11, 13, 14, 15, 26, 27, 28
July	**4**	6, 7, 8, 16	**14**	5, 6, 7, 11, 12, 14, 15, 16, 17, 25, 28, 29, 30, 31
Aug	**7**	3, 4, 5, 14, 15, 21, 23	**13**	1, 11, 12, 13, 14, 16, 17, 20, 21, 22, 23, 30, 31
Sept	**8**	1, 2, 3, 4, 5, 20, 22, 23	**8**	7, 12, 14, 15, 19, 20, 21, 22
Oct	0		**1**	30
Nov	0		0	
Dec	0		0	

Data source: meteorological station of the INIA Las Brujas Experimental Station, located 12 km from CRS.

A4.5. Specifications of the statistical model and error model distribution per variable

Table A4.5.1. Summary of response variables, statistical model structure, and error model distribution

Response variable	Model structure	Error distribution
Total yield Commercial yield Plant density	~ Tillage + Block + (1|Block:Tillage) + NEM + Tillage:NEM	Gamma
Bulb weight		Gaussian
Onion biomass Leaf-N concentration Number of leaves Bulbing ratio Soil N-NH_4 SOC Respiration PMN Dehydrogenase Urease PNA	~ Tillage + Block + (1|Block:Tillage) + NEM + Tillage:NEM + DateNumber + Tillage:DateNumber + NEM:DateNumber + Tillage:NEM:DateNumber + (1|Block:Tillage:NEM)	Gamma
LAI at BI, Leaf-N content Soil mineral-N Soil N-NO_3 Soil temperature		Gaussian
Weed biomass	~ Tillage + Block + (1|Block:Tillage) + NEM + Tillage:NEM + DateNumber + Tillage:DateNumber + NEM:DateNumber + Tillage:NEM:DateNumber + (1|Block:Tillage:NEM)+ (1|Block:Tillage:NEM:DateNumber)	Poisson
Bulk density		Gaussian
Soil cover by each type of cover	~ Tillage+ Block + (1|Block:Tillage) + NEM + Tillage:NEM + DateNumber + Tillage:DateNumber + NEM:DateNumber + Tillage:NEM:DateNumber + (1|Block:Tillage:NEM) + (1|Block:Tillage:NEM:DateNumber)	Negative binomial and Poisson

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A4.6. Experiment set up, soil and crop management on the two commercial farms

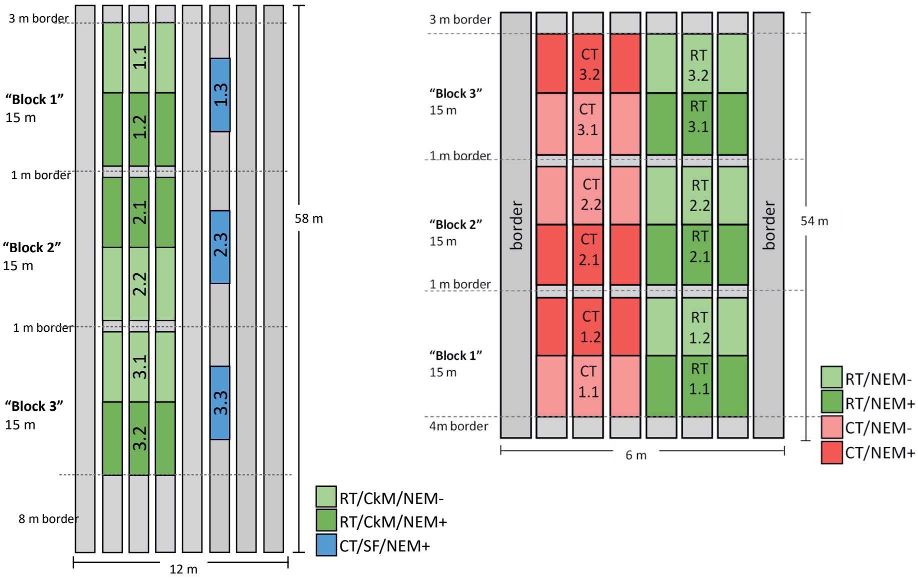

Fig. A4.6.1. Schematic representation of the field experiment in Farm 1 (left) and Farm 2 (right). RT is reduced tillage, CT is conventional tillage, NEM is native effective microorganisms (+ present, - absent), CkM is chicken manure, and SF is synthetic fertilizers.

Table A4.6.1. Soil and crops management in the two commercial farms

Farm 1
31/1- chicken manure incorporation RT (11.7 kgDM ha^{-1})
13/3 –cover crop sowing

6/8 – CT tillage: once mower, twice rotovator with bed forming
3/8 – RT tillage: once furrow opener

6/8 – onion transplanting (3 rows per bed)
9/12 – harvest

No herbicides.
Pesticide applications: 2 copper, 3 curative fungicide, 3 insecticide.
RT: no synthetic fertilizers. CT: with synthetic fertilizers
24/8 y 25/9 – CT urea (100 and 50 kg ha^{-1})
22/9 y 8/10 – CT Fertilon combi
6/8 to 1/11 – CT and RT: 8 applications Mixamin + compost tea (same doses CRS)

No irrigation.

NEM treatment: root immersion of the seedling before transplanting + 8 applications (same doses CRS)

Farm 2
31/1 – compost incorporation (20.000 L ha^{-1})
13/3 – cover crop sowing

24/7 – CT: once disc ridger
31/7, 17/8, 19/8 – CT: disc ridger and furrow forming
17/8 – RT: once mower (to cut oat "weed")
19/8 – RT: once furrow opener

19/8 – onion transplanting (1 row per furrow)
11/12 – harvest

No herbicides.
No pesticide applications.
No synthetic fertilizers.
19/8 to 1/11 – CT and RT: 8 applications Mixamin + compost tea (same doses CRS)

Irrigation only at transplanting.

NEM treatment: root immersion of the seedling before transplanting + 5 applications (same doses CRS)

A4.7. Crop growth and development in CRS

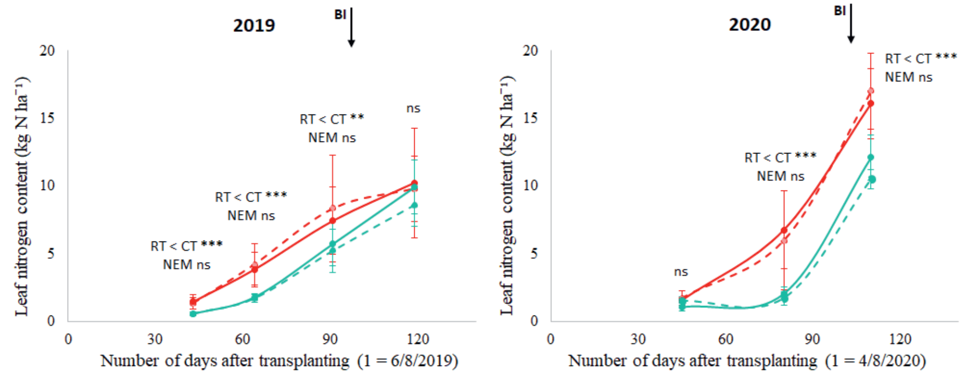

Fig A4.7.1. Leaf nitrogen content of onion during the 2019 (left) and 2020 (right) growing seasons, for conventional tillage (CT, red) and reduced tillage (RT, green) without NEM (solid) and with NEM (dashed). Black arrows indicate bulb initiation. Asterisks express statistical significance among treatments per sampling date: *p < 0.05; ** p < 0.01; *** p < 0.001, ns: no significant.

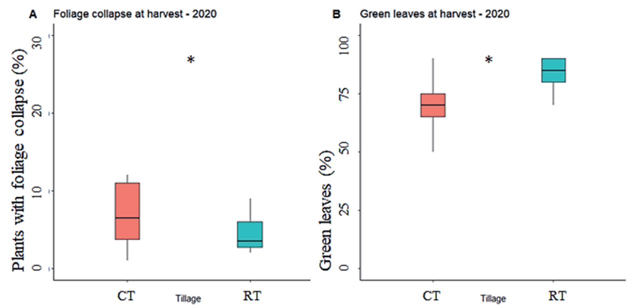

Fig. A4.7.2. Percentage of foliage collapse (left) and percentage of green leaves (right) assessed at harvest in 2020 for conventional tillage (red) and reduced tillage (green). Asterisks express statistical significance among tillage treatments: *p < 0.05. There was not significant effect of NEM application treatments.

Downy mildew incidence and severity

Downy mildew incidence and severity was assessed three times from the mid of October to the end of November, at 15 randomly selected plants per plot, scored on a 0-4 scale: 0 (no disease), 1 (≤ 10% leaf injury), 2 (> 10 % and ≤ 40 % leaf injury), 3 (> 40 % and ≤ 80 % leaf injury), and 4 (> 80 % leaf injury). Incidence was calculated as the number of plants injured per number of plants assessed and severity was calculated as the weighted average of injury level.

In both years, there were not significant differences among treatments. In 2019, the crop had earlier and higher incidence and severity of downy mildew than in 2020. In 2019, downy mildew appeared at the end of September, on 28 October incidence was of 80% and the average severity was 1, and on 11th November incidence was 100% and average severity was 2.1. In 2020, the first records of downy mildew were on 19th of October, and in November incidence was 60% and the average severity was 1.3.

A4.8. Weed species in CRS

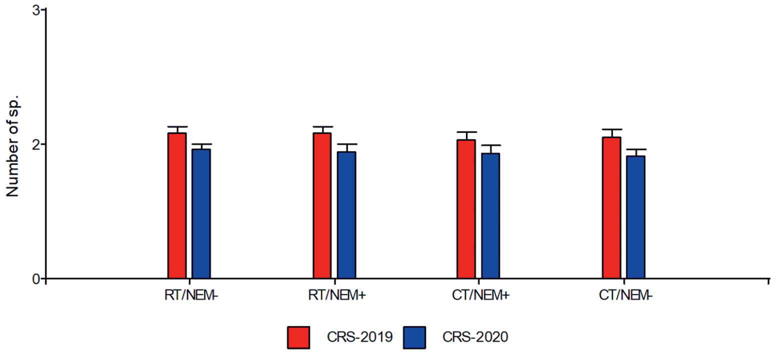

Fig. A4.8.1. Number of weed species explaining 50% or more of the soil cover by weeds by treatment in CRS in 2019 (red) and 2020 (blue)

Table A4.8.1. Relative frequency of main weed species identified per treatment and year in CRS

Plant species (Family)	2019				2020			
	CT/NEM-	CT/NEM+	RT/NEM-	RT/NEM+	CT/NEM-	CT/NEM+	RT/NEM-	RT/NEM+
Bowlesia incana (Apiaceae)	0.07	**0.10**	**0.18**	**0.35**	**0.15**	**0.11**	**0.22**	**0.10**
Cerastium glomeratum (Caryophyllaceae)	0.02	0.04	0.02	0.03	**0.10**	0.00	0.00	0.00
Coronopus dydimus (Brassicaceae)	0.00	0.02	0.00	0.03	0.00	0.04	0.00	0.00
Cyperus sp. (Cyperaceae)	0.02	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Digitaria sanguinalis (Poaceae)	0.09	0.06	0.03	0.05	**0.28**	**0.16**	**0.15**	**0.17**
Echinochloa crus-galli (Poaceae)	**0.13**	**0.18**	**0.15**	**0.17**	0.00	0.00	0.00	0.00
Portulaca oleraceae (Portulaceae)	0.00	0.00	0.02	0.00	0.00	0.00	0.02	0.00
Raphanus sativus (Brasscicaceae)	0.00	0.00	0.00	0.00	0.05	0.00	0.00	0.00
Rumex crispus (Polygonacea)	0.00	0.00	0.00	0.00	0.08	0.04	0.05	0.03
Setaria italica (Poaceae)	0.00	0.00	0.00	0.00	0.00	0.04	0.00	0.00
Sonchus oleraceus (Asteraceae)	0.00	0.00	0.07	0.07	0.00	0.04	0.00	0.02
Stachys arvensis (Lamiacea)	**0.64**	**0.58**	**0.43**	**0.22**	**0.26**	**0.36**	**0.30**	**0.33**
Stellaria media (Caryophyllaceae)	0.04	0.02	0.08	0.08	0.08	**0.20**	**0.27**	**0.35**
Trifolium repens (Fabaceae)	0.00	0.00	0.02	0.00	0.00	0.00	0.00	0.00
	1.01	1.00	1.00	1.00	1.00	0.99	1.01	1.00

A4.9. Soil chemical, biological and physical properties in CRS

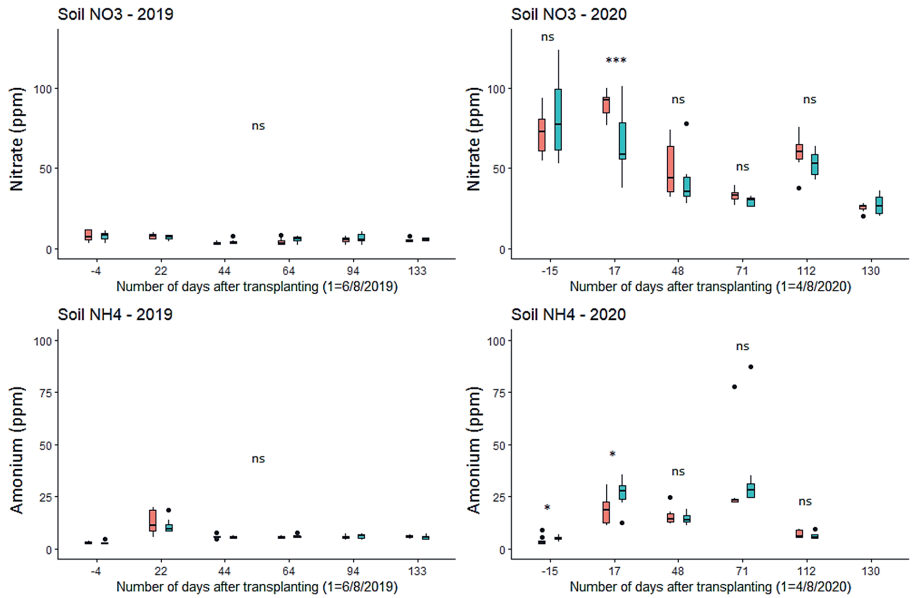

Fig. A4.9.1. Soil mineral N-NO3 (top) and N-NH4 during onion cycle (bottom) in 2019 (left) and 2020 (right) for conventional tillage (CT, red) and reduced tillage (RT, green). Asterisks express statistical significance among tillage treatments per sampling date: *p < 0.05; ** p < 0.01; *** p < 0.001, ns: no significant. There were not significant effect of NEM application treatments.

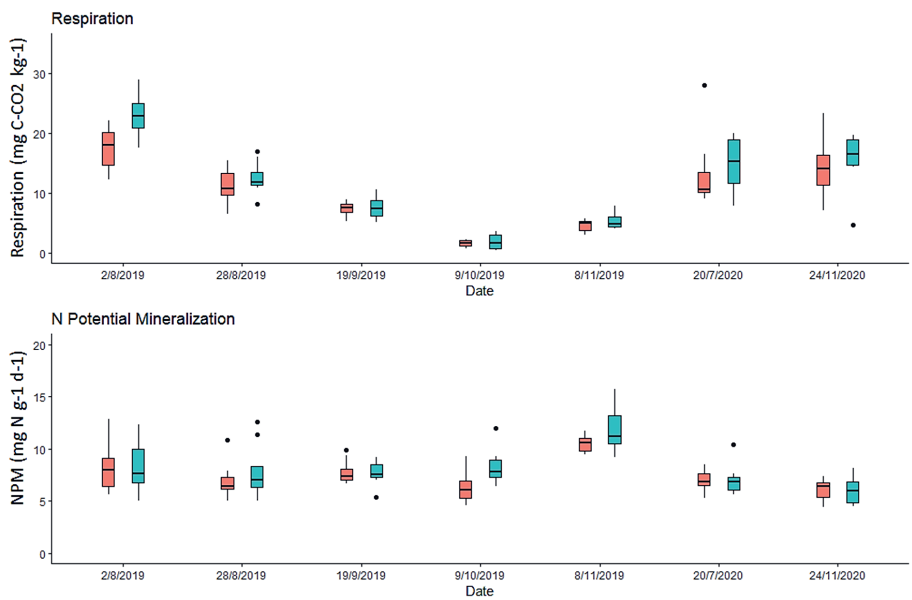

Fig. A4.9.2. Soil respiration (top) and potentially mineralisable nitrogen (down) during onion cycle in the two-year experiment for conventional tillage (CT, red) and reduced tillage (RT, green). Asterisks express statistical significance among tillage treatments: *p < 0.05; ** p < 0.01; *** p < 0.001, ˙ p < 0.1, ns: no significant. There were not significant effect of NEM application treatments.

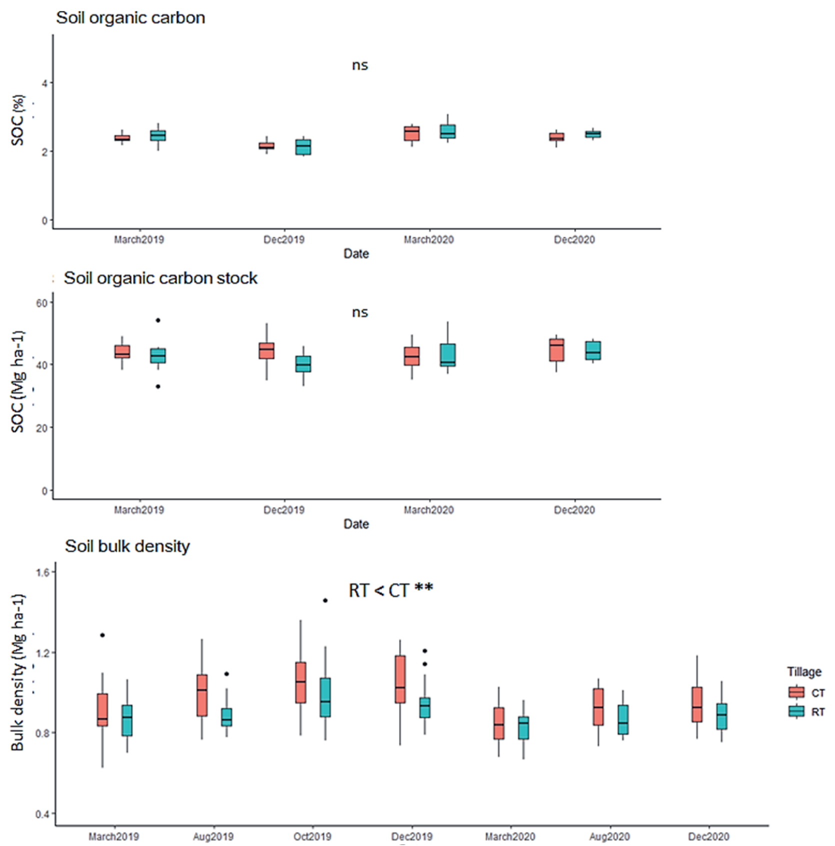

Fig. A4.9.4. Percentage of soil organic carbon, soil organic carbon stock and bulk density during the two-year experiment for conventional tillage (CT, red) and reduced tillage (RT, green). Asterisks express statistical significance among tillage treatments: *p < 0.05; ** p < 0.01; *** p < 0.001, ns: no significant.

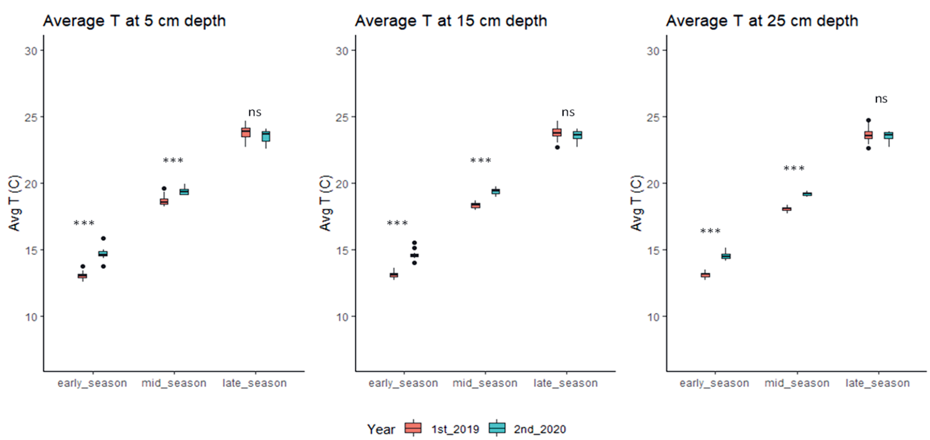

Fig A4.9.5. Average soil temperature at 5, 15 and 25 cm depth in early (1 to 15 Sept), mid (15 to 31 Oct) and late (1 to 15 Dec) onion growing seasons, for 2019 (red) and 2020 (green). Asterisks express statistical significance among years: *p < 0.05; ** p < 0.01; *** p < 0.001, ns: no significant.

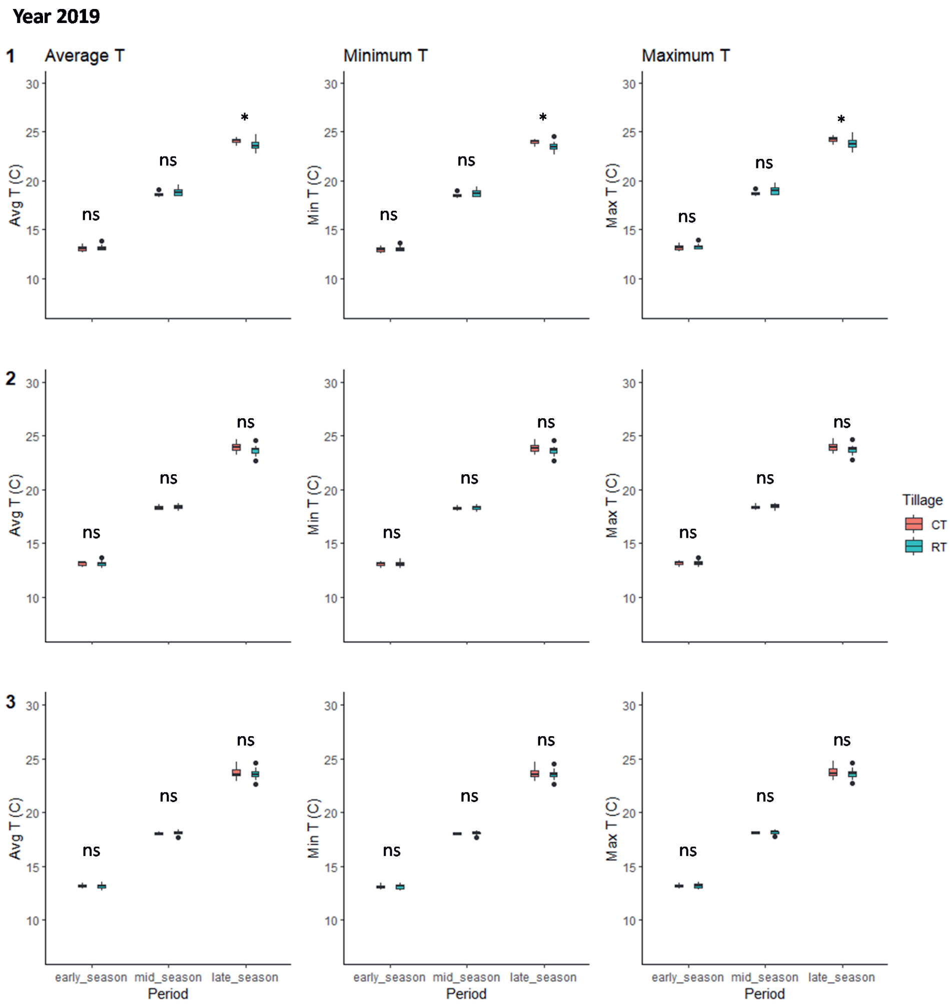

Fig A4.9.6. Average, minimum and maximum soil temperature at 5 (top), 15 (middle) and 25 cm depth (bottom) in early (1 to 15 Sept), mid (15 to 31 Oct) and late (1 to 15 Dec) onion 2019 growing seasons, for conventional tillage (CT, red) and reduced tillage (RT, green). Asterisks express statistical significance among tillage treatments per sampling date: *p < 0.05; ** p < 0.01; *** p < 0.001, ns: no significant. There was not significant effect of NEM application treatments.

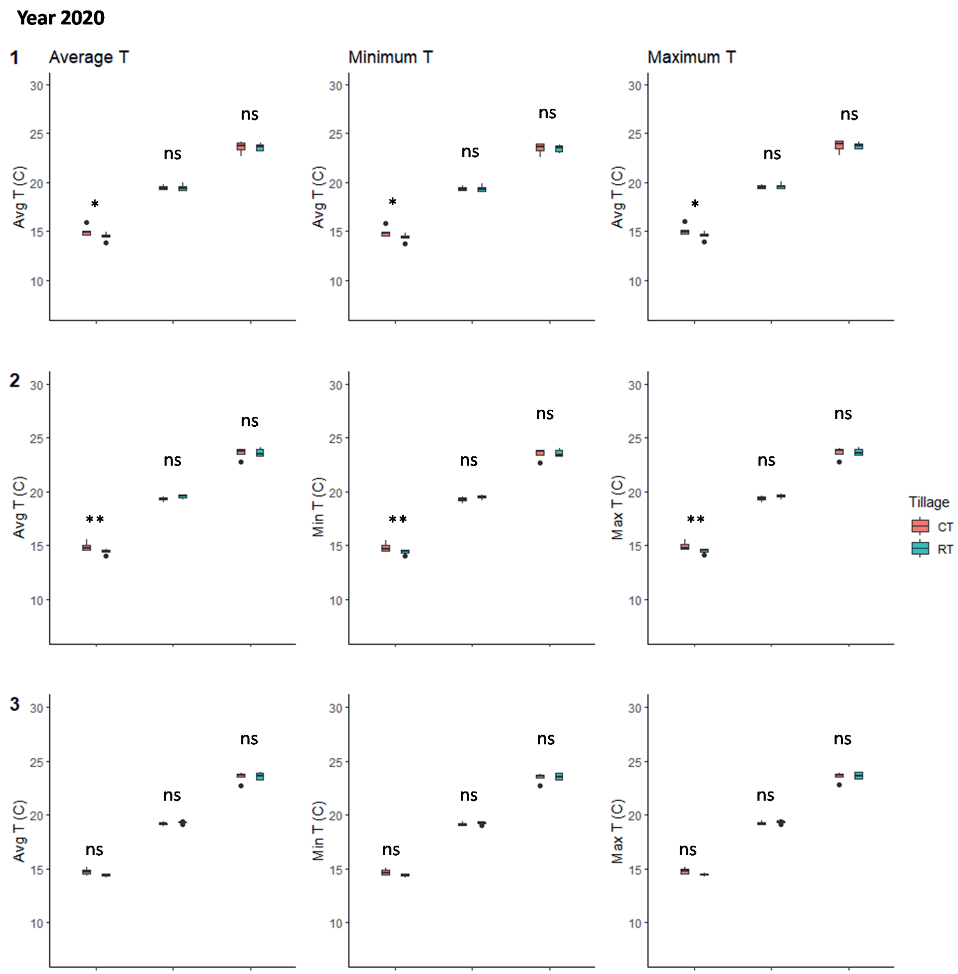

Fig A4.9.7. Average, minimum and maximum soil temperature at 5 (top), 15 (middle) and 25 cm depth (bottom) in early (1 to 15 Sept), mid (15 to 31 Oct) and late (1 to 15 Dec) onion 2020 growing seasons, for conventional tillage (CT, red) and reduced tillage (RT, green). Asterisks express statistical significance among tillage treatments per sampling date: *p < 0.05; ** p < 0.01; *** p < 0.001, ns: no significant. There was not significant effect of NEM application treatments.

A4.10. Results at the two commercial farms

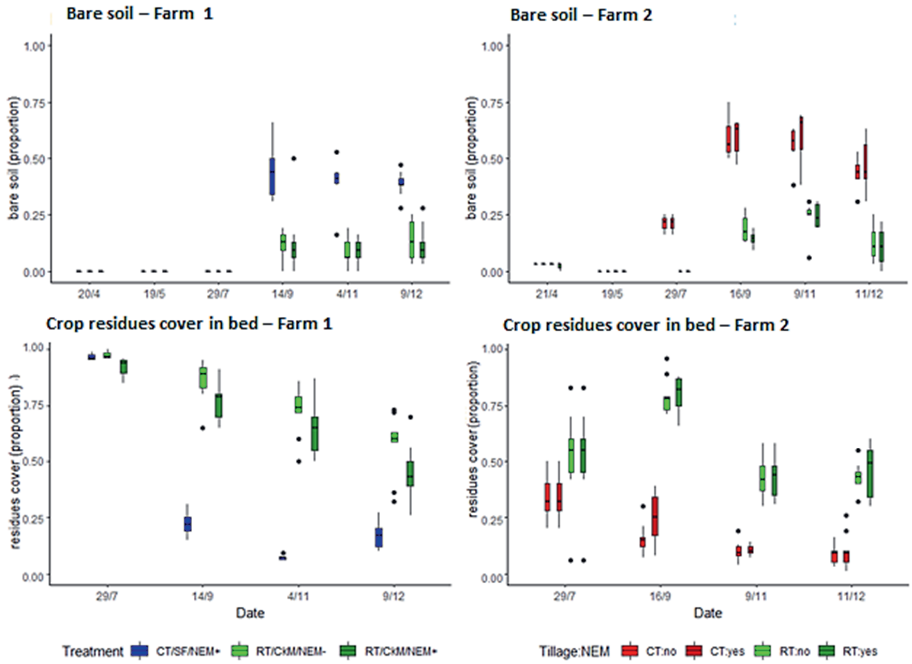

Fig A4.10.1. Proportion of bare soil (top) and crop residues cover in the raised beds (bottom) in Farm 1 (left) and Farm 2 (right) for each treatment of tillage and NEM application (colours specified for each Farm).

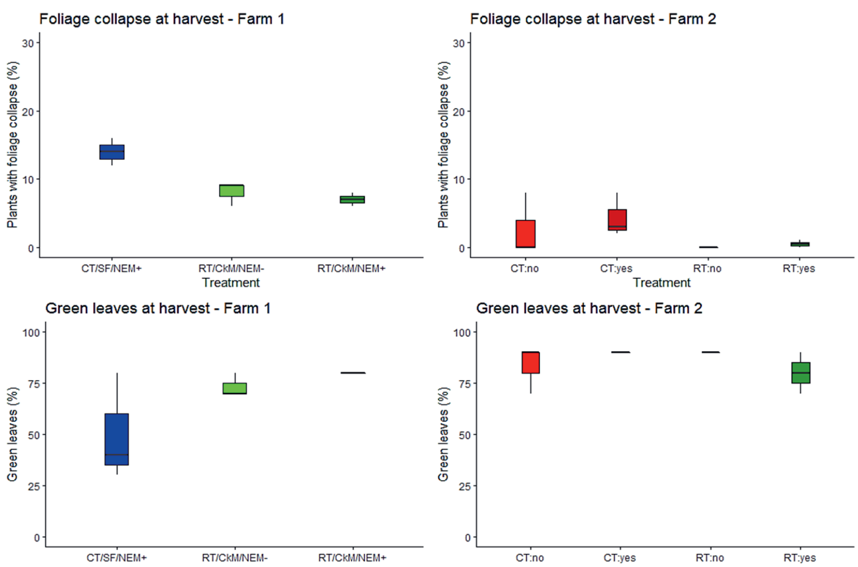

Fig. A4.10.2. Percentage of foliage collapse (top) and percentage of green leaves (bottom) assessed at harvest in Farm 1 (left) and Farm 2 (right) for each treatment of tillage (conventional tillage: CT or reduced tillage: RT) and NEM application (NEM+ or NEM-).

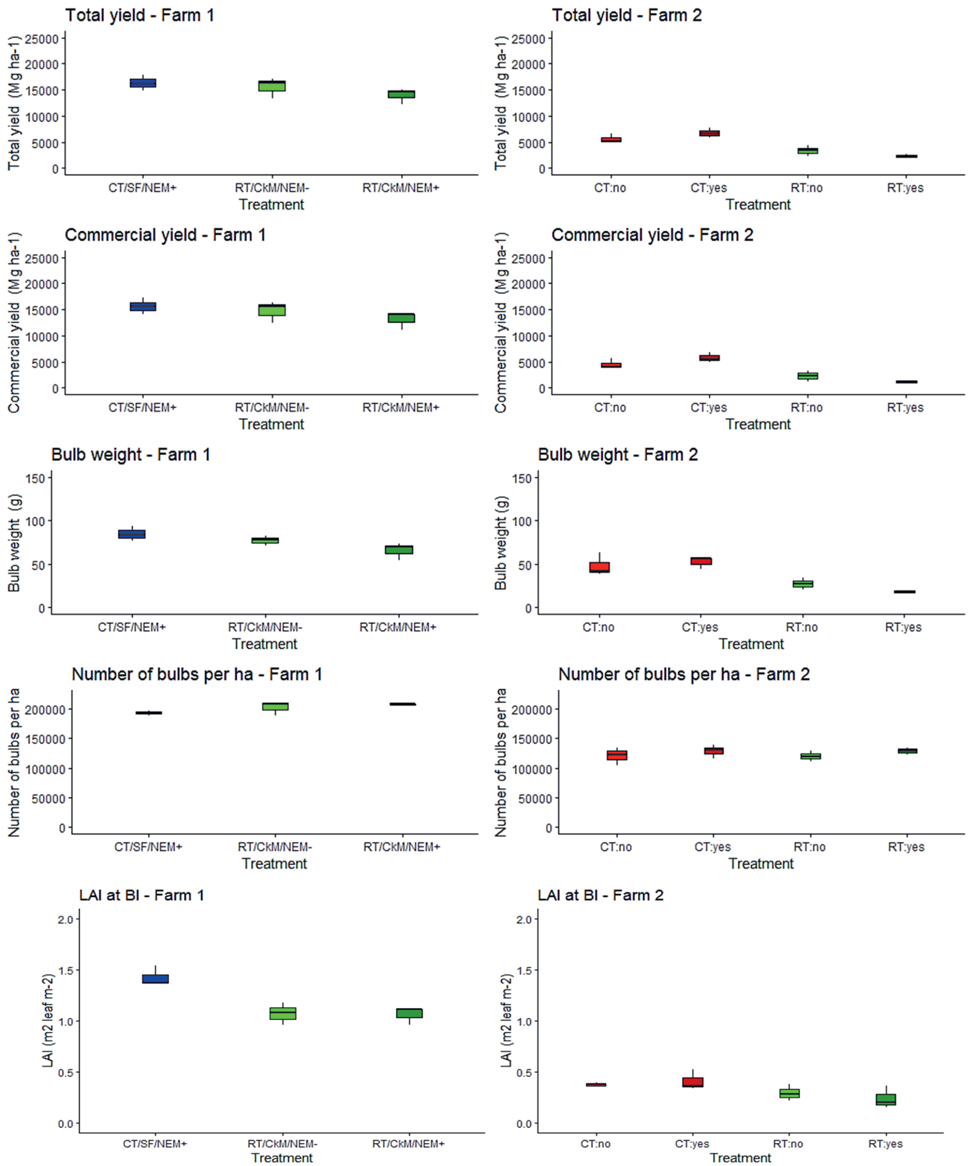

Fig. A4.10.3. Total yield, commercial yield, bulb weight and number of bulbs per ha at harvest, and leaf area index (LAI) at bulbing initiation in Farm 1 (left) and Farm 2 (right) for each treatment of tillage (conventional tillage: CT or reduced tillage: RT) and NEM application (NEM+ or NEM-).

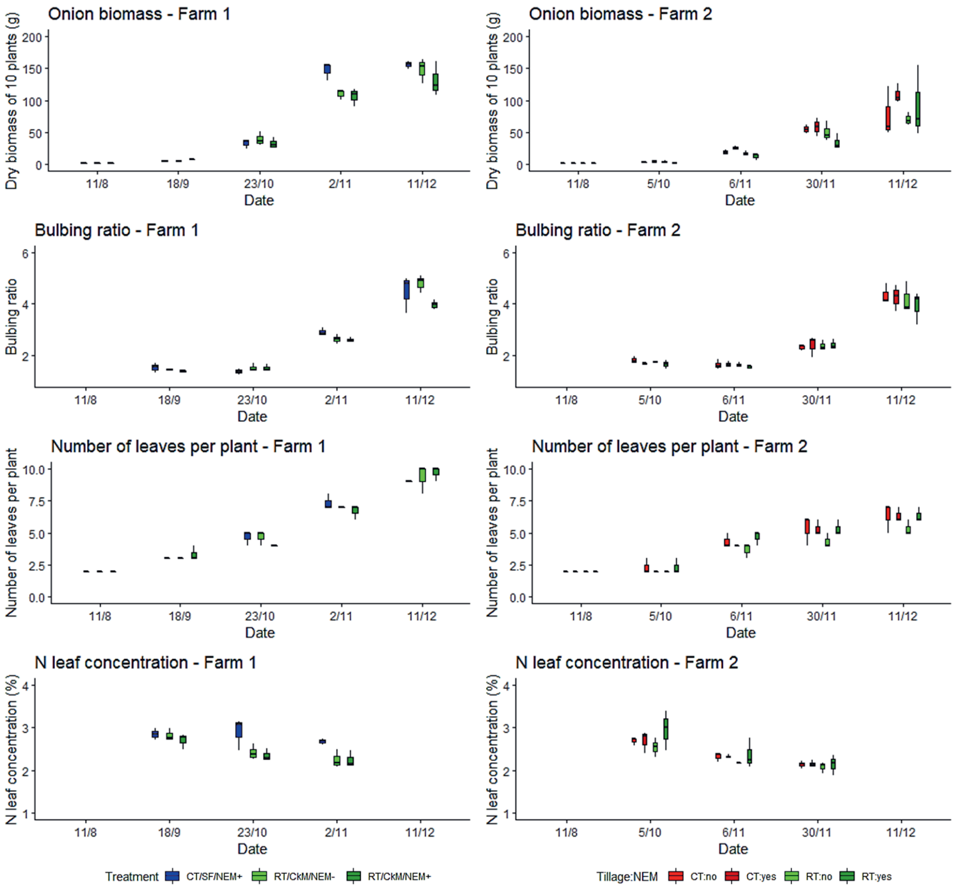

Fig. A4.10.4. Onion aboveground biomass, bulbing ratio, number of leaves per plant and N-leaf concentration in Farm 1 (left) and Farm 2 (right) for each treatment of tillage (conventional tillage: CT or reduced tillage: RT) and NEM application (NEM+ or NEM-).

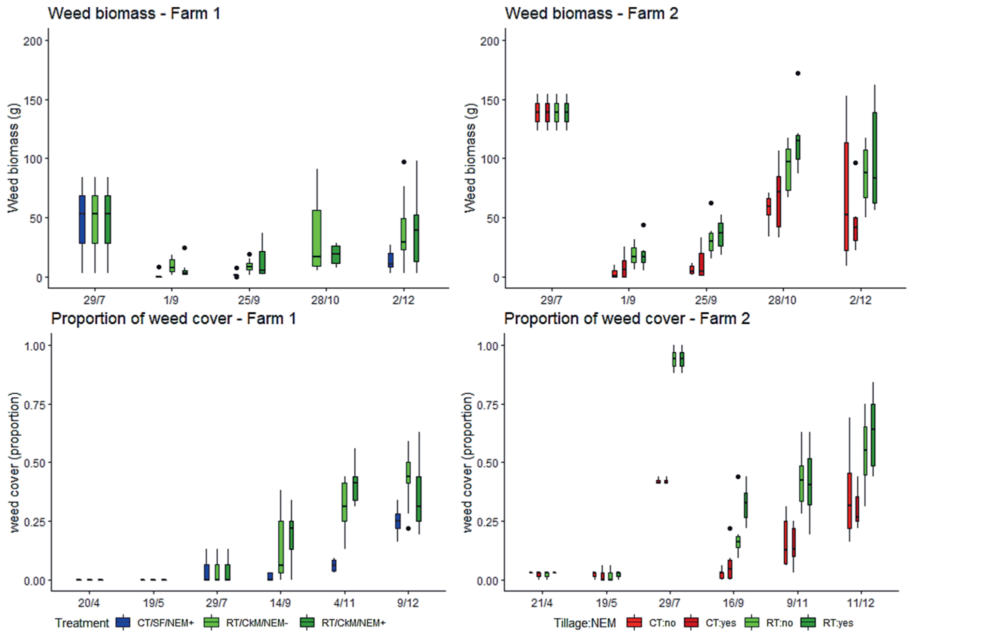

Fig. A4.10.5. Weed biomass and proportion of weed cover in Farm 1 (left) and Farm 2 (right) for each treatment of tillage (conventional tillage CT or reduced tillage RT) and NEM application (NEM+/NEM-).

Table A4.10.1. Relative frequency of main weed species per treatment at the two commercial farms

Species (Family)	**FARM 1** [1,2]			**FARM 2** [1]			
	CT/SF/NEM+	RT/CkM/NEM+	RT/CkM/NEM-	CT/NEM-	CT/NEM+	RT/NEM-	RT/NEM+
Avena sativa (Poaceae)	0.00	0.08	0.03	**0.33**	**0.33**	**0.83**	**0.75**
Anagallis arvensis (Primulaceae)	0.08	0.00	0.00				
Bowlesia incana (Apiaceae)	**0.17**	0.06	0.08				
Bromus sp. (Poaceae)				0.05	0.10	0.13	0.08
Convolvulus arvensis (Convolvulaceae)	**0.42**	**0.28**	**0.17**	**0.10**	0.00	0.00	0.00
Conyza bonariensis (Asteraceae)	0.00	0.00	0.03				
Cynodon dactylon (Poaceae)	0.00	0.00	0.08	0.00	0.05	0.00	0.00
Lolium multiflorum (Poacea)	0.00	0.03	0.00	**0.14**	**0.43**	0.04	**0.17**
Matricaria chamomilla (Asteraceae)	0.00	0.06	**0.19**				
Paspalum sp. (Poaceae)	0.08	0.00	0.03				
Picris echioides (Asteraceae)				**0.19**	0.00	0.00	0.00
Poa annua (Poaceae)	0.00	0.03	0.00				
Polygonum aviculare (Polygonaceae)	0.08	**0.19**	**0.22**				
Raphanus sativus (Brasscicaceae)				0.05	0.00	0.00	0.00
Setaria italica (Poaceae)				0.00	0.05	0.00	0.00
Stellaria media (Caryophyllaceae)	0.00	0.00	0.03	**0.14**	0.05	0.00	0.00
Trifolium or Melilotus (Fabaceae)	**0.17**	**0.28**	**0.14**				
	1.00	1.01	1.00	1.00	1.01	1.00	1.00

[1] Tillage: conventional (CT), reduced tillage (RT). NEM application: with (NEM+) and without (NEM-).[2] SF: synthetic fertilizer, CkM: chicken manure

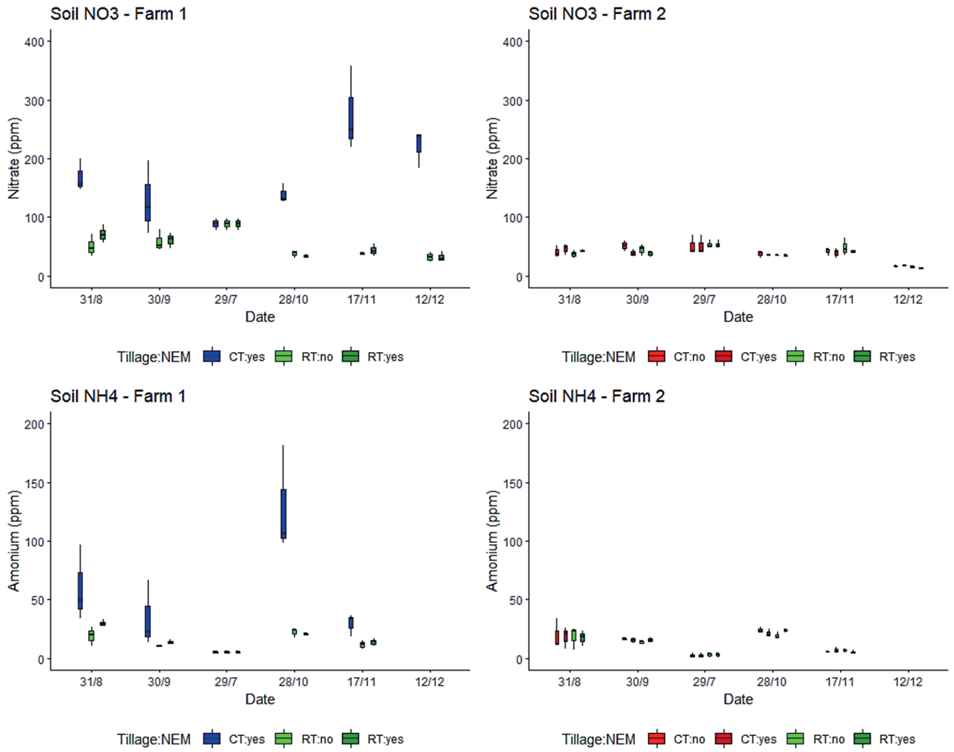

Fig A4.10.6. Soil mineral N-NO3 (top) and N-NH4 during onion cycle (bottom) in Farm 1 (left) and Farm 2 (right) for each treatment of tillage (conventional tillage: CT or reduced tillage: RT) and NEM application (NEM+ or NEM-).

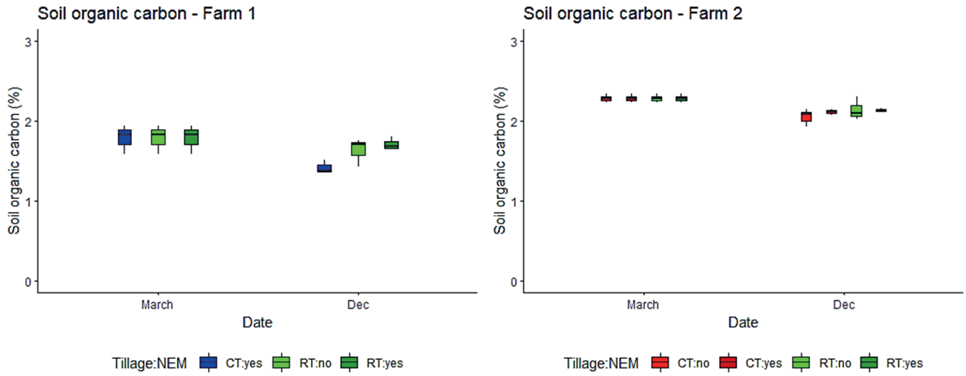

Fig. A4.10.7. Percentage of soil organic carbon at cover crop sowing (March) and before onion harvest (December) in Farm 1 (left) and Farm 2 (right) for each treatment of tillage (conventional tillage: CT or reduced tillage: RT) and NEM application (NEM+ or NEM-).

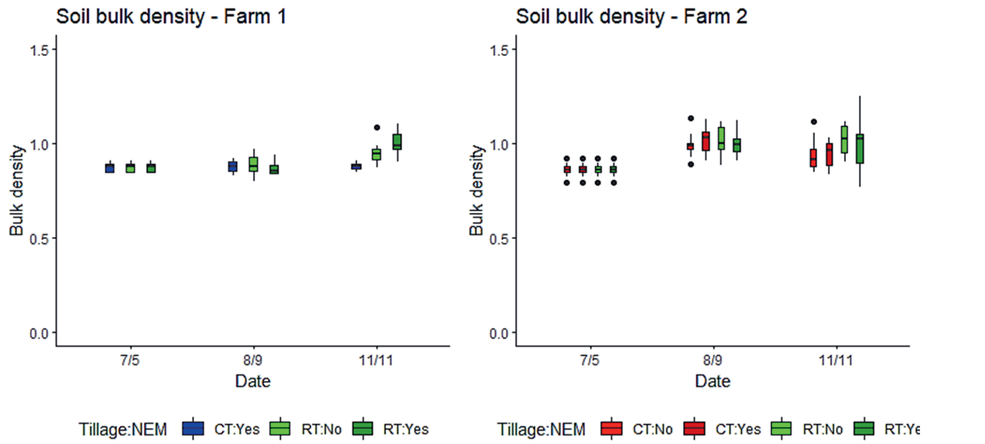

Fig. A4.10.8. Soil bulk density at mid-season of the cover crop (May), one month after onion-transplanting (Sept) and before harvest (November) in Farm 1 (left) and Farm 2 (right) for each treatment of tillage (conventional tillage: CT or reduced tillage: RT) and NEM application (NEM+ or NEM-).

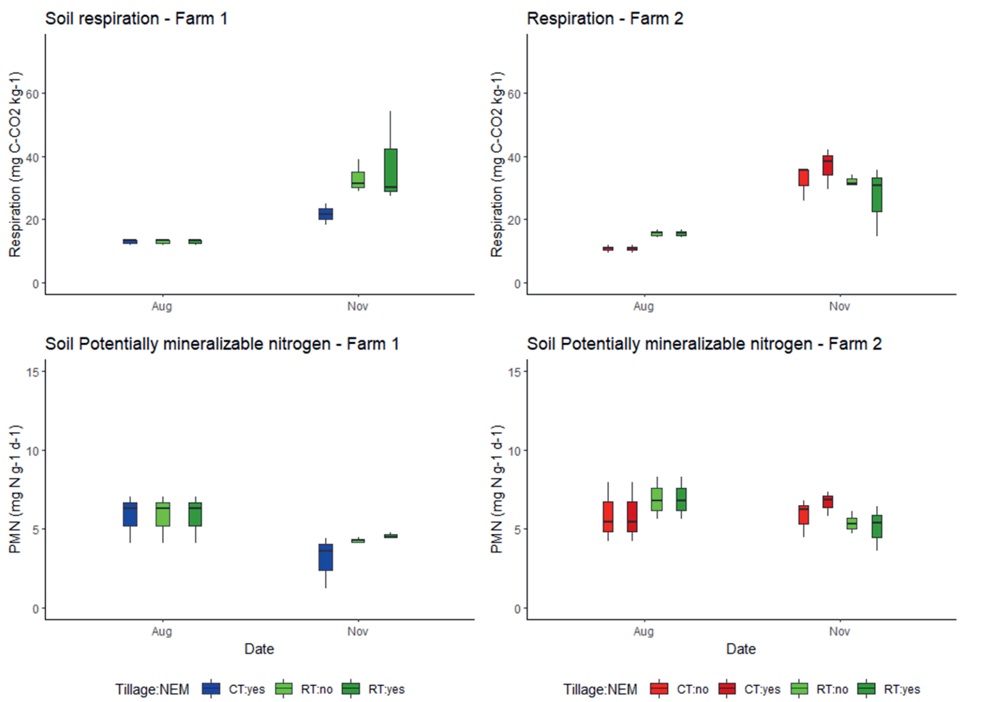

Fig. A4.10.9. Soil respiration (top) and potentially mineralisable nitrogen (down) before onion transplanting (Aug) and before onion harvest (Nov) in Farm 1 (left) and Farm 2 (right) for each treatment of tillage (conventional tillage: CT or reduced tillage: RT) and NEM application (NEM+ or NEM-).

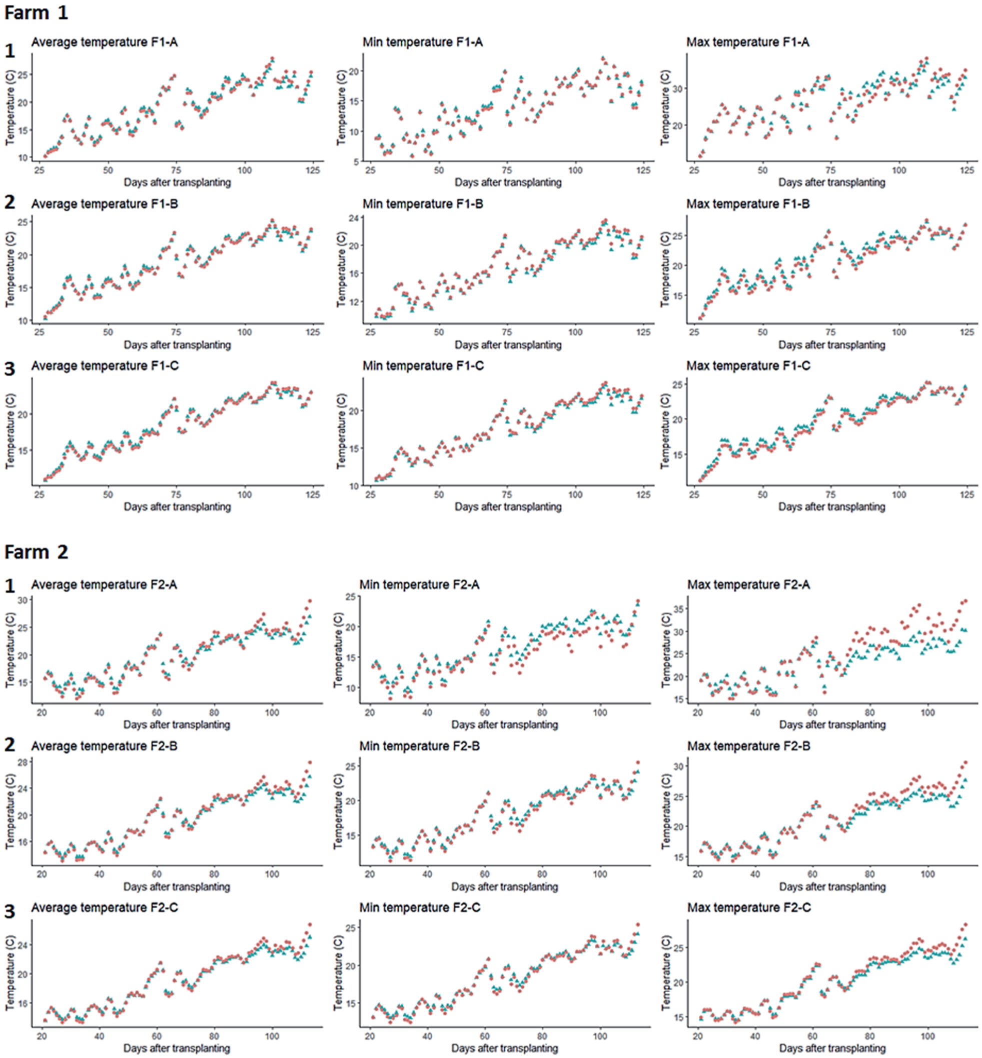

Fig. A4.10.10. Average, minimum and maximum soil temperature during onion growing seasons in Farm 1 (top) and Farm 2 (bottom) at 5 (1), 15 (2) and 25 cm depth (3), for conventional tillage (CT, red) and reduced tillage (RT, green).

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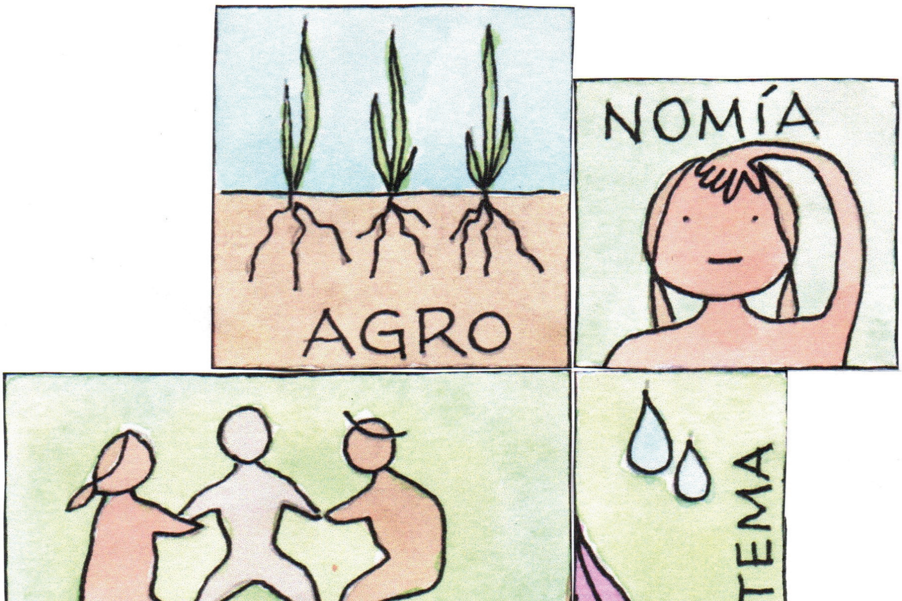
AGRO
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Chapter 5

Operationalizing an agroecological perspective for the diagnosis of vegetable farm systems to support co-innovation: the MEDITAE framework

This chapter is in preparation to be submitted as:

Scarlato, M.; Rieppi, M.; Ferreira, I.; Irurueta, S.; Fernández, D.; Bianchi, F.J.J.A.; Rossing, W.A.H.; Dogliotti, S. Operationalizing an agroecological perspective for the diagnosis of vegetable farm systems to support co-innovation: The MEDITAE framework.

Abstract

The transition of farm systems towards agroecology requires learning about the ecological processes underlying system functioning. The co-innovation approach has been proven effective in supporting learning towards sustainability transitions. However, the farm diagnosis framework used as part of the approach thus far does not emphasise the analysis of the ecological processes that underpin the system's functioning and need to be enhanced. Thus, it may fall short of reflecting an agroecological perspective. In this chapter, we present a novel diagnostic framework (MEDITAE) developed together with practitioners to support the characterisation, diagnosis and redesign of farm systems. We illustrate its effects by an application to five case study farms involved in a co-innovation project in the south of Uruguay. The framework makes explicit connections among agroecological processes, management and farm performance. In the framework, six key socio-ecological processes are distinguished that underlie system functioning: cycling of nutrients, carbon and water; plant succession and biotic regulation; energy flow; and the socio-economic and cultural processes. We describe the main components of each process and their interconnections. Using a characterization of desirable qualities and functioning, we propose performance indicators associated with each process and practice-based indicators to assess the management practices that affect performance. The diagnosis framework contributed to raising awareness, promoting learning, and creating consensus among all actors involved in the co-innovation approach. Although its focus is on the farm-level, we discuss how the framework could also contribute to informing public policies promoting agroecological transitions, improving the training of agronomy students, and framing inter- and transdisciplinary research.

Keywords: vegetable production, sustainability, assessment, co-creation, re-design, transition.

5.1. Introduction

Concerns about the negative impacts of agricultural intensification have triggered interest in agroecology (Altieri, 2002) as a more sustainable way of farming (FAO, 2015). Agricultural intensification is characterized as a process of simplifying production systems, reducing their biodiversity by introducing large areas of homogeneous crop varieties, increasing chemical fertilization, irrigation, mechanical interventions, and applying pesticides (Matson et al., 1997; Baraibar Norberg, 2020). This process has boosted crop production over the past 60 years but, at the same time, has generated huge negative social and environmental consequences (Mahmood et al., 2016; Rasmussen et al., 2018; Tittonell et al., 2016; UNCTAD, 2017). In Uruguay, the intensification of vegetable production systems has contributed to soil erosion and the decline of soil fertility (Alliaume et al., 2013; Dogliotti et al., 2014), water pollution (Barreto et al., 2017; Rodríguez-Bolaña et al., 2023), biodiversity loss (MVOTMA, 2016), and human health hazards (Burger & Pose Román, 2012; Burger, 2013). Furthermore, despite the high external input use, crop yield gaps average 50% and most farms have low labour productivity and family incomes (Berrueta et al., 2019; Colnago & Dogliotti, 2020; Colnago et al., 2023; Dogliotti et al., 2014; Dogliotti et al., 2021; Scarlato et al., 2017). In response to these problems, interest by farmers, consumers and society in general in agroecology has increased over the past decade (Bizzozero, 2020; Blum et al., 2006; Chiappe et al., 2003; CNFR, 2016, 2017; FAO, 2015; Poder Legislativo ROU, 2018).

In contrast to agricultural intensification, agroecology aims to maintain or increase production by enhancing ecological processes and concomitantly reducing external input use and minimizing negative impacts on the environment and society (Nicholls et al., 2016; Tittonell, 2014; Wezel et al., 2020). Thus, agroecological transitions require understanding the main ecological processes and their interconnections that underly agroecosystem functioning by all actors involved in farm system management (Prost et al., 2023). Learning about these processes is challenging, as it implies integrating knowledge about complex relations among soil and farming system components, the resulting ecosystem services, and their interaction with practices. Learning-support tools combined with an adaptive management approach can facilitate the learning process in this context with high uncertainty and multiple possible controls via management practices (Duru et al., 2015; Jouan et al., 2021). The analysis and diagnosis of farm systems provide a fruitful entry point for learning about current interrelations between system components and practices by scientists and practitioners. During such assessments, agreement on locally relevant indicators provides a basis for discussing system performance, mobilizing scientific and local knowledge on underlying ecological processes and how they are affected by practices (Altieri, 1999; Gliessman, 2002;

Nicholls et al., 2020). Such analysis and diagnosis results would provide the basis for the joint design of a strategy to transition towards agroecology-based systems.

Various approaches have been developed to support redesigning current farm systems towards more sustainable ones (e.g. Lacombe et al., 2018; Meynard et al., 2012), among which co-innovation has proven effective. By conceptually building on complex adaptive systems thinking, social learning, and monitoring and evaluation, co-innovation has generated actionable knowledge to support sustainability transitions (Rossing et al., 2021). While in Europe, the co-innovation approach evolved to a complexity-aware project governance method (Douthwaite & Hoffecker, 2017; Ingram et al., 2020), in Uruguay, co-innovation maintained its basis in work at the farm level through a step-by-step methodological approach, including characterization, diagnosis, redesign, implementation-monitoring and evaluation (Dogliotti et al., 2014). Generating learning processes during co-innovation is essential to promote change (van Mierlo et al., 2020). The joint process of describing, or, characterizing and diagnosing the farm system has been shown to generate trust between farmers and researchers, build a collective cognition of what the system should look like, build consensus about how to move from the current situation to the desired one and engage in change (Darnhofer, 2015; Hoffecker, 2021; Krzywoszynska, 2019). As such, the diagnosis phase of the co-innovation approach can be regarded as both a change mechanism in addition to a result *per se* (de Olde et al., 2018).

The framework guiding characterization and diagnosis strongly influences how the production systems are seen (de Olde et al., 2017; Eichler Inwood et al., 2018). The MESMIS framework (Masera et al., 1999) has been used for farm diagnosis in previous co-innovation approaches (Colnago et al., 2023; Dogliotti et al., 2014; Ruggia et al., 2021). The MESMIS framework distinguishes productivity, stability, resilience, adaptability, reliability, and self-reliance as the core attributes of a sustainable system. From these diagnosis criteria, indicators and critical points for the system sustainability are derived. However, this framework does not support how the system attributes, and thus the diagnosis criteria, indicators and critical points are connected with the underlying agroecological processes. Crucial agroecological aspects of system functioning are not explicitly considered, such as biodiversity or soil functioning. Other diagnosis frameworks are strongly focused on practice-based indicators (Altieri & Nicholls, 2002; Moreno, 2013; Mottet et al., 2020; Nicholls et al., 2020; Sellepiane & Sarandón, 2008; Trabelsi et al., 2016; Van Cauwenbergh et al., 2007). Informed by dedicated surveys and field observations, these frameworks focus on classifying used practices rather than generating discussion about why these practices are used or how farm performance can be further improved (Prost et al., 2023). While these approaches are quick and time efficient, they do not show the interconnectedness of practices, system elements, and ecological processes that we posit as important for sustainability transitions. Thus, they may fall short in reflecting a systemic approach, which would also be meaningful for fostering learning. There is a need for a new framework that supports learning towards agroecology-based systems in the context of co-innovation processes.

This chapter presents the Assessment and Diagnostic Framework to Inform Agroecological Transitions (MEDITAE, for its acronym in Spanish: **M**arco de **E**valuación y **D**iagnóstico para **I**mpulsar **T**ransiciones **A**gro**E**cológicas) developed to support the transition of vegetable farm systems to agroecology. We combine scientific insights and empirical experiences to revisit the steps leading up to farm diagnosis as a basis for the agroecological redesign of farm systems. This framework is intended to be used within co-innovation processes with conventional and organic farmers and technical advisors as main actors. It can also be used in the practical education of agronomy students, integrating disciplinary knowledge to diagnose and redesign real farms. The framework is demonstrated by applying it to five case study vegetable farms in south Uruguay that were engaged in a co-innovation project.

5.2. Diagnosis framework

5.2.1. Framework rationale

The MEDITAE framework's core consists of six key socio-ecological processes that underlie the farm system's functioning, with their main components and connections characterising their desirable qualities and functioning from an agroecological perspective. Associated with each process are indicators that address process performance and indicators that address management practices that affect process performance (Fig. 5.1). The framework thus highlights the ecological processes that (may) drive change to enable learning on the “why” and “how” ecological processes, farm performance, and farm management are interrelated. This approach sets the framework apart from others that either focus on the implementation of practices that are considered agroecological (e.g. Nicholls et al., 2020) or on high-level system attributes that are not explicitly connected to local system functioning (e.g. Masera et al., 1999; Dogliotti et al., 2014) (Fig. 5.1). The MEDITAE framework is conceived as a tool to support the transition towards agroecology-based farm systems, positioning diagnosis as a phase in which there is a need for individual and collective reflection and learning to promote change.

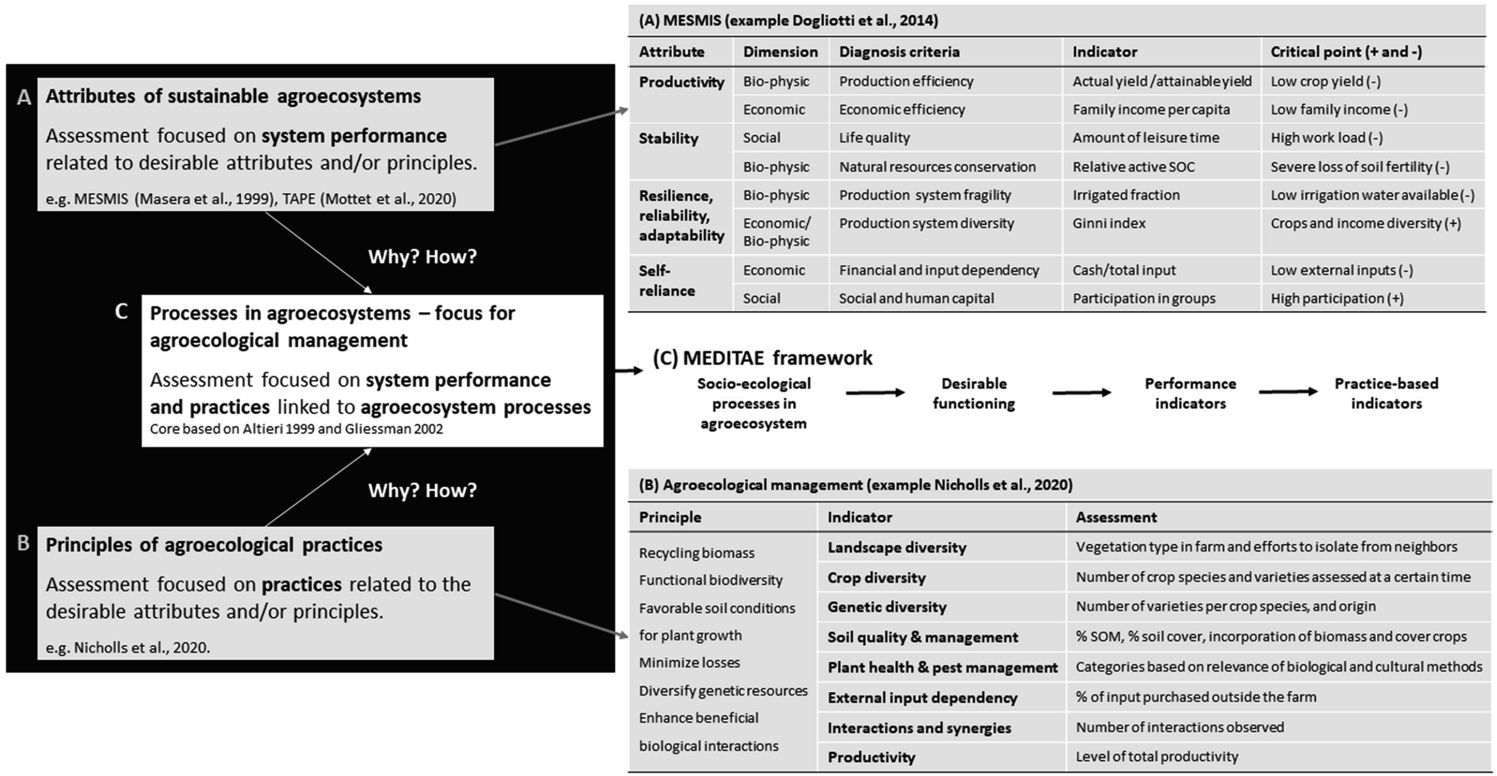

Fig. 5.1. Conceptual diagram representing core ideas and an example of operationalization of existing diagnosis frameworks which (A) focus on high-level system attributes (e.g. Masera et al., 1999; Dogliotti et al., 2014), or (B) focus on the application of practices generally considered agroecological (e.g. Nicholls et al., 2020). The proposed framework (MEDITAE, C) makes explicit the ecological processes underlying agroecological systems that (may) drive change to enable learning by reflecting on the effects of management practices.

5.2.2. The MEDITAE framework

We defined five key ecological processes of an agroecosystem: cycling of (i) nutrients, (ii) carbon, and (iii) water; (iv) plant succession and biotic regulation; and (v) energy flow based on Altieri (1999) and Gliessman (2002). These processes occur simultaneously and interact with the (vi) socioeconomic and cultural process representing the farmers' history, context, needs and objectives (Altieri, 1999). Here, we describe the processes focusing on their main components and connections and identify the contribution per process to farm system functioning as the core of our diagnosis framework (Table 5.1).

Table 5.1. The MEDITAE framework's core for the agroecological diagnosis of farm systems consists of six key socio-ecological processes occurring in the agroecosystem, their description, and their desirable functioning from an agroecological perspective.

Process[1]	Description[1]	Desirable functioning in agroecological systems[2]
Nutrient cycling	Circulation of nutrients in the agroecosystem involves soil, plants, microorganisms & animals, and the atmosphere and is mediated by biological and chemical activity.	- Maximise nutrient recycling in the system - Minimise nutrient losses to increase efficiency and reduce pollution risk - Attain high levels of biological fixation of nitrogen - Maintain high and balanced levels of stable forms of nutrients in the system and labile forms in an adequate balance with production requirements.
Carbon cycling	Circulation of C in the agroecosystem involves soil, plants, microorganisms & animals, and the atmosphere and is mediated by biological and chemical activity.	- Maximise C sequestration in system biomass and soil - Minimise soil organic carbon losses - Maintain high soil organic carbon levels in diverse C-forms.
Plant succession and biotic regulation	Organisms gradually modify the environmental conditions such that other species can appear or replace the original species. Biotic regulation modulates carbon and nutrient cycles and pest, weed and pathogen populations.	- Increase the abundance and diversity of biotic communities in the system - Promote antagonists that can suppress pathogens, pests, and weeds.
Water cycle	Water moves through the atmosphere, soil, plants, animals, and water bodies.	- Maximise the ability to capture and retain rainwater - Maximise water cycling - Minimise waterlogging and erosive surface runoff - Minimise water losses - Attain and maintain high water quality
Energy flow	Energy flow in an ecosystem involves capturing solar energy by plants and storing it in biomass structures. In an agroecosystem, energy also comes from fossil-fuel-based inputs and leaves with exported products.	- Maximise the ability to capture and use renewable energy and reduce the use of non-renewable sources - Maximise energy flows in the system - Minimise energy losses
Socio-economic and cultural	Ecological processes and socio-economic conditions are interdependent. For example, the development and/or adoption of farming systems and technologies result from interactions between farmers (their history, experiences, knowledge, needs and objectives), with others, and with the biophysical environment.	- Generate good life conditions for farmers and workers - Maximise high-quality food production - Achieve a low dependence level on external input, technologies and knowledge - Promote collaborative work and networks - Generate and promote fair relationships between farmers, workers, and consumers

[1] Based on Altieri (1999) and (Gliessman (2002). [2] Based on Altieri (1999), Gliessman (2002), and Wezel et al. (2020)

5

Performance indicators reflect or are *proxies* of the functioning of each process. They are related to the state of main components (e.g. soil organic carbon, soil nutrient stock, or soil water retention capacity) or connections among the main components (e.g. nutrient and carbon balances, crop nutrient deficiencies, pest or disease incidences, pest/natural enemy ratio). Practice-based indicators reflect farmer management as a means to explain the result of the performance indicators (e.g. amount of nutrient input, use of crop rotation, annual area of green manure, crop diversity, soil tillage frequency, seed source). Appendix A5.1 presents detailed information on performance (Table A5.1.1) and practice-based (Table A5.1.2) indicators for the six socio-ecological processes. As an example, the following paragraph describes and explains the performance and practice-based indicators linked to the nutrient cycling process in vegetable production.

In vegetable production systems, nutrients mainly cycle between soil and cultivated and non-cultivated vegetation biomass. Nutrients enter the system through organic and synthetic inputs, biological nitrogen fixation from the air, and in some cases, with water. Nutrients leave the system through the harvested biomass, leaching, volatilization and soil erosion (Congreves & Van Eerd, 2015; Tei et al., 2020). From an agroecological perspective, the objective is to maintain a quasi-closed nutrient cycle within the system so that the level of nutrients allows acceptable production levels and nutrients leaving the system in the form of harvest can be replaced sustainably (Altieri, 1999). Thus, an agroecological system should maintain high and balanced levels of stable forms of nutrients in the system and labile forms in an adequate balance with production requirements, maximise nutrient recycling in the system, minimise nutrient losses to increase use efficiency and reduce pollution risk, and attain high levels of biological nitrogen fixation to reduce the need for external nitrogen sources (Table 5.1).

The state of the main components involved in the nutrient cycling process can be assessed by performance indicators such as macronutrient balances of the system (Gysi & Schwaninger, 2000; Hedlund et al., 2003) or the main crops (Scarlato et al., 2022), input use efficiency (Hedlund et al., 2003), level of biological N fixation, soil nutrient stocks, and the presence of nutrient deficiency problems in crops (Appendix A5.1, Table A5.1.1). Practice-based indicators such as the type and dose of fertilizers, the proportion of the area of legumes and cover crops during the year, soil cover during the year, soil use frequency, and soil tillage frequency and intensity (Norris & Congreves, 2018; Tei et al., 2020. Appendix A5.1, Table A5.1.2), may help to identify the management practices explaining system performance, to identify levers to improve system functioning.

5.2.3. MEDITAE framework development and application

The MEDITAE framework presented in Section 5.2.2 was developed and applied as part of a co-innovation project on five farms (Section 5.3), whereby the research team (researchers and students) proposed the framework structure, and farmers provided feedback.

The framework was discussed at the project's first diagnosis phase meeting. The objective of the meeting was to arrive at a shared vision of the system's desirable functioning from an agroecological perspective. At that moment, the team had been working with the farmers for one and a half years, having regular farm visits to interview, observe, and quantify variables to characterize the system. During the regular visits, informal discussions around the ecological processes supporting agroecological systems functioning already took place.

In the meeting, the research team presented the framework without quantification of the indicators. The team invited the farmers to evaluate whether the framework included all aspects needed and if assessing these dimensions would allow them to reflect what they expected from an agroecological system. To support the discussion, on some farms improvised diagrams reflecting the "conventional" and the desirable agroecology-based system functioning were drawn (Fig. 5.2). These diagrams helped to make the discussion about components and interactions of each process more concrete, to discuss the meaning and relevance of the performance indicators and to reflect on the effect of practices on process performances (Fig. 5.3).

5.3. Contribution of the MEDITAE framework during vegetable production systems co-innovation in south Uruguay

This section presents the application of the MEDITAE diagnosis framework as part of a co-innovation project on five case study vegetable farms in the south of Uruguay. We first present the study area, the case study selection and the methodological approach, followed by the results of farm characterization, diagnosis and redesign guided by the diagnosis framework (Section 2).

5.3.1. Study area and selection of case study farms

The study involved five farms in the Canelones department in south Uruguay, where most vegetable production is concentrated (34º21'S to 34º57'S – 55º40'W to 56º40'W). The five farms were selected to encompass different farm resource endowment levels,

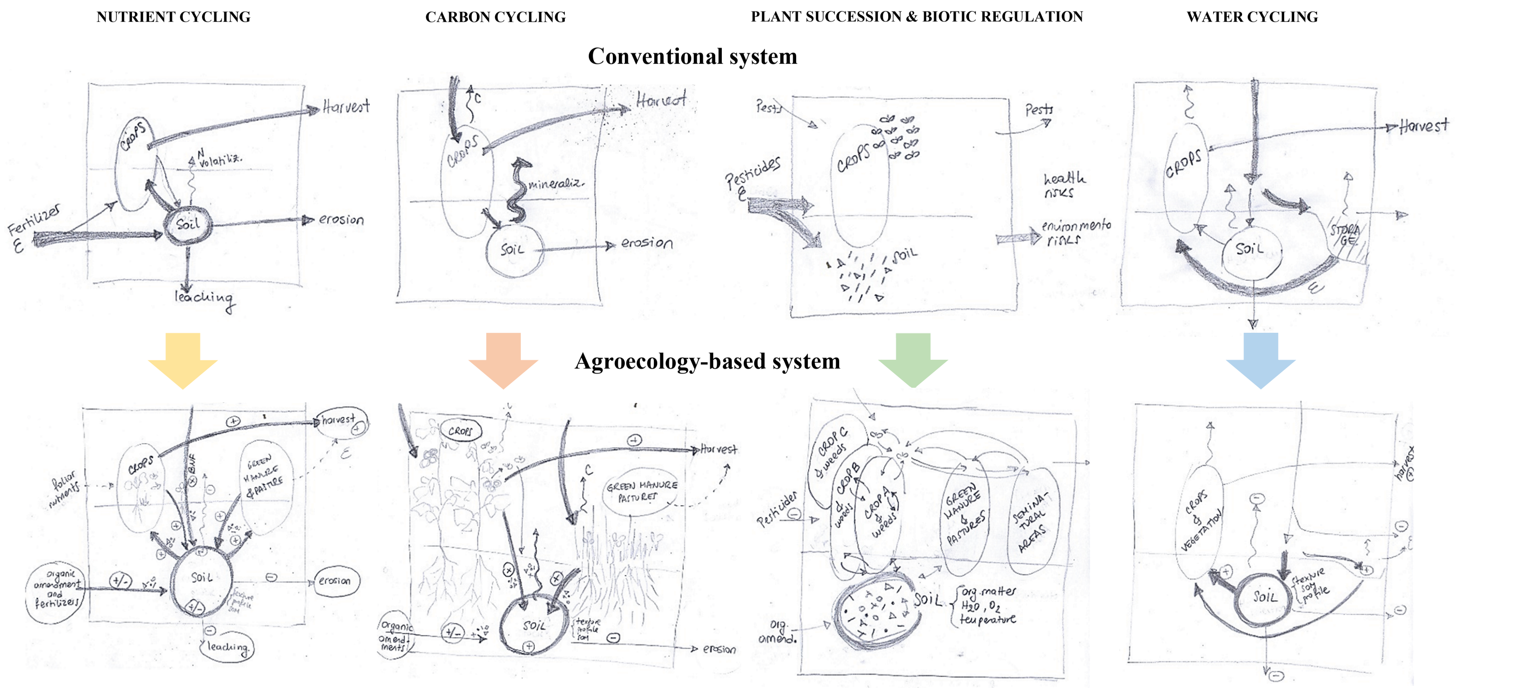

Fig. 5.2. Example of improvised diagrams used during the discussion with farmers on the MEDITAE diagnosis framework, indicating main components and fluxes in nutrient, carbon and water cycles, and biotic regulation in an agroecosystem under conventional management and the desirable functioning in an agroecology-based system. Agroecological management aims to increase the fluxes represented by thick arrows and decrease the fluxes with thin arrows.

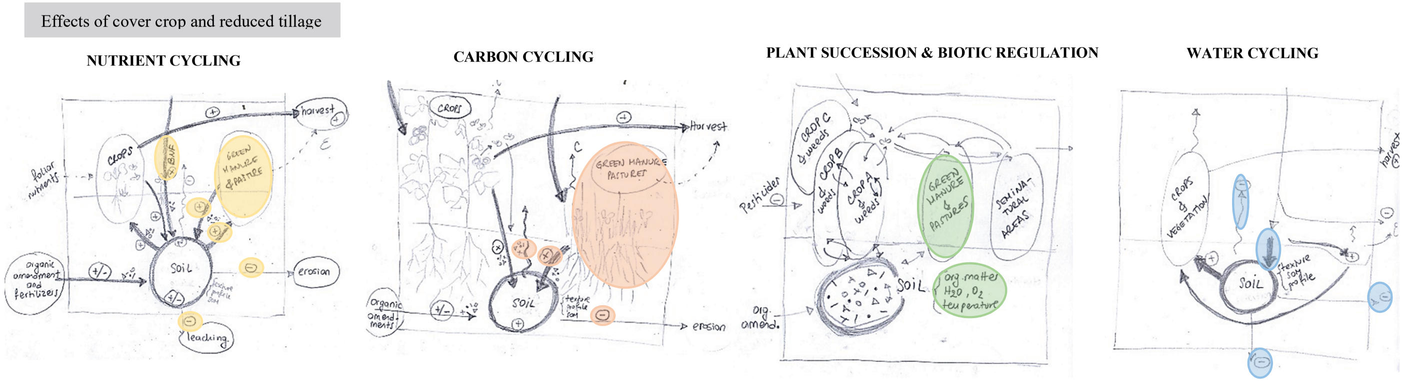

Fig. 5.3. Example of an improvised diagram to discuss the effects of using a particular practice on the ecological processes in an agroecosystem. In the example, the effects of introducing a green manure consisting of a legume and grass combination together with reduced tillage are highlighted (in yellow). During the discussion, we first identified components (ovals) and their links (arrows), then their desirable functioning (+ or -), and thus discussed the effect of the practice in these components and relations. For example, concerning nutrient and carbon cycles, the technology increases N and C input, enhances nutrient cycling from soil to biomass and vice-versa, and reduces C and nutrient losses. About plant succession and biotic regulation, it increases and diversifies below and aboveground niches enhancing weed suppression and biological control. Water cycling affects soil surface cover and rugosity, increasing water infiltration and reducing water losses.

types of crops (greenhouse and field crops), agrochemical input use levels, yield levels, farm management types (organic or conventional), and relationships with the market (direct selling or through intermediaries). Additional selection criteria were (i) participation in local farmer's groups, (ii) willingness to discuss strategic changes, and (iii) previous involvement in research processes linked to agroecological or ecological intensification strategies (Chapters 3 and 4 of the thesis).

5.3.2. Methodological approach

We used a co-innovation approach (Rossing et al., 2021). Similar to previous co-innovation projects in the region (Berrueta et al., 2021; Colnago et al., 2023; Dogliotti et al., 2014; Ruggia et al., 2021), the process started with an initial characterization and diagnosis of farms followed by the redesign, and the subsequent implementation, monitoring and evaluation of the performance of the new farm system. This chapter focuses on the characterization and diagnosis phase results and their link to the redesign illustrating the evolution and use of the MEDITAE diagnosis framework proposed in Section 5.2.

The research team visited the farms every two or three weeks throughout 2019 – 2022, except for critical periods during the Covid pandemic (March – August 2020, March – July 2021). The routine during the visits was to go around the farm with the farmers, make observations or take measurements, and discuss the observations with the farmers. Farm characterisation (between June 2019 and December 2021) required 6-10 visits per farm. During characterization, we described the structure and functioning of the system based on the six processes defined in the framework (Section 2), considering the process components and their interactions and how the farmers managed them. The information was collected through open and semi-structured interviews with the farmers and their families, the study of farm records, and direct observations and measurements during the regular visits.

The diagnosis phase comprised three on-farm meetings over approximately two months (between June 2021 and October 2022, depending on the farm). In the first meeting, the MEDITAE framework itself was discussed (Section 5.2.3). The second and third meetings were dedicated to discussing the farm diagnosis and arriving at a shared vision of the farm system and its performance concerning the needs and expectations of the family and the desirable functioning from an agroecological perspective. Each meeting was attended by two to four researchers and the family members involved in the management team of the focal farm.

The diagnosis of each farm involved assessing the six socio-ecological processes based on the calculation of the performance and practice-based indicators. The research team presented the framework and the quantitative or qualitative results of the indicators, along with a brief report with supporting information. The exchange was conducted in two steps. First, the performance of each process was discussed using traffic light colours reflecting good or bad indicator results. In some farms, we used diagrams (Fig. 5.2) to contextualize results and compare them to the desired system functioning. Second, based on the performance indicators, we identified which processes performed most positively and which were the weakest. In this way, we identified the main processes to focus on in the redesign phase. Based on the practice-based indicators, we discussed possible strategies to include in the redesign.

5.3.3. Results

5.3.3.1. Farm system characterization

The farms represented a diversity of resource endowment, management, and commercial strategies (Table 5.2). Farms 1 and 5 combined vegetable production with livestock production, while the other three specialized in vegetable production. Three farms (1, 2 and 3) had greenhouse production. They were characterized by having higher total labour, larger irrigated area and greater diversity of crops than the farms with only open-field crops (4 and 5). Among the farms with greenhouses, the two organic farms (1 and 3) that combined greenhouse production with open-field crop production had higher crop diversity and a higher proportion of hired labour than the conventional farm (Farm 2) (Table 5.2). Fertilizer and pesticide use levels in the main crops on the two conventional farms were around the average value for the region (Scarlato et al., 2022). Organic farms were below (Farm 1 and 4) or around the average value of input use for the region (Farm 3), explained by the amount of nutrient input from compost and chicken manure.

The two conventional farms (Farms 2 and 5) had a single commercial strategy. They sold individually and through an intermediary to the wholesale market. The three organic farms had diversified commercial strategies. The three of them combined collective and individual strategies. Farm 4 always operated through intermediaries, while Farms 1 and 3 sold part of the production to consumers directly through organic bags, street markets, organic shops and supermarkets. All the farmers participated in farmer´s organizations. Farms 1, 2, 3 and 4 were active members of two or more organizations, visiting four or more events per year, and had taken up responsibilities in the organisation. Farm 5 was part of one organization and participated in annual meetings or if there were specific project subsidies.

Table 5.2. Characterization of the five case study farms.

Farm	Farm size (ha)[1]	Management type[2]	Total labour (FTE)[3]	Family/total labour	Soil type[4]	Mechanization level [5]	Irrigated area[6]	Cultivated area (ha)	Vegetables crop area (ha)	Greenhouse area (ha)	Number of crops	Life cycle & succession[7]	Management team[8]	Farm records [9]
1	130	O	15.6	0.2	1, 2	5	2	45	15	2.3	40	2-2	3 B	2
2	2.2	C	4.3	1	2, 3	3	3	0.7	0.8	0.34	12	3-1	3 B, P	3
3	24	O	15.8	0.3	2	4	2	9.2	9	1.14	44	2-2	4 B, P	1
4	8	O	1.5	1	1	3	1	4.5	3.0	0	6	3-1	2 C	4
5	20	C	2.2	0.84	1	4	0	5.8	8	0	6	3-2	2 P, S	4

[1] Farm size: total area managed by the farmer.

[2] Management type: O: Organically certified, C: Conventional.

[3] Full-time equivalent (FTE). 1 FTE = 300 days of work and 8 hours per day = 2400 hours per year of labour.

[4] Soil types, 1 = Mollic Vertisols, 2 = Luvic/Vertic Phaeozems (Pachic), 3 = Luvic Phaeozems (Abruptic).

[5] Scale 1 to 5: 1: no tractor or one tractor but no tractor sprayer, greenhouse sprayer, mulching machine, disc ridger, rotary tiller, cultivator; 2: one tractor and one implement mentioned for 1; 3: one tractor and two or more implements, or two tractors and two implements; 4: two tractors and more than two implements; 5: three or more tractors and two or more implements.

[6] Scale 0 to 3: 0: less than 10% of the annual vegetable area under irrigation, 1: less than 50% of the annual vegetable area under irrigation, 2: between 51 and 80% of the annual vegetable area under irrigation, 3: 81 to 100% of the annual vegetable area under irrigation.

[7] Life cycle stage: 1 = entry or establishment, 2 = expansion, 3 = consolidation or stabilization, 4 = exit. Farm succession, 0 = no succession expected or possible, 1 = possible but not defined yet, 2 = defined or in transition to next generation.

[8] Management team composition: number of members of the management team, C = couple, F = father, M = mother, S = son, B = brothers, P = partners non-relatives.

[9] Farm records: 1. No, 2. Partial (production or economic) not for making decisions, 3. Partial and used for making decisions, or complete but not used for making decisions, 4. complete and used for making decisions.

5.3.3.2. Farm system diagnosis

Nutrient cycling

Performance indicators showed that the nutrient cycling process was a weak aspect of the five farms (Table 5.3). The results of soil analyses on four of the farms (Farm 1, 2, 3 and 5) evidenced an increase in the soil's nutrient stock levels compared to the original levels for the type of soil and region. In these four cases, the farm had high and positive N, P and K balances (ranging between +8 to +386 kg cultivated ha^{-1} yr^{-1}) (Table 5.3), which increased costs, reduced nutrient use efficiency, and increased environmental risks (N and K leaching, and losses with erosion) in particular because soil cover during the year was generally low. On one organic farm (Farm 4), the soil analysis indicated a depletion of the soil nutrient stock, linked to a negative N, P and K balance (-3 to -43 kg cultivated ha^{-1} $year^{-1}$ depending on the nutrient) and coinciding with visual crop nutrient deficiencies (Table 5.3), which may have been limiting crop yield and reducing future production capacity. On all farms, the nutrient application was based on a "routine" criterion without considering soil nutrient levels or crop requirements (Table 5.3). A positive aspect was that all farmers used (to some extent) organic sources of nutrients (Table 5.3). The organic farmers used chicken and hen manure and compost, and the conventional farmers used a combination of synthetic fertilizers and manure. There were very few or no legume crops in four of the five farms, and only one (conventional) had more than 20% of the farm area with legume crops (Table 5.3). Greenhouse soils exhibited higher levels of electric conductivity than open-field soils, with values above 1.0 dS m^{-1} vs less than 0.6 dS m^{-1}, but only on Farm 2 levels were high enough to cause limitations for crop development with a conductivity of 1.9 dS m^{-1} and a Na concentration of 15% of total bases (Table 5.3).

5

Carbon cycling

Two of the five farms achieved good results in the performance indicators of the carbon cycling process (Table 5.4). These two organic farms had a Relative Active SOC (RASOC) content higher than 0.7. This indicator was below 0.5 in the other three farms, indicating mineralisable soil organic carbon (SOC) content lower than 50% of the pristine conditions (Table 5.4). SOC balances were around zero or positive on four farms and negative on Farm 4 (-0.59 Mg SOC ha^{-1} $year^{-1}$) (Table 5.4). Farm 4 combined a negative SOC balance with low RASOC, indicating ongoing soil degradation. This farm had low soil use intensity and frequency (0.7), but high soil tillage frequency (12 interventions per year), very low amounts of organic inputs per year (2 Mg DM ha^{-1} $year^{-1}$) and a low proportion of green manure in the rotation (0.11) (Table 5.4). Farms 1 and 3 (organic) had high RASOC levels and positive SOC balance, mainly associated with high organic amendment inputs each year (7 and 22 Mg DM ha^{-1} $year^{-1}$, on farms 1 and 3, respectively) (Table 5.4). Farm 3 had high soil tillage frequency, disturbance, and use intensity and a low proportion of cover crops (0.2) and soil cover during the year (0.5) (Table 5.4). Farms 2 and 5 (conventional) had low RASOC but slightly positive SOC balances (between 0.1 and 0.7 Mg SOC ha^{-1} $year^{-1}$), explained by organic amendments on Farm 2, and relatively low soil and tillage frequency, high soil cover, green manure and pastures on Farm 5 (Table 5.4).

Green manure and pastures were systematically implemented only on Farm 5 (Table 5.4). Although all farmers were aware of the positive effects of these practices on soil quality, the lack of planning and time often prevented farmers from doing so. All farms used intensive and inversion tillage systems. Organic farms relied on several mechanical interventions to control weeds (Table 5.4). All farmers knew that inversion and intense tillage were not recommended but were unaware of the consequences.

Plant succession and biotic regulation

Organic farms had a higher diversity of weed species in open-field crops than conventional farms (between 5 and 20 weed species vs less than 5). Still, on all farms, the number of problematic weed species varied between 4 and 5, constituting a bottleneck on all farm systems (Table 5.5). Conventional systems relied on herbicide applications, while organic systems relied on mechanical control and plastic mulch. The low use of green manure or cover crops, the high proportion of bare soil during the year (indicators explained in the C cycle process), the lack of rotation, and allowing weeds to produce viable seeds constituted reasons for the high weed pressure.

Pest and disease problems were higher on the two conventional farms than on the three organic farms (Table 5.5). On conventional farms, problematic levels of pests and diseases occurred every year in all main crops, while on organic farms, pests and diseases were observed in some of the main crops. The ratio between pest and natural enemy abundances in tomato crops of the farms with greenhouses was around 3 in the organic farms and 12 in the conventional farm. Conventional farmers frequently applied pesticides, while on two organic farms, applications of alternative products were frequent (Table 5.5). Semi-natural vegetation covered more than 20% of the farm area on all farms. However, only on Farms 1 and 4 (organic) semi-natural vegetation was explicitly valued as providing ecological services such as pollination or biological control, and farmers tried to preserve it. All farms had four or more crop species, and organic farms used intercropping (Table 5.5). Although all farmers applied some criteria when deciding about land use, such as not repeating the same crop for two consecutive years, there was no long-term planning (Table 5.5). The current share of main crops (such as Solanaceae crops in greenhouses on Farms 1, 2 and 3, or onion and sweet potato on Farm 5) would not allow sustainable crop rotations.

Table 5.3. Performance and practice-based indicators related to the nutrient cycling process. Traffic light colours indicate bad (red), good (green) or intermediate (yellow) situations.

Nutrient cycling							
			Farm 1	Farm 2	Farm 3	Farm 4	Farm 5
Performance indicators	**Method**	**Sources of information**					
System-level macronutrient balances (N, P, K kg (cultivated ha)$^{-1}$ year^{-1})	N, P, K outputs – N, P, K input (Gysi and Schwaninger, 2000; Hedlund et al., 2003, Ciampitti and García, 2012).	Records of nutrient inputs (organic amendments + fertilisers + BNF), and outputs (sold products)	+ 40, +59, +59	+187, +153, +239	+276, +357, +386	-17, -3, -43	+87, +27, +3
Macronutrient balance of main crops (N, P, K kg ha^{-1})	N, P, K harvested – N, P, K input (Scarlato et al., 2022).	Records of nutrient inputs (organic amendments + fertilisers + BNF), and outputs (sold products)	Tomato: -54, 99, 96. Pumpkin: 61, 73, 156	Tomato: 50, 142, 196	Tomato: 92, 173, 303 Pumpkin: 140, 182, 373	Onion: -28, -5, -70 Sw. pot: -107, -18, -161	Onion: 82, 10, -15 Sw. potato: 30, 51, 54
Input macronutrient use efficiency (kg product (kg nutrient)$^{-1}$)	kg harvested product/ (N+P+K input) (Hedlund et al., 2003)	Records of nutrient inputs (organic amendments + fertilisers + BNF), and outputs (sold products)	47	41	23	398	58
Nutrient deficiency problems (scale: 1-low to 4-high)	Frequency of occurrence of visible symptoms: 1: no symptoms, 2: not every year in some crops, 3: every year in some main crops, 4: every year in all main crops	Direct observation and interview	2	3	2	3	2
Soil P, K, Na, Ca/Mg, Mg/K	Available P (ppm, Bray & Kurtz, 1945), exchangeable K, Na, Ca, Mg (meq 100g^{-1}, Isaac & Kerber, 1971)	Soil analysis on representative fields or greenhouses (GH)	GH: P 316, K 1.5, Na 2.0; Ca/Mg 3.9, Mg/K 4.7	GH: P 517, K 1.7, Na 3.6; Ca/Mg 2.0, Mg/K 3.7; Field: P 101, K 1.1, Na 1.1; Ca/Mg 1.6, Mg/K 4.6	GH: P 665, K 2.97, Na 1.84; Ca/Mg 2.59, Mg/K 2.06; Field: P 300, K 0.84, Na 0.77	P 40, K 0.7, Na 0.7; Ca/Mg 4.8, Mg/K 7.8	P 89, K 0.8, Na 0.3; Ca/Mg 4.6, Mg/K 7.6
Soil pH and EC	pH and EC (1:2.5 soil:water and soil:KCl ratio)	Soil analysis on representative fields or greenhouses (GH)	GH: pH 6.8, EC: 1.1	GH: pH 6.8, EC 1.9; Field: pH 6.6, EC 0.5	GH: pH 6.8, EC 1.87; Field: pH 7	pH: 6.5, EC: 0.6	pH: 6.5, EC; 0.3
Soil erosion (scale: 1-low to 4-high)	1: no visual signs, 2: local and light, 3: local and severe, or wide-spread and light, 4: wide-spread and severe.	Direct observation	1	1	2	2	2
Practice-based indicators	**Method**	**Sources of information**					
Relative amount of organic fertiliser (%) and amount (Mg DM ha^{-1} year^{-1})	Relative amounts of nutrients from organic sources, and amount of organic amendments (Mg DM ha^{-1} year^{-1})	Records and interview	100 % (GH:8, Field: 6)	66% (12)	100% (GH.23, Field:21)	100% (2)	21% (2)
Fertilization criteria (scale 1 to 3)	1: not considering soil and/or crop, i.e. calendar-based or routine; 2: considering crop requirements or soil status; 3: considering crop and soil	Direct observation, records, interview	1	1	1	1	1
Proportion of legumes in cultivated area	(ha legumes) (ha cultivated)$^{-1}$ year^{-1}	Direct observation, records	0.05	0	0.14	0.06	0.27
Annual soil cover (0-low to 1-high)	Estimated averaging soil cover by semester. Values of cover: 1 high cover (GM or crops with high cover), 0.5 intermediate cover (crops with low cover), 0 low cover (bare soil, tilled soil).	Direct observation, records, interview	0.75	0.5	0.5	0.5	0.75
Proportion of green manure (GM) or pastures in cultivated area	(ha GM + pastures) (ha cultivated)$^{-1}$ year^{-1}	Direct observation, records, interview	0.3	0	0.2	0.11	0.51

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Table 5.4. Performance and practice-based indicators related to the carbon cycling process. Traffic light colours indicate bad (red), good (green) or intermediate (yellow) situations.

Carbon cycling							
			Farm 1	Farm 2	Farm 3	Farm 4	Farm 5
Performance indicators	**Method**	**Sources of information**					
Relative Active SOC (RASOC, %)	Actual mineralisable SOC/ Original mineralisable SOC * 100 (Dogliotti et al. 2014). Soil texture (Forsythe 1975) and SOC analysis (Nelson & Sommers,1996).	Soil analysis	GH: 0.80 Field: 0.70	GH: 0.48 Field: 0.26	GH: 0.97 Field: 0.67	0.50	0.32
Annual SOC balance (Mg SOC ha^{-1} year^{-1})	C input (green manure+pastures+organic amendments+crop residues) and C output (harvest, mineralization) in a representative field or greenhouse based on the last four years	Soil analysis, records, interview	GH: 0.28 Field: -0.25	GH: 0.1 Field: 0.7	GH: 1.4 Field: 1.9	-0.59	0.13
Soil erosion (scale: 1-low to 4-high)	1: no visual signs, 2: local and light, 3: local and severe, or wide-spread and light, 4: wide-spread and severe.	Direct observation	1	1	2	2	2
Practice-based indicators	**Method**	**Sources of information**					
Soil use frequency (year^{-1})	Number of crops per field or greenhouse year^{-1}.	Direct observation, farm records, interview	GH: 3.4 Field: 0.70	GH: 1.8 Field: 0.7	GH: 4.0 Field: 1.7	0.70	0.90
Soil use intensity (-)	ha vegetables per ha cultivated area	Direct observation, farm records, interview	0.86	1.12	0.98	0.67	0.87
Annual soil cover (scale: 0-low to 1-high)	Estimated averaging soil cover by semester. Values of cover: 1 high cover (GM or crops with high cover), 0.5 intermediate cover (crops with low cover), 0 low cover (bare soil, tilled soil).	Direct observation, farm records, interview	0.75	0.5	0.5	0.5	0.75
Proportion of green manure or pastures in cultivated area (-)	(ha GM + pastures)per ha cultivated per year	Direct observation, farm records, interview	0.3	0	0.2	0.11	0.51
Amount of organic ammendments (Mg DM ha^{-1} year^{-1})	Mg DM (cultivated ha^{-1}) year^{-1}	Farm records, interview	GH:8, Field: 6	12	GH.23, Field:21	2	2
Tillage frequency (year^{-1})	Number of tillage interventions per field or greenhouse per year (Alliaume et al., 2013; typically: 4 to 8).	Direct observation, farm records, interview	GH: 12 Field: 4	GH: 5 Field: 4	GH: 12 Field: 6	12	7
Type of physical soil disturbance (scale: 0-low to 4-high)	0: no tillage, 1: tillage disturbance <5-10 cm, 2: tillage disturbance >10 cm and no inversion, 3: inversion tillage <25cm, 4: inversion tillage >25cm (Gaba et al., 2014).	Direct observation	4	3	4	3	4

Table 5.5. Indicators related to plant succession and biotic regulation. Traffic light colours indicate bad (red), good (green) or intermediate (yellow) situations.

Plant succession and biotic regulation							
			Farm 1	Farm 2	Farm 3	Farm 4	Farm 5
Performance indicators	**Method**	**Sources of information**					
Incidence of problematic pests (scale: 1-low, to 4-high)	Footnote (1).	Direct observation, interview	3	4	3	2	4
Incidence of problematic diseases (scale: 1-low, to 4-high)	Footnote (2).	Direct observation, interview	3	4	3	3	4
Weed diversity (number)	Number of weed species in main crops. Scale: <5, 5-10, 10-15, 15-20, >20.	Direct observation	GH: 5-10 Field: 15-20	GH: <5 Field: <5	GH: 5-10 Field: 10-15	15-20	<5
Incidence of problematic weeds (number of species)	Table footnote (3).	Direct observation, interview	4	4	5	4	5
Weed cover or biomass in main crops	One month after installation and at harvest (Scarlato et al., under review)	Direct observation	not assessed	not assessed	high	high	intermediate
Pest/natural enemy ratio in main crops	One month after installation and at harvest (Scarlato et al., 2023).	Direct observation	GH tomato: 4.1 ± 1.1	GH tomato: 11.6 ± 6.9	GH tomato: 1.8 ± 0.6	not assessed	not assessed
Practice-based indicators	**Method**	**Sources of information**					
Activities diversification	Number of activities (vegetables, livestock, hen-eggs, fruit trees, other).	Direct observation and interview.	2	2	2	2	2
Crop rotation	No rotation, rotation with number of years	Direct observation, farm records, interview	partial, two years	no rotation	no rotation	3 years	3 years
Crop families, species and varieties diversity	Number of crop families (F), species (S) and varieties (V) diversity.	Direct observation, farm records, interview	9 F, 23 S, 45 V	6 F, 12 S, 17 V	16 F, 44 S, 92 V	5 F, 6 S, 10 V	3 F, 4 S, 9 V
Number of species covering 75% of cultivated area	Number of species	Farm records	more than 10	less than 5	more than 10	less than 5	less than 5
Crop seasonality	Ha summer vegetable crop area / ha winter vegetable crop area	Direct observation, farm records, interview	3..5	0.96	1.9	3	1.3
Number of crops in intercropping	Number of species in intercropping/total species.	Direct observation, interview	0.7	0	0.81	0.50	0
Area of crops in intercropping	Ha intercropping/ha total vegetable area	Direct observation, interview	0.53	0	0.52	0.17	0
Proportion of semi natural area in total area	Ha with more than 10 years without disturbance per ha. Animal grazing at low densities was not considered	Direct observation	0.21	0.23	0.36	0.19	0.22
Proportion of semi natural area in cultivated area	Ha with more than 10 years without disturbance per ha cultivated area. Animal grazing at low densities was not considered	Direct observation	0.60	0.71	0.96	0.43	0.38
Pest management criteria (scale: 1-4)	1-fully pesticide- based to 4-fully cultural-based. Table footnote (4)	Direct observation, farm records, interview	3	2	2	3	1
Application of synthetic pesticides in main crop	Number of applications	Direct observation, farm records, interview	0.00	Tomato: 9 Celery: 2	0.00	0.00	Onion: 10 Sweet potato: 2
Application of alternative products	Number of applications of botanicals / biologicals / other products	Direct observation, farm records, interview	Tomato: 6	Tomato: 20	Tomato: 10 Potato: 4	0	0

[1] Frequency of problematic pests (requiring specific control or affecting crop yield or quality): 1: no occurrence, 2: not every year in some main crops, 3: every year in some main crops, 4: every year in all main crops. [2] Frequency of problematic diseases (requiring specific control or affecting crop yield or quality): 1: no occurrence, 2: not every year in some main crops, 3: every year in some main crops, 4: every year in all main crops. [3] Problematic weeds: perennial or annual with high initial growth rate, high multiplication rates and diverse mechanisms, resistant mechanisms, present in more than 20% of cultivated fields. [4] Scale based on the prevalence of pesticide or cultural practices (quality of the seed, resistant/tolerant varieties, elimination of diseased plants, management of intercrop period, cleaning of implements, air circulation, crop rotation). Scale: 1. pesticide-based, calendar applications; 2. 2 or 3 practices, partial monitoring, still pesticide-based; 3. 4 or + practices, crop and risk conditions monitoring.

Water cycling

The soil water retention at field capacity was more than 80% of the water retention capacity with original SOC levels on the two farms with high RASOC and less than 80% on the other three farms with low RASOC (Table 5.6). The farms with lower water retention capacity were less efficient in capturing and retaining rainwater and required more frequent irrigation than those with higher retention capacity. On most farms, the low soil cover during the year and the low proportion of green manure or pastures (indicators explained in the C cycle process) reduced water infiltration into the soil. There were differences in the availability of water sources (Table 5.6). The organic farms had better water access in terms of quantity and quality. Specific problems were identified on Farms 4 and 2. On Farm 4, the irrigation capacity allowed to irrigate summer crops and strategically irrigate winter crops (Table 5.6). However, it was under-used, and irrigation was less and later than required by the crops. Moreover, the sprinkler irrigation system was less efficient than drip irrigation, enhancing weed development in all fields, increasing labour demand and/or reducing crop yield. On Farm 2, the high electrical conductivity and Na content of the water (Table 5.6), in conjunction with the use of fertilizers and chicken manure, resulted in soil problems in the greenhouses: high electric conductivity and poor structure, as well as crop nutrient deficiencies (Table 5.3).

Energy flow

Crop yields and green soil cover during the year are important aspects of energy flow in the system, as they determine solar energy interception allowing inputs and resources to be mainly allocated to crops. We found high yield gaps in all or some of the main crops on all farms (relative yield gap ranging from 0.11 to 0.8) (Table 5.7). In most cases, the yield gaps were explained by a delay in the timing of crop management practices (e.g. sowing or transplanting, weeding, irrigation) caused by a mismatch between labour demand and availability throughout the year. Farms 1 and 3 showed extreme situation where a high proportion of the crop area could not be harvested (Table 5.7). Time constraints during the growing season resulted in such extremely high weed pressure that farmers abandoned crops. The yield gaps decreased productivity and income, accentuated the system's positive nutrient balance, reduced solar energy interception and carbon fixation, and generated inefficiencies in input use (e.g. mechanical interventions) and resources (e.g. labour, soil). The low soil cover during the year, in particular on farms 2, 3 and 4 (50%), caused a gap between the actual and the potential biomass production of the system (Table 5.7), which implied a gap in solar radiation interception and carbon fixation in the system. Fossil-fuel-based inputs were not quantified because of a lack of precise information. However, it was discussed with the farmers that fertilizers, pesticides and fossil fuel oil should be reduced in the two conventional farms, and fossil fuel and plastic mulch (on Farms 1 and 3) should be reduced in the organic farms. Other indicators (energy balances) were impossible to estimate because of a lack of information.

Table 5.6. Performance and practice-based indicators related to the water cycling process. Traffic light colours indicate bad (red), good (green) or intermediate (yellow) situations.

Water cycling							
			Farm 1	Farm 2	Farm 3	Farm 4	Farm 5
Performance indicators	**Method**	**Sources of information**					
Water retention at field capacity in the rooted zone (mm)	mm in layer A+B of the soil profile. Estimate based on soil texture and organic matter analysis (Silva et al. 1988)	Soil analysis and soil profile description	GH: 216 Field: 197	GH: 165 Field: 129	GH: 218 Field: 183	150	168
Relative water retention at field capacity (%)	Actual water retention capacity / Water retention capacity at original soil organic matter content * 100. Table footnote (1)	Soil analysis and soil profile description	GH: 93 Field: 86	GH: 81 Field: 77	GH: 99 Field: 83	77%	76%
Water storage capacity per year (m^3)		Direct observation	12000	1350	2010	2360	1250
Water quality (scale: 1-good to 3-bad)	Table footnote (2)	Water analysis	1	3	1	1	1
Soil erosion (scale: 1-low to 4-high)	1: no visual signs, 2: local and light, 3: local and severe, or wide-spread and light, 4: wide-spread and severe.	Direct observation	1	1	2	2	2
Practice-based indicators	**Method**	**Sources of information**					
Type of irrigation system	Drip or sprinkler, and in the case of sprinkler continuous or occasional	Direct observation, interview	drip irrigation	drip and sprinkler	drip irrigation	sprinkler, occasional	sprinkler, occasional
Irrigated area/cultivated area	ha with any type of irrigation / ha cultivated	Direct observation, interview	0.42	0.9	0.26	0.17	0.2
Type of water sources	Superficial or underground; natural or artificial	Direct observation	superficial artificial	superficial and underground	superficial artificial	superficial artificial	superficial artificial
Annual soil cover (0-low to 1-high)	Estimated averaging soil cover by semester. Values of cover: 1 high cover (GM or crops with high cover), 0.5 intermediate cover (crops with low cover), 0 low cover (bare soil, tilled soil).	Direct observation, records, interview	0.75	0.5	0.5	0.5	0.75

[1] Estimated based on soil texture and organic matter analysis (Silva et al. 1988) and the soil type's original level of organic matter (Durán, 1985).
[2] Scale according to chemical and/or biological restrictions for production: 1: no problem, 1: <50% sources with restrictions, 2: 50-75% sources with restrictions, 3: >75% with restrictions.

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Table 5.7. Performance and practice-based indicators related to energy flow. Traffic light colours indicate bad (red), good (green) or intermediate (yellow) situations.

Energy flow							
			Farm 1	Farm 2	Farm 3	Farm 4	Farm 5
Performance indicators	**Method**	**Sources of information**					
Food production from cultivated land (Mg food (ha cultivated)$^{-1}$ year^{-1})	Marketable production per ha cultivated	Farm records	19	36	24	9	21
Actual yield/attainable yield of main crops for the region	Dogliotti et al., 2014; Dogliotti et al., 2021; Berrueta et al. 2019; Colnago et al., 2023	Farm records	Tomato: 0.77 Pumpkin: 0.11	Tomato: 0.64 Celery: 0.45	Tomato: 0.56 Pumpkin: 0.67	Onion: 0.75 Sweet potato: 0.58	Onion: 0.65 Sweet potato: 0.8
Proportion of harvested area in planted area	Harvested area / planted area	Direct observation, interview	0.75	0.92	0.72	0.83	0.9
Practice-based indicators	**Method**	**Sources of information**					
Proportion of vegetable area in total area	Ha vegetables / ha total land	Direct observation, interview	0.16	0.36	0.38	0.38	0.87
Proportion of greenhouse vegetable area in cultivated area	Ha greenhouse vegetables / ha cultivated	Direct observation	0.10	0.49	0.13	0	0
Annual soil cover (0-low to 1-high)	Estimated averaging soil cover by semester. Values of cover: 1 high cover (GM or crops with high cover), 0.5 intermediate cover (crops with low cover), 0 low cover (bare soil, tilled soil).	Direct observation, records, interview	0.75	0.5	0.5	0.5	0.75
Tillage frequency (year^{-1})	Number of tillage interventions per field or greenhouse per year (Alliaume et al., 2013; typically: 4 to 8).	Direct observation, farm records, interview	GH: 12 Field: 4	GH: 5 Field: 4	GH: 12 Field: 6	12	7

The socio-economic and cultural process

All farmers experienced an excessive workload (Table 5.8). On conventional farms, this was related to production activities, while on organic farms, the workload was related to the combination of production and commercialization activities. The two conventional farms had lower income, lower prices, higher variability among years associated with lower income diversification, and lower satisfaction with their life quality than organic farmers (Table 5.8). The farmers of the three organic farms had previously been conventional. When asked about their quality of life, organic farmers not only considered aspects such as family income, housing quality and access to services but also mentioned their satisfaction in knowing that they do good for consumers, the environment and their own health. For example, they highlighted the change in the quality of life that came from going in and out of their houses and fields without worrying about changing clothes or bathing to wash off the smell of pesticides each time after work. The organic farmers also highlighted the reduced dependency and sense of risk concerning the sale of their products, particularly because they were closer to consumers and had several commercial strategies and channels (Table 5.8). Moreover, these commercial strategies allowed them to produce high diversity of crops. In the case of Farm 3, where 80% of the products were sold directly to consumers and farmers were proactive in looking for new consumers, they faced an increasing demand that promoted an increase in production area beyond their capacity to handle properly. Conventional farmers, who sold through intermediaries (Table 5.8), experienced price uncertainty, as they depended on the wholesale market and the intermediary, and sometimes the products were not sold and returned to the farms. Moreover, it was not easy to include new crops to increase the diversity cultivated, as the intermediaries specialized in selling only a few products.

Social interaction related to institutional and farmers' organization networks was a positive aspect on most farms, with farmers' active participation in more than two institutional networks and three farmers' networks (Table 5.8). The exception was Farm 5 (conventional), with a low participation level in one farmer’s organization solely to access public project subsidies (Table 5.8). The farmers highlighted the relevance of the networks to exchange experiences, learn, and have support for making important decisions in their farms. Organic farmers, in particular, also highlighted the relevance of farmer's organizations for implementing the Uruguayan organic certification label, generating collective commercial strategies, and negotiating government support policies.

5.3.3.3. Connecting the diagnosis with farm system redesign

On each farm, the main processes that needed to be strengthened were discussed and defined based on the results of the performance indicators and the farmers' interests

Table 5.8. Performance and practice-based indicators related to socio-economic and cultural processes. Traffic light colours indicate bad (red), good (green) or intermediate (yellow) situations.

Socio-Economic and cultural							
			Farm 1	Farm 2	Farm 3	Farm 4	Farm 5
Performance indicators	**Method**	**Sources of information**					
Relative family income (FI) per capita per month (-)	Family income per capita per month / average family income per capita per month in rural areas (Statistics National Institute) (Colnago et al., 2021; Dogliotti et al., 2014)	Farm records, interview	3.8	0.82	not information available	1.4	0.9
Relative family income per hour (-)	Family income per h ourfamily work / labour opportunity cost in the region (Colnago et al., 2021)	Farm records, interview	3.2	0.58	not information available	1.2	0.57
Income diversification among crops	Number of crops making up 50% of family income	Records, interview	more than 10	2	more than 10	2	2
Financial input/output relation	Colnago et al., 2021; Dogliotti et al., 2014	Records, interview	0.68	1.07	not information available	not information available	1.04
Number of people potentially fed per year	kg food year⁻¹ / 0.4*365 (WHO: 400 g of fresh vegetables per person per day)	Farm records, interview	2648	152	1476	262	834
FTE / cultivated area	Full-time equivalent / ha cultivated	Farm records, interview, direct observation	0.90	6.95	1.74	0.33	0.50
Family FTE / total FTE	Family full-time equivalent / Total full-time equivalent	Farm records, interview, direct observation	0.54	1	0.27	1	0.84
Price obtained/price market	Average price obtained / price of the wholesale market. Estimated per month and for main crops.	Farm records, interview	1.6	1	1.4	1.15	1
Family farms workload (scale: 1-5)	1-bad to 5-good. Table footnote (1)	Interview, direct observation	2	3	1.5	3	3
Hired workers workload (scale:1-5)	1-bad to 5-good.	Interview, direct observation	4	not applicable	2	not applicable	5
Family farms holidays (scale: 1-5)	1-bad to 5-good. Table footnote (2)	Interview	4	4	4	4	4
Hired workers holidays (scale: 1-5)	1-bad to 5-good	Interview	5	not applicable	5	not applicable	5
Health problems (scale: 1-5)	1-bad to 5-good. Table footnote (3)	Interview	4	4	4	3	3
House quality and basic services (scale: 1-5)	1-bad to 5-good. Table footnote (4)	Interview, direct observation	5	4	5	4	4
Generational succession (scale: 1-5)	1-no to 5-yes. Table footnote (5)	Interview	4	3	5	4	5
Life quality perception (scale: 1-5)	1-very dissatisfied, 2-somewhat dissatisfied, 3-satisfied, 4-very satisfied, 5-extremely satisfied	Interview	4	2	4	3.5	2

[1] 5: 8 hours/day, free weekends, 4: 8 hours/day, 1.5 days free on weekends, 3: >8 hours/day, free on weekends, 2: >8 hours/day, 1.5 days free on weekends, 1: >8 hours/day, less than 0.5 days free on weekends.

[2] 1: at least 1 day per month, 2: 2 to 4 days per month, 3: at least 1 week per year, 4: at least 1 day per month and 1 week per year, 5: 2 to 4 days per month and more than 1 week per year (Dogliotti et al., 2014).

[3] 1: at least one chronic problem without treatment, 2: at least one chronic problem under treatment, 3: more than one specific problem per year and solved, 4: one problem per year, solved, 5: No problems (Dogliotti et al., 2014).

[4] Sum of values per item: drinking water (1 yes, 0 no), electricity (1 yes, 0 no), overcrowding (1 parents and children separated and less than 3 pers/room, 0 other), house construction problems (1 no, 0 yes), quality of the surrounding area (1 good, 0 close to rubbish dumps, polluted drains, etc.).

[5] 1: farmer over 50 and no successor, 2 farmers between 40 and 50 and no successor, 3 farmers between 40 and 50 successors with a low predisposition, or over 50 with successor medium predisposition, 4 farmers between 40 and 50, a successor with an intermediate predisposition, 5 transition in progress or farmer less than 40.

Table 5.8 (cont). Performance and practice-based indicators related to socio-economic and cultural processes. Traffic light colours indicate bad (red), good (green) or intermediate (yellow) situations.

Socio-Economic and cultural							
			Farm 1	Farm 2	Farm 3	Farm 4	Farm 5
Practice-based indicators	**Method**	**Sources of information**					
Seed origin (%)	Percentage of varieties from own propagation (O), locally bought (L), and imported (I)	Direct observation, records, interview	14% O; 14% L, 72% I	19% O; 6% L, 75% I	35% O; 12% L, 53% I	50% O, 30% L, 20% I	63% O, 25% L, 15% I
Cultivated area according to seed origin (%)	Percentage of cultivated area with own propagation (O), locally bought (L), and imported (I)	Direct observation, records, interview	2% O; 2% L, 96% I	23% O; 1% L, 76% I	10% O; 18% L, 72% I	28% O, 14% L, 58% I	48% O, 23% L, 29% I
Fertiliser origin (%)	Percentage per type: own (O), local (L), imported (I)	Direct observation, records, interview	99% L, 1% I	15% O, 5% 1 L, 34% I	97% L, 3% I	20% O, 80% L	80% I, 20% L
Type of commercialization (%)	Direct (D), close intermediary (CI), far intermediary (FI). Table footnote (6)	Direct observation, records, interview	85% CI, 15% D	100% FI	80% D, 10% CI, 10% FI	80% CI, 20% FI	100% FI
Commercial strategy diversification	Number of type of strategies	Direct observation, records, interview	4	2	6	3	1
Commercial channels diversification	Number of commercial channels	Direct observation, records, interview	29	3	14	8	1
Workers with social benefits (-)	Number of workers with social benefits/total number of workers	Interview	1	0.75	0.33	1	0.67
Institutional networks	Number of institutional networks connected to	Interview	4	2	5	3	2
Organization networks (number)	Number of organization networks connected to	Interview	3	3	3	4	1
Level of participation (scale: 1-4)	Table footnote (7)	Direct observation, interview	4	4	4	4	2
Equity in intra-family decision-making (-)	Number of family workers that decide / total family workers	Direct observation, interview	0.6	1	0.57	1	1
Farm records (scale: 1-4)	1-no records to 4-complete records and used for decision-making. Table footnote (8)	Direct observation, interview	2	3	1	4	4

[6] Direct: farmers to consumers, close intermediary: one intermediary between farmers and consumers, far intermediary: more than one intermediary between farmers and consumers.
[7] Scale: 1. no active participation, 2. punctual participation in general spaces, 3. frequent participation (more than 4 times a year), 4. frequent participation and responsibilities.
[8] Scale: 1. No, 2. Partial (production or economic) not for making decisions, 3. Partial and used for making decisions, 4. complete and used for making decisions.

(Table 5.9). There were situations where the process performance was not identified as a problem, but some practice-based indicators had bad scores (e.g. Farm 3 with low pest and diseases incidence but high and routine alternative product applications). In such cases, the practice-based indicators related to these processes were also reviewed to identify room for improvement or avoid future problems. The discussion around the socioeconomic and cultural aspects helped to understand the objectives and needs of the families, which was a guiding principle in the redesign phase. For example, on Farm 1 and 3, we agreed to focus on improving energy and nutrient cycling processes while maintaining good performance in the carbon cycling process and reducing weeds pressure (within regulation processes) while reducing workload and maintaining family income (Table 5.9). On Farm 2, we agreed to enhance the biotic regulation process while increasing family income (Table 5.9).

The discussion about the practice-based indicators focused on the possible strategies and management practices that could be changed to improve performance (Table 5.9). Adjusting the production plan and planning crop rotations was a central strategy in redesigning all the farms, as they affect all the socio-ecological processes, e.g. soil-borne diseases pressure, carbon input and soil cover, income diversification, and workload related to management organization aspects. The emphasis on the design of the rotation varied according to each situation, focusing on the main aspects that needed to be strengthened. For example, Farm 2 focused on reducing pest and soil disease problems, Farm 4 on increasing SOC and reducing weed pressure, or Farm 1 and 3 on reducing excessive large nutrient balance and weed pressure (Table 5.9). Other aspects included depending on the farm were the change of organic amendments type and doses, the design of non-crop cultivated vegetation (e.g. flower and shrub strips), conservation of semi-natural areas, the analysis of alternative commercialization strategies, the improvement of farm records, and analyse alternatives to increase water availability (Table 5.9).

5.4. Discussion

An agroecological perspective on farm systems calls for enhancing ecological processes underlying the system's functioning and promoting human learning processes to inspire and sustain these changes. Working with farmers, technical advisors and agronomy students asking for causes of farm system’s behaviour, we set out to identify a suitable framework. Jointly, we developed the MEDITAE framework to support the characterization, diagnosis and redesign of farm systems as part of a co-innovation project aimed at the agroecological redesign of vegetable farm systems in Uruguay. Based on the results of this experience, we discuss three main aspects (i.) The agroecological farm system perspective afforded by the framework; (ii.) The role of the

Table 5.9. Summary of the agreement between the research team and farmers concerning the agroecosystem processes that needed to be enhanced and the objectives and strategies of the redesign on the five farms. Farms 1, 3 and 4 had organic management, and Farms 2 and 5 had conventional management.

	Farm 1	Farm 2	Farm 3	Farm 4	Farm 5
Processes with good overall performance	Carbon, water, plant succession and biotic regulation, socio-economic		Carbon, water, plant succession and biotic regulation, socio-economic	Plant succession and biotic regulation, socio-economic	
Processes that need to be strengthened	Nutrients, energy	All. Prioritized: socio-economic, carbon, and plant succession and biotic regulation.	Nutrient, Energy	Carbon (water), nutrients, energy	All. Prioritized: socio-economic, carbon, plant succession and biotic regulation.
Redesign objectives	Maintain family income, consolidate new generational participation in the farm, and reduce the environmental and social impact (workload and stress).	Increase family income, improve soil quality and reduce environmental risks. Become agroecologically certified.	Consolidate and stabilize income, increase production efficiencies, and reduce environmental and social impact (workload and stress).	Stabilize family income and improve soil quality and biodiversity.	Increase family income and stability (reduce stress), improve soil quality and reduce environmental and health risks related to pesticide use. Continue as "conventional farmers" but with sustainable management.
Redesign strategies	i. Stabilize and re-organize cultivated areas, reducing crop areas, in particular in open-field crops. ii. Plan crop rotations focused on maintaining a positive SOC balance but reducing and changing organic amendments for controlling pests and diseases, reducing nutrient over-fertilisation (particularly in greenhouses), and controlling weeds in open-field crops. iii. Define non-cultivated semi-natural areas to preserve, design and plan management of strips of vegetation among fields and greenhouses.	i. Increase greenhouse area to increase the crop area and crop diversity, increasing production and allowing rotation. ii. Plan a crop rotation, including solarization, green manure and organic amendments, to improve soil quality, reduce pest and disease incidence, and adjust nutrient balance. iii. Continue working towards biological control (BC) with previous strategies, reducing pesticide use, increasing associated vegetation around and inside greenhouses, and trying new BC tools. iv. Explore alternatives to increase the quantity of good-quality water iv. Explore commercial alternatives to increase crop diversity.	i. Stop expanding (stabilize for a period) commercialisation and cultivated area. Adjust crop areas to reduce labour demand. ii. Plan crop rotations focused on maintaining a positive SOC balance but reducing and changing organic amendments types to reduce nutrient over-fertilisation. iii. Adjust the timing of cropping practices. iv. Define non-cultivated semi-natural areas to preserve, design and plan management of cultivated strips among fields and greenhouses. v. Solve the situation of workers without social benefits. vi. Farm records system: improve the quality of the information to make better decisions.	i. Adjust the production plan: maintain total crop area, change the proportion of each crop area according to labour availability, and increase production and resource use efficiency. ii. Re-organize crop rotation focused on increasing SOC, improving nutrient balances, and reducing weed pressure by increasing the amount of organic amendments, including cover crops and pastures, including legumes, reducing periods with bare soils and reducing the number of mechanical interventions. ii. Adjust timing in cropping activities. iii. Consolidate non-cultivated areas, particularly those that are between fields. iv. Explore direct selling commercial alternatives and/or crop diversification alternatives to stabilize income.	i. Adjust production plan: reduce the area of current main crops, include new crops to improve rotation and spatial diversification and provide income in spring. ii. Re-organize crop rotation to reduce soil disease pressure (and reduce pesticide use) and increase SOC balance. ii. Reduce herbicide use through rotation, using green manure and regular tillage, and adjust fertilization management according to crop requirements and soil nutrient status. iii. Redefine the commercialization strategy of main products to reduce post-harvest losses. iv. Explore alternatives to invest in increasing water availability for irrigation.

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framework in raising awareness, promoting learning and creating consensus; (iii.) The capacity of the framework to support agroecological transitions.

5.4.1. The framework's agroecological perspective in analysing the farm system

By defining the main processes and how they should function in an agroecosystem, the MEDITAE framework guides the analysis and highlights the role of key socio-ecological processes supporting production in an agroecological system (Nicholls et al., 2016; Tittonell, 2015). The resulting indicators were not all new. Attention for family income, labour productivity and farmer workload, yield gaps of main crops, and soil organic carbon balance (Section 5.3) were similar to those used in previous co-innovation projects in Uruguay (Dogliotti et al. 2014; Colnago et al., 2023) that were based on the MESMIS approach (Masera et al., 1999). Other indicators had been overlooked in previous projects. Indicators related to nutrient cycling, plant succession and biotic regulation processes are prominent in the new framework but virtually absent in the previous projects. The diagnosis found that nutrient cycling was weak in all farms, reflected in either excess nutrient balances or soil nutrient depletion. Scarlato et al. (2022) found these extremes to be co-existing general phenomena in Uruguay caused by routine-based nutrient application without considering crop requirements and soil nutrient status. Imbalances are further accentuated by the low implementation of cover crops and pastures and low annual soil cover, which reduce nutrient cycling and increase nutrient loss risk. Pest, disease and weed incidences differed among farms and were linked to management practices, such as crop diversity and the use of crop rotation (e.g. Peralta et al., 2018; Peters et al., 2003; Wright et al., 2015), the type, timing and dose of pesticides used (Bommarco et al., 2011; Walsh et al., 2022), and the presence of non-cultivated land and intercropping (Bianchi, 2022; Tamburini et al., 2020). Consolidating the six socio-ecological processes in one framework helped highlight their relevance and characterize their performance and the underlying reasons, which in the following step helped guide the redesign.

Compared to previous projects, the new framework led to different redesign solutions. For example, excessive workload is a common problem that in previous projects was solved by reducing cropping area and reorganizing tasks, which sometimes implied reducing crop diversity. Using the framework, solutions for the workload problem always maintained or increased crop diversity, in line with the agroecological perspective. On some farms, diversification within the cropped area was proposed, for instance, by including flowering islands and borders in the greenhouses of Farm 2. Semi-natural areas were delimited on other farms, and their management was elaborated. For two farms (Farms 2 and 4), commercial strategies provided the entry point to increase farm system diversity and improve selling prices. Although the actual effect of these strategies on each farm needs to be assessed in the next steps of the co-innovation cycle, the framework made a difference in guiding the redesign phase compared to previous experiences.

A weakness of the framework is that the six processes are not explicitly connected, leading to a lack of systemic perspective. For example, natural pest regulation (biotic regulation) depends on the presence and activity of natural enemies, which is affected by the cultivated and non-cultivated vegetation diversity (plant succession) (Estrada-Carmona et al., 2022; Iuliano & Gratton, 2020). At the same time, natural pest regulation depends on the abundance and quality of host plants supporting pests (Altieri et al., 2012; Bianchi, 2022). Plant quality is determined by nutritional status (nutrient cycle) and hydric status (water cycle) (Buckland et al., 2013; Butler et al., 2012; Han et al., 2019; Hanet al., 2014). Plant nutritional status depends on soil nutrient stocks and their availability to plants, which is affected by physical soil conditions (carbon cycle), water availability (water cycle), and biological activity (biotic regulation) (Puerta et al., 2019; Terrazas et al., 2016). In the diagnosis process reported here, these interconnections were considered during the on-farm discussions but are not explicitly represented in the framework.

In addition, another issue to be improved would be to include longitudinal data to understand better the systems' evolution (Lamine & Bellon, 2008; Prost et al., 2023; Toffolini et al., 2016). With time series on SOC or yields trends and variability may become part of the diagnosis. Similarly, insight into how long specific practices were applied and what was done before may cause reflection on routines.

While it can continue improving, the MEDITAE diagnosis framework gave us a consensual and holistic view of farm functioning and management to identify weak and robust processes and their supporting practices. It helped create a problem hierarchy and provide entry points for redesign strategies in organic and conventional farm systems.

5.4.2. The framework's contribution to raising awareness, promoting learning and building consensus

In developing the MEDITAE framework, we connected agroecological principles to the underlying socio-ecological processes that need to be fostered (Nicholls et al., 2016; Tittonell, 2015) to engage in system change based on learning processes and a shared understanding of the context-specific levers for change (Prost et al., 2023). In comparison with other diagnosis frameworks that are focused on assessing the agroecological status of a system (e.g. Mottet et al., 2020; Nicholls et al., 2020), the proposed framework is both an analytical tool as well as a means for rethinking system functioning among researchers, technical advisors, and farmers as the decision-makers.

Based on a shared understanding of the current system and the shortfall on the various objectives, a backcasting process is set to bridge the gap between what is now and what is aspired (e.g. Robèrt et al., 2002) as a basis for action.

In the illustration, the discussion among researchers, advisors and farmers first focused on making explicit how an agroecological system should function; the challenge was to not directly focus on the practices but identify the main ecological processes underpinning the system functioning (Nicholls & Altieri, 2018). Connections between system functioning and management were identified by combining generic ecological knowledge and contextual knowledge and answering questions such as: how should the system function? How is it functioning? Why and how do management practices affect the system's functioning? Going from abstract, generic knowledge to contextual knowledge created common ground to question what the farmers were doing concerning the consequences of current management practices, which helped identify transition strategies adequate for each farm.

The farmers considered the first version of the framework that the researchers presented relevant to assessing an agroecological system. They also suggested new elements that were included in the final version. For example, related to the commercialization strategies: *"Maybe it is possible to reflect somehow the type of power that we have in the commercialization of our products, for example considering the closeness with the consumers"* (farmer of Farm 3 during the first meeting). Related to how to assess input and technology dependency: *"It is not enough to assess input/output. It is not the same to buy seeds from your neighbour or an international company, or to buy compost produced with residues from the region and a local company than bio-fertilizers from Europe, or to use an entomopathogenic fungus from a local farmers organization or an international company, for example [...] the dependency is completely different. Also, maybe having local dependency should be valued as a good thing"* (farmer of Farm 1 during the first meeting).

In this study, we conceived the framework as a means, not a result *per se* (de Olde et al., 2018). In comparison to other experiences applying agroecological diagnosis frameworks thought for rapid and easy assessments (e.g. Mottet et al., 2020; Nicholls et al., 2020), this framework was developed to be used in the context of a co-innovation process in which dedicating time to generate awareness trust among participant actors is essential for generating appropriate conditions enabling joint learning processes (Albicette et al., 2017; Darnhofer, 2015; Dogliotti et al., 2014; Hoffecker, 2021; Krzywoszynska, 2019; Rossing et al., 2021). In addition, the indicators are the frameworks' core in previous diagnosis frameworks (e.g. Mottet et al., 2020; Nicholls et al., 2020). Such looking for "the best indicators" is a very disruptive process (de Olde et al., 2017). People have different ways of assessing reliable knowledge, making it extremely difficult and conflicting to consider this plurality of views and generate maximum collaboration and trust amongst stakeholders. In the discussion guided by the proposed framework, the indicators were not relevant by themselves but in relation to their role in assessing the processes. Thus, the discussion around the indicators took second place, where there was opinion exchange but not hard disputes. In addition, discussing the indicators within this framework made all participants focus on the desirable system and not lose sight of the "slow responding" variables (e.g. SOC, soil nutrient stocks, weed diversity, or pest and diseases incidence) that would probably not experience any measurable change within the 2-year time frame of the project but were essential to assess system functioning.

From this experience, we identified some key elements to consider when applying the MEDITAE framework to promote learning and create consensus enabling redesign: i. Discuss the framework after building trust and a "common language" among participants (in our case, after developing the characterization phase); ii. Focus the discussion on the framework's core ideas (processes and desirable functioning), not the indicators, to promote learning about the main ecological processes and how management practices affect them, to follow with the indicators later; iii. Discuss and agree on the relevance and suitability of the framework (relevant system components and processes to consider) without presenting or calculating indicators helps to think broader and avoids participants being defensive; iv. Plan the discussion meetings considering the farmers' workload in the year and scheduling meetings to leave enough time between sessions for the participant families to think and discuss; v. Use "boundary objects" (Klerkx et al., 2010) to support the joint reflection, represent current situations and visualize desirable ones, such as the diagrams that we ended up using in this case (Fig. 5.2) or serious games (Jouan et al., 2021; Stanitsas et al., 2019).

5.4.3. The capacity of the framework to support agroecological transitions

The MEDITAE framework was developed as a tool to support change towards agroecology-based systems in a co-innovation project. The added value is the way of structuring the analysis jointly with relevant actors, from socio-ecological processes and their desirable functioning to characterizing process performance and evaluating management practices. These characteristics, starting from generic system processes and subsequently contextualizing together with relevant actors, afford the transportability of the framework to novel regions or production systems.

Our research team is determined to continue engaging with farmers, extension agents and other actors in co-innovation projects to produce actionable knowledge towards sustainable agricultural production systems. We have been developing and applying our own version of the co-innovation approach for a while, but it is still far from "perfect" or "finished". As time evolves, farmers and researchers evolve, and from every experience, we learn, and new feedbacks contribute to improving this tool. The work of Albicette et al. (2017) and Rossing et al. (2021) evidence the potential of working on co-innovation not only focusing on the farm level but involving the organizations and institutions at a regional level. In this chapter, we developed and tried a tool to help better develop the process at the farm level with farmers willing to transition to agroecology.

While the work presented in this Chapter is focused on the farm-level analysis and working between researchers, farmers and their technical advisors, the MEDITAE framework could also support the transition process with other actors and in other contexts. For example, it could be used to inform public policies promoting agroecological transitions, such as the policies related to the National Agroecology Plan in Uruguay (CHPNA, 2021). The framework could be used by technical advisors working in the context of public extension and development projects promoting agroecological systems, and it could contribute a holistic view to the national agroecology certification system. The framework can contribute to the training of agronomy students. For example, it could be used for promoting conceptual discussion around the socio-ecological processes and in practical work on agroecological farm system analysis and design courses. The framework could also be used to frame new research. The experience presented in this Chapter helped identify relevant topics where there is a need for actionable knowledge to support agroecological transition processes. For example, concerning alternatives to manage crop nutrition in organic systems or assess, design and manage seminatural areas and crop mixtures to enhance their ecological function. In this context, the framework itself could help to position (inter)disciplinary research in a broader farm system context.

Finally, the MEDITAE framework could be enriched by, as well as enriching other proposed approaches to working towards sustainability. For example, an early and deep involvement of other actors in the food system discussing the farm system (e.g. other farmers of their organizations and neighbours, other technical advisors, consumers, intermediaries, students, researchers and technicians from public institutions) would reduce the need for trade-offs, stimulate uptake and support agroecological transitions (e.g. Elzen & Bos, 2016). In addition, the framework could guide the discussion in transition management at the territorial or landscape scale, discussing and analysing the six socio-ecological processes but connecting farm-level analysis with the landscape-level analysis (e.g. Duru et al., 2015). Thus, the framework may contribute to coordinated transition processes within farming systems, supply chains and natural resource management.

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Appendix 5

A5.1. Description and calculation of performance and practice-bases indicators per process.

Table A5.1. Performance indicators per process and method for calculation.

Process	Performance indicators	Calculations and references
Nutrient cycling	System-level macronutrient balances (N, P, K kg (cultivated ha)$^{-1}$ year^{-1})	N, P, K outputs – N, P, K input (Gysi and Schwaninger, 2000; Hedlund et al., 2003, Ciampitti and García, 2012).
	Macronutrient balance of main crops (N, P, K kg ha^{-1})	N, P, K harvested – N, P, K input (Scarlato et al., 2022).
	Input macronutrient use efficiency (kg product (kg nutrient)$^{-1}$)	kg harvested product/ (N+P+K input) (Hedlund et al., 2003)
	Level of biological N fixation	kg BNF / total kg N input. BNF estimated based on area of legume crops and bibliography according to plant species.
	Soil P, K, Na, Ca/Mg, Mg/K	Available P (ppm, Bray & Kurtz, 1945), exchangeable K, Na, Ca, Mg (meq 100g^{-1}, Isaac & Kerber, 1971)
	Soil pH and EC	pH and EC (1:2.5 soil:water and soil:KCl ratio)
	Nutrient deficiency problems (scale: 1-low to 4-high)	Frequency of occurrence of visible symptoms: 1: no symptoms, 2: not every year in some crops, 3: every year in some main crops, 4: every year in all main crops
	Soil erosion (scale: 1-low to 4-high) [a]	1: no visual signs, 2: local and light, 3: local and severe, or wide-spread and light, 4: wide-spread and severe.
Carbon cycling	Soil Organic Carbon (SOC) [a]	Based on soil analysis of cultivated land. When previous analysis available, determine trajectory (increasing – reducing or maintaining levels).
	Relative Active SOC (RASOC, %) [a]	Actual mineralisable SOC/ Original mineralisable SOC * 100 (Dogliotti et al. 2014). Soil texture (Forsythe 1975) and SOC analysis (Nelson & Sommers,1996).
	Relative topsoil depth	cm (in relation to "original" or pristine for the region and type of soil)
	Annual SOC balance (Mg SOC ha^{-1} year^{-1})	Estimated by C input (green manure+pastures+organic amendments+crop residues) and C output (harvest, mineralization) in a representative field or greenhouse based on the last four years. When possible, using empirical model for the region (Alliaume et al., 2013)
	Soil erosion risk (Mg soil ha^{-1} year^{-1}) [a]	USLE-RUSLE (Dogliotti et al., 2014)
	Soil erosion (scale: 1-low to 4-high)	1: no visual signs, 2: local and light, 3: local and severe, or wide-spread and light, 4: wide-spread and severe.
Plant succession and biotic regulation	Incidence of problematic pests (scale: 1-low, to 4-high)	Frequency of problematic pests (requiring specific control or affecting crop yield or quality): 1: no occurrence, 2: not every year in some main crops, 3: every year in some main crops, 4: every year in all main crops
	Incidence of problematic diseases (scale: 1-low, to 4-high)	Frequency of problematic diseases (requiring specific control or affecting crop yield or quality): 1: no occurrence, 2: not every year in some main crops, 3: every year in some main crops, 4: every year in all main crops.
	Weed diversity (number)	Number of weed species in main crops. Scale: <5, 5-10, 10-15, 15-20, >20.
	Incidence of problematic weeds (number of species)	Problematic weeds: perennial or annual with high initial growth rate, high multiplication rates and diverse mechanisms, resistant mechanisms, present in more than 20% of cultivated fields.
	Weed cover or biomass in main crops	One month after installation and at harvest (Scarlato et al., under review)
	Pest/natural enemy ratio in main crops	One month after installation and at harvest (Scarlato et al., 2023).
	Soil biological activity	e.g. respiration

Table A5.1 (cont). Performance indicators per process and method for calculation.

Process	Performance indicators	Calculations and references
Water cycling	Topsoil water retention at field capacity (FC)	mm/10cm
	Relative water retention at field capacity (%)	Actual water retention capacity / Water retention capacity at original soil organic matter content * 100. Estimated based on soil texture and organic matter analysis (Silva et al. 1988) and the soil type's original level of organic matter (Durán, 1985).
	Water retention at field capacity in the rooted zone (mm)	mm in layer A+B of the soil profile. Estimate based on soil texture and organic matter analysis (Silva et al. 1988)
	Water storage capacity per year (m^3)	
	Water quality (scale: 1-good to 3-bad)	Scale according to chemical and/or biological restrictions for production: 1: no problem, 1: <50% sources with restrictions, 2: 50-75% sources with restrictions, 3: >75% with restrictions.
	Soil erosion (scale: 1-low to 4-high)	1: no visual signs, 2: local and light, 3: local and severe, or wide-spread and light, 4: wide-spread and severe.
Energy flow	Food production of the system	Mg food ha total^{-1} year^{-1}
	Food production from cultivated land (Mg food (ha cultivated)$^{-1}$year^{-1})	Marketable production per ha cultivated
	Actual yield/attainable yield of main crops for the region	Dogliotti et al., 2014; Dogliotti et al., 2021; Berrueta et al. 2019; Colnago et al., 2023
	Proportion of harvested area in planted area	Harvested area / planted area
	Classical Energy Balance	E product – E inputs (Hercher-Pasteur et al., 2020)
	Energy use efficiency	E input / E products (Hercher-Pasteur et al., 2020)
	Agroecological Energy Balance (AEB)	Guzmán & González de Molina, 2015; Hercher-Pasteur et al., 2020
Socio-Economic and cultural	Relative family income (FI) per capita per month (-)	Family income per capita per month / average family income per capita per month in rural areas (Statistics National Institute) (Colnago et al., 2021; Dogliotti et al., 2014)
	Relative family income per hour (-)	Family income per h ourfamily work / labour opportunity cost in the region (Colnago et al., 2021)
	Farm Labour productivity (U$S) [a]	Net return/total labour (Colnago et al., 2021)
	Labour productivity / hired workers salary	Labour productivity per hour / hired workers salary per hour
	Income diversification among crops	number of crops explaining 50% income
	Financial input/output relation	Colnago et al., 2021; Dogliotti et al., 2014
	Number of people potentially fed per year	kg food year^{-1} / 0.4*365 (WHO: 400 g of fresh vegetables per person per day)
	FTE / cultivated area	Full-time equivalent / ha cultivated
	Family FTE / total FTE	Family full-time equivalent / Total full-time equivalent
	Price obtained/price market	Average price obtained / price of the wholesale market. Estimated per month and for main crops.
	Family farms workload (scale: 1-5)	1-bad to 5-good. 5: 8 hours/day, free weekends, 4: 8 hours/day, 1.5 days free on weekends, 3: >8 hours/day, free on weekends, 2: >8 hours/day, 1.5 days free on weekends, 1: >8 hours/day, less than 0.5 days free on weekends.
	Hired workers workload (scale:1-5)	1-bad to 5-good.
	Family farms holidays (scale: 1-5)	1-bad to 5-good. 1: at least 1 day per month, 2: 2 to 4 days per month, 3: at least 1 week per year, 4: at least 1 day per month and 1 week per year, 5: 2 to 4 days per month and more than 1 week per year (Dogliotti et al., 2014).
	Hired workers holidays (scale: 1-5)	1-bad to 5-good
	Health problems (scale: 1-5)	1-bad to 5-good. 1: at least one chronic problem without treatment, 2: at least one chronic problem under treatment, 3: more than one specific problem per year and solved, 4: one problem per year, solved, 5: No problems (Dogliotti et al., 2014).
	House quality and basic services (scale: 1-5)	1-bad to 5-good. Sum of values per item: drinking water (1 yes, 0 no), electricity (1 yes, 0 no), overcrowding (1 parents and children separated and less than 3 pers/room, 0 other), house construction problems (1 no, 0 yes), quality of the surrounding area (1 good, 0 close to rubbish dumps, polluted drains, etc.).
	Generational succession (scale: 1-5)	1-no to 5-yes. 1: farmer over 50 and no successor, 2 farmer between 40 and 50 and no successor, 3 farmer between 40 and 50 successor with a low predisposition, or over 50 with successor medium predisposition, 4 farmer between 40 and 50, successor with an intermediate predisposition, 5 transition in progress or farmer less than 40.
	Life quality perception (scale: 1-5)	1-very dissatisfied, 2-somewhat dissatisfied, 3-satisfied, 4-very satisfied, 5-extremely satisfied

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Table A5.2. Practice-based indicators per process and method for calculation

Process	Practice-based indicators	Calculations and references
Nutrient cycling	Relative amount of organic fertiliser (%) and amount (Mg DM ha^{-1} $year^{-1}$)	Relative amounts of nutrients from organic sources, and amount of organic amendments (Mg DM ha^{-1} $year^{-1}$)
	Use of bio fertilizers	Classes: 1: No, 2: Yes, occasional, 3: Yes, every year all main crops
	Fertilization criteria (scale 1 to 3)	1: not considering soil and/or crop, i.e. calendar-based or routine; 2: considering crop requirements or soil status; 3: considering crop and soil
	Proportion of legumes in cultivated area	(ha legumes) $(ha\ cultivated)^{-1}$ $year^{-1}$
	Annual soil cover (0-low to 1-high)	Estimated averaging soil cover by semester. Values of cover: 1 high cover (GM or crops with high cover), 0.5 intermediate cover (crops with low cover), 0 low cover (bare soil, tilled soil).
	Proportion of green manure (GM) or pastures in cultivated area	(ha GM + pastures) $(ha\ cultivated)^{-1}$ $year^{-1}$
Carbon cycling	Soil use frequency ($year^{-1}$) [a]	Number of crops per field or greenhouse $year^{-1}$.
	Soil use intensity (-)	ha vegetables per ha cultivated area
	Annual soil cover (scale: 0-low to 1-high)	Estimated averaging soil cover by semester. Values of cover: 1 high cover (GM or crops with high cover), 0.5 intermediate cover (crops with low cover), 0 low cover (bare soil, tilled soil).
	Proportion of green manure or pastures in cultivated area (-)	(ha GM + pastures)per ha cultivated per year
	Amount of organic ammendments (Mg DM ha^{-1} $year^{-1}$)	Mg DM (cultivated ha^{-1}) $year^{-1}$
	Tillage frequency ($year^{-1}$)	Number of tillage interventions per field or greenhouse per year (Alliaume et al., 2013; typically: 4 to 8).
	Type of physical soil disturbance (scale: 0-low to 4-high)	0: no tillage, 1: tillage disturbance <5-10 cm, 2: tillage disturbance >10 cm and no inversion, 3: inversion tillage <25cm, 4: inversion tillage >25cm (Gaba et al., 2014).
Plant succession and biotic regulation	Activities diversification [a]	Number of activities (vegetables, livestock, hen-eggs, fruit trees, other).
	Crop rotation [a]	No rotation, rotation with number of years
	Crop families, species and varieties diversity	Number of crop families (F), species (S) and varieties (V) diversity.
	Number of species covering 75% of cultivated area	Number of species
	Varieties diversification in main crops	Number of varieties
	Crop seasonality	Ha summer vegetable crop area / ha winter vegetable crop area
	Number of crops in intercropping	Number of species in intercropping/total species.
	Area of crops in intercropping	Ha intercropping/ha total vegetable area
	Proportion of semi natural area in total area	Ha with more than 10 years without disturbance per ha. Animal grazing at low densities was not considered
	Proportion of semi natural area in cultivated area	Ha with more than 10 years without disturbance per ha cultivated area. Animal grazing at low densities was not considered
	Pest management criteria (scale: 1-4)	Scale based on prevalence of pesticide or cultural practices (quality of the seed, resistant/tolerant varieties, elimination of diseased plants, management of intercrop period, cleaning of implements, air circulation, crop rotation). Scale: 1. pesticide-based, calendar applications, 2. 2 or 3 practices, partial monitoring, still pesticide-based, 3. 4 or + practices, crop and risk conditions monitoring.
	Amount of active ingredient (ai) of synthetic pesticides used	g ia cultivated ha^{-1} $year^{-1}$
	Application of synthetic pesticides in main crop	Number of applications, g ai per ha
	Application of alternative products	Number of applications of botanicals / biologicals / other products

Table A5.2 (cont). Practice-based indicators per process and method for calculation

Process	Practice-based indicators	Calculations and references
Water cycling	Type of irrigation system	Drip or sprinkler, and in the case of sprinkler continuous or occasional
	Irrigated area/cultivated area [a]	ha with any type of irrigation / ha cultivated
	Type of water sources	Superficial or underground; natural or artificial
	Annual soil cover (0-low to 1-high)	Estimated averaging soil cover by semester. Values of cover: 1 high cover (GM or crops with high cover), 0.5 intermediate cover (crops with low cover), 0 low cover (bare soil, tilled soil).
	Irrigation management criteria	
Energy flow	Proportion of vegetable area in total area	Ha vegetables / ha total land
	Proportion of greenhouse vegetable area in cultivated area	Ha greenhouse vegetables / ha cultivated
	Annual soil cover (0-low to 1-high)	Estimated averaging soil cover by semester. Values of cover: 1 high cover (GM or crops with high cover), 0.5 intermediate cover (crops with low cover), 0 low cover (bare soil, tilled soil).
	Tillage frequency ($year^{-1}$)	Number of tillage interventions per field or greenhouse per year (Alliaume et al., 2013; typically: 4 to 8).
Socio-Economic and cultural	Seed origin (%)	Percentage of varieties from own propagation (O), locally bought (L), and imported (I)
	Cultivated area according to seed origin (%)	Percentage of cultivated area with own propagation (O), locally bought (L), and imported (I)
	Fertiliser origin (%)	Percentage per type: own (O), local (L), imported (I)
	Type of commercialization (%)	Direct (D), close intermediary (CI), far intermediary (FI). Direct: farmers to consumers, close intermediary: one intermediary between farmers and consumers, far intermediary: more than one intermediary between farmers and consumers.
	Commercial strategy diversification	Number of type of strategies
	Commercial channels diversification	Number of commercial channels
	Workers with social benefits (-)	Number of workers with social benefits/total number of workers
	Institutional networks	Number of institutional networks connected to
	Organization networks (number)	Number of organization networks connected to
	Level of participation (scale: 1-4)	Scale: 1. no active participation, 2. punctual participation in general spaces, 3. frequent participation (more than 4 times a year), 4. frequent participation and responsibilities.
	Equity in intra-family decision-making (-)	Number of family workers that decide / total family workers
	Farm records (scale: 1-4)	1-no records to 4-complete records and used for decision-making. Scale: 1. No, 2. Partial (production or economic) not for making decisions, 3. Partial and used for making decisions, 4. complete and used for making decisions.

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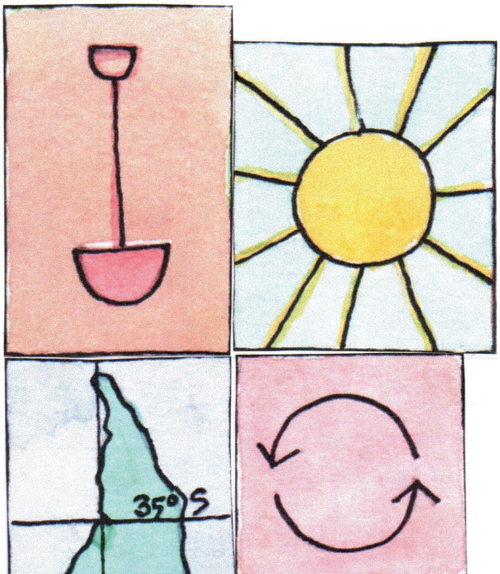

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56° O

Chapter 6

General discussion

6.1. Overview of the main findings

The general objective of this thesis was to generate actionable knowledge, which is contextualised knowledge to support decision-making and actions, to support the ecological intensification of vegetable production systems in Uruguay. I approached this main objective through the study of the efficacy of agrochemical inputs use in enhancing vegetable yields in main vegetable crops in Uruguay (Chapter 2), the development and testing of two technologies to reduce agrochemical input use while enhancing ecological processes based on habitat diversification and soil health (Chapter 3 and 4), and the development and application of a diagnosis framework to support agroecological transitions within co-innovation processes (Chapter 5). Figure 6.1. presents a graphical overview of the main findings.

The study in Chapter 2 showed that the relationships between pesticide and nutrient inputs and yield in main vegetable crops in Uruguay were generally weak or non-significant, indicating inefficiencies and overuse of inputs. Agronomic criteria or best management practices did not inform management of inputs, but instead, farmers relied on personal experience, tradition, or intuition. Thus, it often resulted in a "routine of doing" at the farm level consistent across fields and years, irrespective of the specific

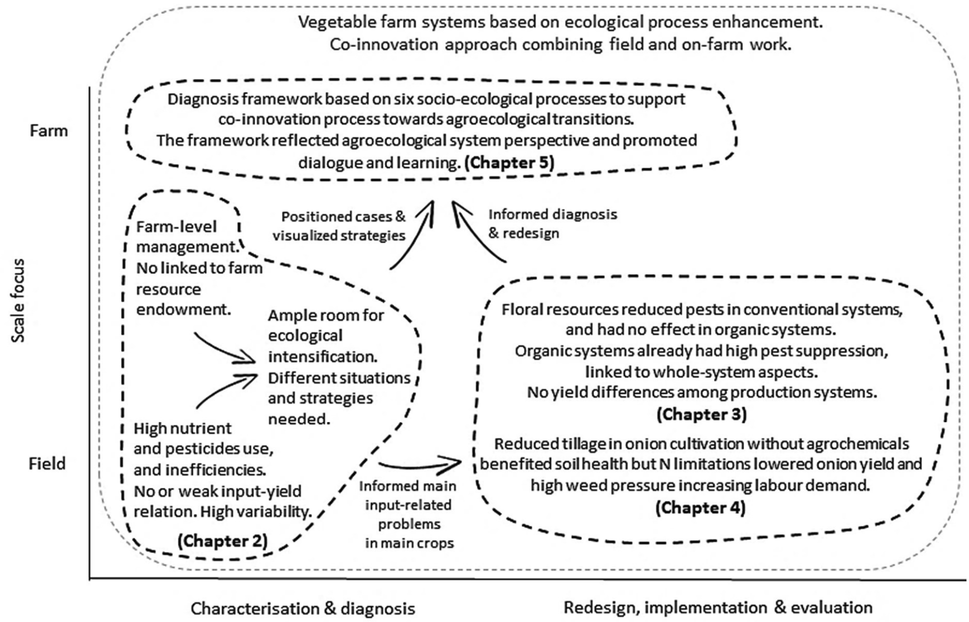

Fig. 6.1. Graphical overview of the main findings. Chapters are positioned based on the main spatial scale of application (from field to farm level) and the main phase in the co-innovation process (characterisation & diagnosis of current practices or redesign, implementation & evaluation).

crop growth conditions. The analysis also showed substantial variation in input use among crops, fields, and farms. We found that 21% of the fields and 17% of the farms achieved higher yields than average with lower input use than average and that neither input use nor yields were related to the farm resource endowment. Most farms needed to increase yields without increasing or reducing input use, while a smaller group needed to reduce input use while maintaining yields. These findings indicate that while there is ample room for reducing agrochemical use without reducing yields, there is no universal solution. Different strategies for ecological intensification according to each specific situation are needed. A detailed diagnosis, systemic redesign at the crop and farm level, and the generation of local context-specific knowledge and technologies involving farmers to enhance ecologisation are required.

In Chapters 3 and 4, we developed and tested two alternatives for reducing the reliance on agrochemical inputs based on promoting ecological processes. The alternatives included improving soil quality by reducing tillage and organic mulching and enhancing functional biodiversity by introducing flowering plants. The exchange with farmers and their technical advisors during a first workshop in December 2017 informed the definition of these alternatives. In Chapter 3, we focused on assessing the effect of introducing floral resources to enhance biological pest control in greenhouse tomato, the main greenhouse crop in Uruguay. Greenhouse tomato production relies heavily on insecticides for pest control. We found that the effect of introducing flowering plants on arthropods depended on the type of farm management. The increase in floral resources in conventional systems lowered pest abundance but did not significantly influence pest abundance in organic systems. While organic farms had yields comparable to conventional farms, they had fewer pests, less pest injury, and a higher abundance of natural enemies. Chapter 4 focused on onion, a major open-field crop associated with high soil degradation and erosion risks, which heavily relies on herbicides for weed control. We found that reduced tillage in onion cultivation without agrochemicals reduced soil erosion risk, increased soil biological activity and did not negatively impact soil physical conditions for onions. However, it resulted in N limitations that lowered onion yield and in high weed pressure that increased labour demand. The nitrogen limitation and weed pressure varied among the three experimental sites.

Chapters 2 to 4 highlighted the need for working at the farm level, starting from a detailed diagnosis of the farm system and actively involving farmers (Chapter 2) and the context-dependency of the results of the technologies implemented (Chapters 3 and 4). The results depended on how the technology was effectively translated into practice (e.g. the green manure biomass quantity and quality in each experimental site in Chapter 4) and the application context (e.g. organic vs conventional farm management in tomato greenhouses in Chapter 3). Consequently, management practices should not be conceived as sole measures but as complementary to other technologies integrated at the farm level to transition towards ecologically intensive systems. In Chapter 5, we focused on the whole farm system level, actively involving farmers in developing a framework to support the farm diagnosis and redesign of vegetable farm systems to support agroecological transitions within co-innovation processes.

The MEDITAE framework presented in Chapter 5 is based on six socio-ecological processes underlying agroecosystems' functioning: nutrient cycling, carbon cycling, plant succession and biotic regulation, water cycling, energy flow, and socio-economic and cultural processes. It identifies the main components of each process and their connections to the others and characterizes their desirable quality and functioning in a farm system based on agroecology principles. Indicators to address the processes' performance and management practices were associated with each process. The framework contributed to achieving an agroecological perspective on farm system diagnosis and the ensuing redesign during the co-innovation work. It raised awareness, promoted learning and created a consensus among the research team, the farmers, and the technical advisors during the co-innovation work.

This chapter aims to bring together and discuss the main findings and extract overarching conclusions placed in context by (i) analysing opportunities for ecological intensification in vegetable production in Uruguay, (ii) discussing strategies for ecological intensification of production systems and (iv) discussing how research can support this process, and (v) reflecting on the implications of having worked under both ecological intensification and agroecology concepts, then, (vi) discussing the potential of working beyond the farm system level, and, finally, (vii) discussing the implications of the thesis for future research for contributing to the transition of farm systems towards ecological intensification.

6.2. Opportunities for ecological intensification in vegetable production in Uruguay

The opportunities for and the specific needs of ecological intensification are context-dependent. From an ecological intensification perspective, current inequalities in terms of resource levels (assets, labour and external inputs) and current levels of attainable productivity and food demand differ widely worldwide, generating differences between regions for the need to increase food production or reduce input use (Tittonell et al., 2016; Tittonell, 2013). What is the situation in Uruguay regarding fresh vegetable supply? What is the environmental and social impact of vegetable production in current production systems in Uruguay?

To answer these two questions, I focus on how much vegetable food is supplied in the local market and how local vegetable production systems are producing this food. In Uruguay, more than 90% of the fresh vegetable consumption is locally produced by family farmers, and approximately 90% of vegetable production is sold on local fresh markets (Ackermann & Díaz, 2016). There is a per capita consumption of fresh vegetables and fruit (excluding potatoes and sweet potatoes) of 289 g day^{-1} (Zoppolo & Colnago, 2021). This amount is far from the World Health Organisation's recommendation of 400 g day^{-1} and points to the need for increasing vegetable availability and affordability while promoting vegetable consumption. Despite a lack of precise information, overall vegetable and fruit loss or waste is considerable (Giménez et al., 2022). For example, in potatoes, waste is estimated to be around 30-40% of the country's total supply for human consumption (Lema et al., 2017). Around 30% of this loss is related to farm-level production and post-harvest stages, while 28% is related to distribution and household losses (Lema et al., 2017). Thus, increasing vegetable availability requires reducing these food losses. On the other hand, crop yield gaps average 50% and most farms have low family income and labour productivity, excessive workload and work-related health problems, great erosion rates and soil degradation (Alliaume et al., 2013; Berrueta et al., 2019; Colnago & Dogliotti, 2020; Colnago et al., 2023; Dogliotti et al., 2014; Dogliotti et al., 2021; García De Souza et al., 2011; Scarlato et al., 2017), and high use of agrochemicals (Chapter 2). Consequently, increasing the quantity and quality of vegetables for the population does not require increasing the cultivated area. Still, it necessitates transformations in the production systems to reduce yield gaps and on-farm losses while reducing environmental and social impacts (Zoppolo & Colnago, 2021). Therefore, Uruguay needs ecological intensification: increasing quality vegetable production while reducing input and resource use and minimising environmental impacts.

The results in Chapters 2 and 3 reveal ample scope for this transition. For instance, yield levels are not related to input levels in major vegetable crops, and overall, yield could be doubled while reducing nutrient and pesticide inputs by half (Chapter 2). Moreover, outstanding examples of farms achieving high yields with low input use were identified for all the main crops, and these outstanding performances were not related to farm resource endowment but to farm organisation and management (Chapter 2). Chapter 3 evidenced the potential of organic agroecology-based production systems, achieving greenhouse tomato yields similar to conventional farms but without agrochemicals and at lower nutrient input levels. These studies, in conjunction with previous ones (Berrueta et al., 2019; Colnago et al., 2023; Dogliotti et al., 2014), show that even with current farm resources and knowledge, there is scope for ecological intensification in Uruguayan vegetable production.

Despite the overall need and scope for ecological intensification, each farm may have different strategies and room for ecological intensification. Farmers face different realities, where they may or may not need to increase yields or production area and reduce inputs and resources used. Farmers make their crop and farm management decisions within the realm of their production situations, i.e., the physical, biological, technical, social, and economic context in which production occurs (Savary et al., 2006), and their decisions, in turn, shape their production situations. In addition, although almost all situations can be improved (Chapters 2, 3 and 5), sometimes, the context is so restrictive that the options are very limited. The room for improvement may be limited by the current resource availability (Colnago et al., 2021; Dogliotti et al., 2006). For instance, in Farm 2 of Chapter 5, the available land area (2.2 ha) would not allow the generation of sufficient income for the family that depends on the farm. In addition, there may be limitations related to the regional or landscape-level context. For example, the agroecological transition of Farm 2 in Chapter 5 was limited by pest migration and pesticide drift from the surrounding conventionally managed farms. Farm 2 cannot be certified as organic due to this problem. Thus, the current situation, the desirable or possible situation, and the way to move from one to the other will be specific to each farm.

6.3. Strategies for ecological intensification of production systems

The transition toward an agroecology-based production system could be conceptualised at different levels (Gliessman et al., 2007; Hill & MacRae, 1992). These levels are not necessarily sequential, absolute, exclusive, or all necessary in every case (Gliessman et al., 2007; Lamine & Bellon, 2008; Tittonell, 2020). During the co-innovation process described in Chapter 5, we encountered cases that matched the different transition levels to agroecology (Gliessman et al., 2007; Hill & MacRae, 1992). For example, Farm 5 (conventional) could be placed in Level 1, increasing conventional input use efficiency. Farm 5 reduced input use by adjusting fertilisers and pesticide application timing, rotating active ingredients, and reducing the number of products per application. Farm 2 (conventional) could be placed in Level 2, substituting conventional inputs and practices for more sustainable ones. They used biological control tools (e.g. introduction of predator and pheromone traps), biological and organic products (e.g. entomopathogenic fungi and milk), increasing organic amendments and reducing chemical fertilisers. Farms 1 and 3 (organic) could be placed somewhere in between Levels 2 and 3, as they redesigned the production system to enhance ecological processes (Level 3, e.g. crop diversification) but have strong weaknesses related to ecological processes (e.g. nutrient cycling or energy flux) and also relied on the use of alternative inputs. Farm 4 (organic) could be placed in Level 3 as it relied on crop rotation and did not use any alternative product. Despite the differences among farms, all farmers were, to some extent transitioning towards a change in ethics and values (Level 4). All farmers were aware of and wanted to minimize environmental impact, and organic farmers were actively involved in promoting fair links between farmers and with consumers. Thus, while the degree of agroecology conceptualisation certainly helps outline the transition strategy, real cases often lie between the levels.

In the last decades, the development, access and use of biological and organic inputs, such as those based on entomopathogenic fungi, predators and parasitoids, increased (Bajsa et al., 2023; Barbazán et al., 2011; Basso et al., 2020; Lassevich et al., 2021; van Lenteren et al., 2020; van Lenteren et al., 2018). This tendency could contribute to the "ecologisation" of vegetable production, reducing synthetic pesticide and fertiliser use while maintaining yields (Level 2). However, neither the efficiency increase nor the substitution strategies (Levels 1 and 2) address the underlying causes of the problems of many farming systems. Consequently, they make farmers constantly rely on externally derived curative solutions and inputs (Hill & MacRae, 1992; Rosset et al., 1997). For example, the main causes of current yield gaps in vegetable production in Uruguay are not input-related but revolve around the choice of planting dates and planting density, the timing of several management operations, soil organic matter content, and frequency and sequence of crops in the rotation (Berrueta et al., 2019; Dogliotti et al., 2021; Scarlato et al., 2017). Another example is pest management, where Level 1 and 2 solutions can help reduce pest problems at a given time. Still, a much broader approach, such as crop diversification and rotation, is needed to promote natural regulation to prevent pest problems in the long run (Bianchi, 2022; Deguine et al., 2021; Nicholls et al., 2016). Both examples, yield gaps and pest regulation, are usually studied at the crop or field level, but their root causes originate at the farm and landscape level. Thus, the transition towards ecologically intensive or agroecological systems requires, at some (early!) point, going beyond Levels 1 and 2 and embarking on the redesign of the farm system as a whole (Dogliotti et al., 2014; Hill & MacRae, 1992; Lamine & Bellon, 2008; Nicholls & Altieri, 2018).

Farm system redesign is impossible without diagnosing the current farm system and defining the "desired future" or aims of the redesign (de Olde et al., 2018). Thus, the transition process based on step-by-step farm system redesign already starts before implementing changes in the production system when defining how the system is seen. The methods and tools to guide the diagnosis strongly influence how the production system is framed (de Olde et al., 2017; Eichler Inwood et al., 2018). The MEDITAE diagnosis framework developed in Chapter 5 integrates why and how ecological processes and farm performance are connected to management. The framework used in a participatory process contributed to a profound and shared diagnosis of the farm system from an agroecological perspective as a first and crucial step to support the transition to agroecology. At the same time, the diagnosis framework contributed to defining a desirable farm system future and visualising the existing room for improvement, setting the basis to build a feasible farm system redesign plan.

In redesigning the case-study vegetable farms (Chapter 5), the challenge was to include short and mid-term actions within a long-term plan and combined crop-specific management practices as part of more strategic farm system changes (adjusting the production plan and planning crop rotations) while improving or maintaining the family income. Short and mid-term actions may include technologies to increase input use efficiency and substitute conventional input for more sustainable ones (Levels 1 and 2), but not as the main or isolated changes. As shown in Chapter 5, the MEDITAE diagnosis framework may also help develop the redesign as it connects farm performance with management practices. Thus, it contributes to identifying practices that may explain the current situation and that could be improved in the long term. The framework can integrate those multiple management practices in the long-term and whole-farm strategy focusing on enhancing ecological processes.

Management practices to enhance soil quality and functional biodiversity over time and space are the crucial aspects of whole-farm system redesign, as they mediate the ecological processes underlying system functioning, such as nutrient, carbon and water cycling, biotic regulation, and energy flux (Nicholls et al., 2016). In this thesis, the experiments on introducing flowers in greenhouses and cover crop/reduce-tillage systems (Chapters 3 and 4) generated valuable, actionable knowledge on specific practices that could be included in a redesign strategy. For example, including floral resources (Chapter 3) add new components to the system (increasing diversity) to enhance "functional" relationships among the system components, such as biological control or pollination. Cover crops with reduced tillage (Chapter 4) have multiple benefits and are essential components in agroecological systems. However, its implementation requires a whole-farm plan, particularly in organic systems where specific challenges related to killing the green manure and dealing with nitrogen immobilization and weeds exist. While flowers and cover crop/reduced tillage technologies were tested in the experiments as specific management practices, they changed the system components and functioning, modulating multiple ecological processes (Level 3). Consequently, whole farm system redesign enables their use while determining their effectiveness.

As is shown in this thesis, although there is already knowledge to improve production systems, new questions have also emerged. For instance, how to improve crop nutrition based on soil organic matter management and organic amendment dynamics? Or, how to design and manage crop diversity and soil microbiome diversity to promote natural pest regulation? Thus, evidence that the lack of local knowledge to translate biodiversity and soil health enhancement into concrete designs and context-specific management practices still challenges the scaling of agroecology (Duru et al., 2015; Nicholls & Altieri, 2018).

6.4. How can research support the ecological intensification of production systems?

The overarching aim of this PhD thesis was to generate actionable knowledge to promote change, which makes the question of *what to do* intertwined with *how to do* it. Defining actionable knowledge as context-specific knowledge that assists decision-making and consequent actions of stakeholders (Clark et al., 2016; Geertsema et al., 2016), the promotion of learning processes involving all actors around a problem while generating this actionable knowledge is essential to engage in and support ecological intensification (Rossing et al., 2021). Within this aim, credibility, salience and legitimacy are key to effectively connecting knowledge with action and change (Cash et al., 2003) by enabling the learning processes of all actors involved (van Mierlo et al., 2020). The co-innovation approach, based on complex adaptive systems thinking, social learning, and monitoring and evaluation, helped to engage actors in co-creating actionable knowledge (Rossing et al., 2021). During the various studies presented in this thesis, particular attention was paid to transparency about the background concepts, hypothesis, objectives and methods. For instance, we discussed with farmers and technical advisers the biophysical hypotheses underlying management practices tested in Chapters 3 and 4 or the diagnosis framework developed in Chapter 5. Furthermore, we actively promoted the participation and involvement of other researchers, farmers and technical advisors by considering their needs, motivations and feedback. Together, this helped generate actionable knowledge (de Olde et al., 2018).

We combined multiple strategies to promote the active involvement of participants. To involve other researchers, co-authors of thesis chapters, we started by taking a comprehensive and systemic view of each research problem where each researcher could identify a comfortable place to contribute and build a common vision. We regularly met to define, monitor, and discuss the research results. Farmers and technical advisors were engaged by participating in a first workshop where knowledge needs for supporting ecological intensification were discussed and prioritised to inform this thesis. After that, they participated through different mechanisms: experimentation in experimental stations and on-farm experimentation, creating a project support group to collectively monitor the experiments, on-farm co-innovation, workshops and field days. The thesis' final result emerged from the participants' active contributions. For instance, in Chapter 3, farmers suggested increasing flower islands' density and measuring other than the proposed variables. In Chapter 4, they suggested adjusting sowing dates and residue management. The invited researchers suggested adding new variables related to soil biological activity to understand better the underlying mechanisms explaining the results. In Chapter 5, farmers suggested including or emphasising specific dimensions of the diagnosis framework. Moreover, in addition to the specific practical knowledge, the participatory approach generated a shared meaning and perceptions of what is worthwhile doing (Darnhofer, 2015; Hoffecker, 2021; Krzywoszynska, 2019). It helped to collectively visualise what we did not yet know about the system's functioning and to identify new questions for the research agenda to inform the farm redesign.

6.5. Ecological intensification or agroecological transitions?

While there are many concepts revolving around the sustainability of agriculture today (Migliorini & Wezel, 2017; Petersen & Snapp, 2015; Sachet et al., 2021; Struik & Kuyper, 2017; Tittonell, 2014; Wezel et al., 2014), in the thesis, we consciously used both ecological intensification and agroecology concepts. Ecological intensification focuses primarily on the biophysical and ecological dimension of agricultural systems (Tittonell, 2014), while agroecology, in addition to involving a way of farming, also questions social relations, equity and power distribution, knowledge generation and technological dependency (Giraldo & Rosset, 2018; Wezel et al., 2009). At the production level, both agroecology and ecological intensification aim to maintain or increase production by enhancing ecological processes, such as carbon, nutrient and water cycling, energy flow, and biotic regulation, reducing the use of external inputs and minimising negative impacts on the environment and society (Nicholls et al., 2016; Tittonell, 2014).

This thesis focused on the technological and biophysical aspects of production systems. Thus, the principles developed in this thesis can inform transitions of different vegetable farms, going for full agroecological systems or ecological intensification but still using some chemical inputs or staying within the conventional markets. As discussed in section 6.4., we consciously defined a methodological approach with a system perspective, direct and active participation of local actors allowing room to co-steer the research, and the inter- and transdisciplinarity. These methodological aspects are not exclusive but are highlighted by agroecology (Méndez et al., 2013; Sachet et al., 2021). The method used in this thesis might have contributed to promoting changes not only in practices but in ethics and values (Gliessman et al., 2007) and in building self-reliant individuals and communities regarding knowledge, technologies and resources (Altieri, 1999). However, we did not deal with power relations and benefit distribution.

In Uruguay, vegetable farms are mainly "conventional" family farms. Some farmers want to transition towards agroecology, but most want to become more sustainable but not necessarily agroecological. In addition, "agroecology" is perceived as too far from their reality for many conventional farms. For many agroecological farmers, on the other hand, talking about "agroecology" while focusing only on the biophysical aspect of the production system would be perceived as stripping the concept of its essence. Taking these considerations into account and being the focus of this thesis, the biophysical and technological aspects of vegetable production systems, using both ecological intensification and agroecology concepts, helped us to interact and dialogue with both "agroecological" and "conventional" farmers, technical advisors and farmers' organisations. It was a learning experience that can help in future work, highlighting the wide working space that using both concepts gave and the need to be explicit about what we want and mean when engaging diverse actors in co-creation and change processes.

6.6. A transition beyond the farm system level?

There is often ample room for improving farm sustainability by working within farm boundaries, and this was the focus of this thesis (section 6.2). However, it is also true that there is a greater potential for improvement if coordinated actions beyond farm limits could accompany individual farmers' actions. In addition, in some cases, the constraints at the farm level are so limiting that actions beyond the farm level are needed to move forward, such as in the case of Farm 2 (Chapter 5) mentioned in section 6.2.

Since many ecological processes operate at a spatial scale exceeding the farm scale, ecological intensification requires regional and collective rather than individual actions (Renting et al., 2009; Tittonell et al., 2016). A clear example is the case of arthropod dynamics and pest management. Using insecticides on a field may influence pest-natural enemy interactions in neighbouring farms. Thus, a farmer's choice directly affects the possibilities of another farm (Bell et al., 2016). Establishing non-cultivated areas or flowering strips on a farm would affect neighbouring fields beyond the limits of the farm. The landscape context results from integrating all farmers' management, which determines the landscape dynamics (Petit et al., 2020) and modulates the effectiveness of different diversification strategies (Tscharntke et al., 2012). This calls for collective agreements and actions at the landscape level to enhance ecological processes.

In addition, transition in the production system cannot take place in isolation from transformations in the food system as a whole. The food system can be conceptualised as three interrelated components: the agricultural production system, the value chain, and the support structures (support of the innovation and everyday functioning of agricultural production systems and value chains), which are influenced by the socio-technical landscape (Gaitán-Cremaschi et al., 2019). For example, the consumers and intermediaries shape the demand for vegetable food in terms of diversity, quality, seasonality, and volume, which determines whether there is scope for the diversification of production systems (Meynard et al., 2017). Case study Farms 2 and 5 in Chapter 5 were limited in changing crop diversity because the intermediaries specialised in a few specific crops. Public policies can help overcome farm resource limitations (e.g. case study Farm 2 in Chapter 5, limited in land area and water quality) or generate policies and regulations to support and incentivise transitions (e.g. land use and pesticide use). Involving other actors of the food system, such as policymakers, farmer's organizations, extensionists, intermediaries, and consumers, in the discussion at the production system level, and the actors from the production system in the discussion of higher levels of the food system may help to reduce the need for trade-offs, facilitating and stimulating the transition (Elzen et al., 2012). However, the political viability of such a broader social transformation lies in the capacity to create organisations and movements that politicise farmers (and society in general) and respond to local demands (Van den Berg et al., 2022).

Farmers' organisations, as part of a broader social movement, may play a crucial role in facilitating or counteracting ecological intensification transitions (Groot-Kormelinck et al., 2022; Van den Berg et al., 2022). Farmers' organisations play multiple socio-cultural and production-related functions, for example, by sharing experiences and knowledge, facilitating services and input access, facilitating public policy access (Groot-Kormelinck et al., 2022; Rondot & Collion, 2001). Thus, continuing to deepen the involvement of farmers in farmers' organisations can benefit the transition of a particular farm and help scale up and engage other farmers in ecological intensification. But not only do the immediate effects of collective strategies count, but also, essentially, the longer-term building of the capacity of movement (Van den Berg et al., 2022). Social movements involving farmers' organisations and other social actors (e.g. NGOs, academia, and consumer organisations) can influence the value chain or the food system´s support structures (Gaitán-Cremaschi et al., 2019). For example, generating new commercial alternatives or certification processes such as the experience with the participatory certification or creating commercial strategies promoting closer relationships between farmers and consumers in Uruguay (Groot-Kormelinck et al., 2022). This movement may also be relevant in demanding public policies on extension, research, food access, production subsidies and land use planning to promote the transformation of the food system. For example, this was the case with the National Agroecology Plan in Uruguay (CHPNA, 2021),

6.7. Concluding remarks and implications for future research

In this study, I contributed to generating actionable knowledge to support ecological intensification processes to counteract the intensive industrial agriculture model's negative environmental and social impacts. I diagnosed agrochemical use and its relationship with yields in vegetable production in south Uruguay, which allowed me to identify opportunities for change. I tested specific technological alternatives that can be used in local conditions. I generated a diagnosis framework to support farm characterization, diagnosis and redesign during co-innovation towards agroecology-based farm systems. Now, in the end, putting this work into perspective, how can this knowledge be useful for other situations and contribute to the design of future research?

I identify specific biophysical-technological and methodological knowledge that could inform other realities and future research. The comprehensive research approach applied in the technological research in Chapters 3 and 4 allowed us to assess not only the result of the technologies in a certain situation (e.g. reduction of pest abundance in conventional farms with flower islands) but to identify key management and environmental aspects underlying these results. These underlying aspects are the ones that can help to inform in other contexts. For example, in Chapter 3, we identified that pest regulation is the result of whole-farm management, where aspects such as crop diversity, soil quality, fertilization rate, and pesticide applications may play a role. Increasing flower resources (diversity) can significantly contribute to increased biological control in simplified systems, which have surrounding semi-natural areas. This results could inform the suitability and potential contribution of introducing floral resources or increasing biodiversity in other contexts. In the case of the MEDITAE framework developed in Chapter 5, it could be useful to support and structure a joint analysis with relevant actors to characterise farm system functioning and evaluate management practices towards agroecology-based systems. Starting from generic socio-ecological processes and subsequently contextualizing together with relevant actors affords the transportability of the framework to other different regions or production systems.

While focused on the production system level, the knowledge generated in this thesis can contribute to discussing policies related to the value chain and support structures to promote ecological intensification (Gaitán-Cremaschi et al., 2019). For instance, this work may contribute to the training of agronomy students by bringing specific knowledge to disciplinary agronomy courses (e.g. soil management, entomology, vegetable production), or by guiding and promoting the discussion around ecological processes underlying agroecosystem functioning during practical work during agroecological farm system analysis and design courses. The results may also inform policies to promote agroecological production. For example, the new knowledge gaps identified to manage agroecology-based production systems may contribute to the discussion of a national research agenda, and the methodological approach may inform how to design a better research strategy for generating actionable knowledge.

A research agenda should prioritize generating actionable knowledge on translating agroecological principles into concrete practices, particularly concerning biodiversity and soil management, which mediate all the ecological processes underlying the system's functioning (Nicholls et al., 2016). In addition, research should also contribute to developing and testing tools to improve the assessment of agroecosystems' functioning and management impacts. This information is an essential aspect for being able to improve tools to monitor and evaluate the trajectories of changes (e.g. the MEDITAE framework) and also to support social learning to foster and support ecological intensification (Douthwaite et al., 2003; Rossing et al., 2021).

A relevant question from Chapter 3 is why organic farms have fewer pests and more natural enemies than conventional. Is it because they do not use pesticides? Is it because they have more balanced crop nutrition? Is it because of higher functional biodiversity? Is it because of all these reasons together? Future research to further understand the mechanisms underlying such observations may give relevant information to redesign farm systems. In particular, regarding biodiversity management, a crucial topic is studying existing vegetation's potential role and contribution in and around production areas. Wild vegetation, such as semi-natural areas, field margins, or common weeds, size and connectivity, diversification and management, determine the amount, diversity and proximity of natural enemies and pests (e.g. Bàrberi et al., 2010; Bianchi, 2022; Crowther et al., 2023; Landis et al., 2012; Ryelandt et al., 2017). In addition, heterogeneous landscapes composed of cultivated fields interspersed with uncultivated habitats support greater biodiversity than simplified landscapes with mainly arable fields (Bianchi et al., 2006; Estrada-Carmona et al., 2022; Landis et al., 2000). The result of a habitat manipulation strategy (e.g. provision of flower resources) would be modulated by this landscape complexity (Tscharntke et al., 2016, 2012). Thus, research on the potential role of non-cultivated vegetation for biological control might help define principles to manage them and determine the need and suitability of designing specific habitat manipulation strategies.

A second relevant topic refers to how to design and manage crop diversification. Crop diversification involves both spatial and temporal planning. Rotations have been the focus of work in previous projects in Uruguay (e.g. Colnago et al., 2021; Dogliotti et al., 2014; Dogliotti et al., 2004), but the spatial arrangement of crops has received marginal attention. Although polycultures have been used since the beginning of agriculture, scientific research has only become relatively important in the last decade (Stomph et al., 2020). International studies evidence positive effects of polycultures on various ecological processes (Tamburini et al., 2020), but increasing crop diversity can have different effects on biodiversity and ecosystem services, depending on the combination of cultivated species and their arrangement in time and space (Jones et al., 2023). Some experiences in vegetables showed that intercrops reduced the incidence and severity of diseases (Ditzler et al., 2021) and pests (Juventia et al., 2021) and increased production per unit area (Yu et al., 2015). However, there is still a significant gap in scientific knowledge on the basic processes that determine productivity and resource use efficiency in polycultures, and even fewer studies on the benefits and practical difficulties of implementing them that would allow defining principles for the design and management of polycultures (Carrillo-Reche et al., 2023; Juventia et al., 2022). Thus, evaluating intercropping alternatives, identifying principles or key aspects to design them according to each situation, and assessing the spatial and temporal scales at which those strategies work, are key aspects of supporting farm diversification management.

The differences in soil quality between organic and conventional farms in Chapter 3, and the challenge of managing nitrogen supply in Chapter 4, lead to a third relevant research question about soil organic matter and organic amendments mineralisation dynamics. Since the time and amount of N release from organic amendments and soil organic matter is difficult to predict (Geisseler et al., 2022; Hodge et al., 2000; Masunga et al., 2016), estimating the annual amount of organic amendment needed to match nutrient supply, particularly N, and crop demand is challenging. Information on soil organic matter and organic amendments mineralization dynamics under different circumstances (e.g. soil characteristics, temperature, humidity) would better inform farmers´ decisions, particularly in organic systems where nutrient management is based on improving soil fertility by organic amendments

A fourth relevant research question is how to effectively manage cover crops without herbicides to control weeds under reduced tillage. As discussed in Chapter 4 and by previous studies (Carr et al., 2013; Casagrande et al., 2016; Mandal et al., 2021; Peigné et al., 2015), the effectiveness of the technology in controlling weeds is erratic, which poses additional limitation in organic systems where weed control strongly relies on mechanical interventions. Finally, further research should also focus on studying other functionalities of cover crops and reduced tillage technology in the system, such as the potential for pests and disease suppression linked to biodiversity management.

Based on this study, I highlight the benefits of considering three premises to generate this actionable knowledge to support ecological intensification at local scales while informing and inspiring transitions in other situations: i. A comprehensive and systemic research approach, ii. Transparency, inter- and transdisciplinary, and promote learning throughout the research process, and iii. Long-term joint work projection. Researching every possible practice in every place and time is not feasible. A systemic and comprehensive approach facilitates scaling out agroecological practices and tailoring the redesign to each particular farm and moment. Thus, research should focus on understanding the effect of the practices on the underlying processes explaining the result and not on the results *per se* and considering all relevant connections between practice, context and the way of application (Martin et al., 2018). This systemic and comprehensive approach requires a co-creation process involving multiple disciplines and multiple knowledge types (e.g. scientific and experiential) in defining, developing, monitoring and evaluating the research to encompass the complexity of agricultural systems (Méndez et al., 2013; Sachet et al., 2021). Being transparent and making explicit the objectives, methods and hypothesis facilitates arriving at a shared vision and promotes this co-creation process by stimulating participants' awareness, motivation, trust and engagement, which enables learning (de Olde et al., 2017). Thus, the research process demands openness and humility from all actors involved (not being "the one" or "the leader" but being "one more" in a group), and calls for long-term joint work strategies allowing time to enhance and assess ecological processes, and to give space to multiple actors' active participation based on trust. While this is extremely challenging for the current way research projects are conceived and funded, research should be flexible enough to be able to adjust objectives, methods and strategies in light of the results and contributions of participants (Darnhofer, 2021; Prost et al., 2023; Rossing et al., 2021; Sachet et al., 2021).

The co-creation of knowledge implies that the limits between research, innovation and learning are diffuse and that the quality of the process is a result itself. Thus, the question about how to research, positioned in the previous paragraph, is also about how to learn and innovate. From this perspective, and in keeping the three premises highlighted in the previous paragraph, how to better design and organize the co-creation of knowledge may differ according to socio-cultural conditions and farm systems (Berthet et al., 2018). Based on our experience, a research strategy combining two main intertwined components: participatory experimentation (Chapters 2, 3 and 4) and on-farm co-innovation (Chapter 5), is a powerful way to support ecological intensification. The experimentation component aims to test technologies at the field level combining experimental station and on-farm experimentation and to create a permanent support group to discuss and define the agenda and monitor the process. The co-innovation component aims to support farmers and technical advisors in developing farm co-innovation, articulating at the landscape or regional level. This component could be organised with a permanent support group for defining and monitoring the process, several technical advisors working each with a group of farms, and a group of researchers and experienced technical advisors to support technical advisors' work. The experimentation component informs alternatives for farm re-design and ways for monitoring changes, while the co-innovation component help to identify bottlenecks and contextualize technologies. In both components, a support group organizing the participatory strategy facilitates farmers, technical advisors and researchers' active participation. In addition, both components involve higher education students' training.

The technological and methodological knowledge generated considering a comprehensive and systemic research approach, transparency, inter- and transdisciplinary, the promotion of learning and a long-term joint work projection would support farmers and technical advisors in defining transition strategies, contribute to improving higher education programs and the training of professionals and help us researchers position ourselves in a broader and collaborative context. From this perspective, agronomy, as a science, brings the necessary common ground to integrate multiple disciplines and co-create new knowledge to face the challenges of supporting the transition to agroecological systems while also being part of it. However, a transition towards ecological intensification will not be possible if no active and powerful public policies are sustained over time. Ecological intensification goes again the "mainstream" in agriculture and food system, focusing on processes management instead of input technology, which therefore has no relevant attractions for companies. On the other hand, if ecological intensification is distorted and monopolised by industrial interests ending in an input substitution strategy, it will lead to new dependency relations and "technology race". In this context, the knowledge generated based on the previous premises may contribute to defining policies (e.g. land use, agriculture subsidies, extension services, national research agenda and human resources training) at the local, national and international levels to support ecological intensification.

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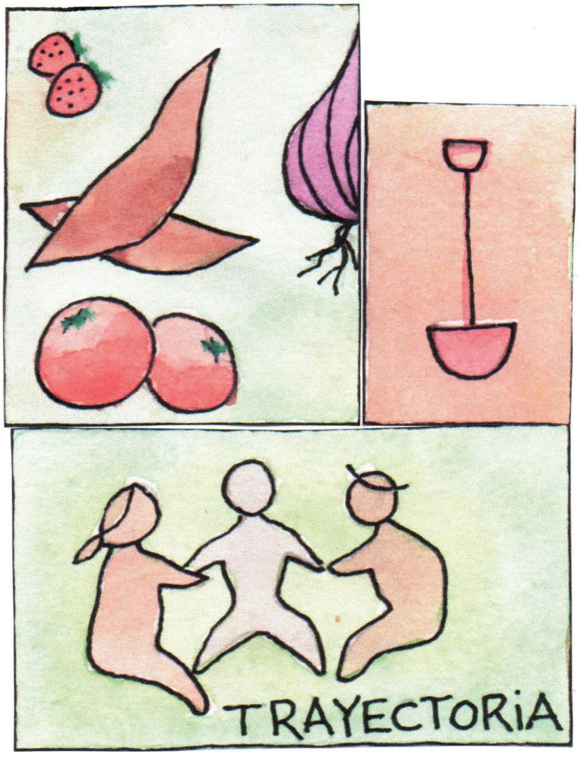
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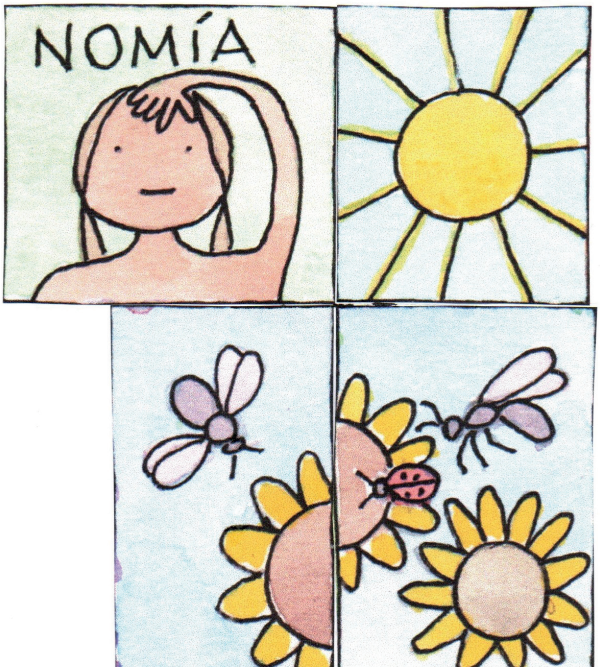
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Summary

Agroecology and ecological intensification are increasingly recognised as more sustainable alternatives to the intensive industrial agricultural model. However, their system design and management guiding principles are often too general to be directly translated into concrete and context-specific strategies. This thesis aims to address this knowledge gap by developing actionable knowledge and conceptual frameworks for the ecological intensification of vegetable farm systems in Uruguay. The thesis starts with assessing the opportunities for ecological intensification by analysing five major vegetable crops' input and output relationships. Next, two technologies were developed and tested to reduce agrochemical input use and enhance ecological processes. Finally, I developed and applied a diagnosis framework to support agroecological transitions during co-innovation. Methodologically, the thesis combined database analysis and on-station and on-farm experimentation, focusing at the field and farm level, with a comprehensive, interdisciplinary and participatory approach.

In **Chapter 2**, I assessed the relationship between pesticide and nutrient inputs and crop yield in main vegetable crops (tomato, onion, sweet potato, and strawberry) based on a dataset of 82 farms and 428 fields from projects developed between 2012 and 2017 in south Uruguay. I found weak or non-significant relationships between inputs and yield, indicating inefficiencies and excessive input use. I identified farms that achieved high yields with low input levels for all five crops, challenging the belief that high agrochemical use is necessary for high productivity. In addition, yield and input use levels were unrelated to farm resource endowment. Agronomic criteria or best management practices did not inform management of inputs, but instead, farmers relied on personal experience, tradition, or intuition. Farmers were into a "routine of doing" consistent across fields and years, irrespective of the specific crop growth conditions. Drawing on these findings, I argue that there is ample room for reducing agrochemical input use without productivity loss. Learning from positive deviant farmers in combination with guided farm redesign, high-quality extension services, and the generation and use of context-specific knowledge and technologies may equip farmers to use more sustainable management practices and support their transition process. In the following chapters of the thesis, informed by the results of Chapter 2 and based on the exchange with farmers and their technical advisers, I contributed to the generation of context-specific knowledge and technologies.

In **Chapter 3**, I assessed the potential of introducing floral resources to enhance biological pest control in greenhouse tomato, the main greenhouse crop in Uruguay. Greenhouse tomato production relies heavily on insecticides for pest control. I conducted a two-year experiment on four organic and four conventional farms. On each farm, one

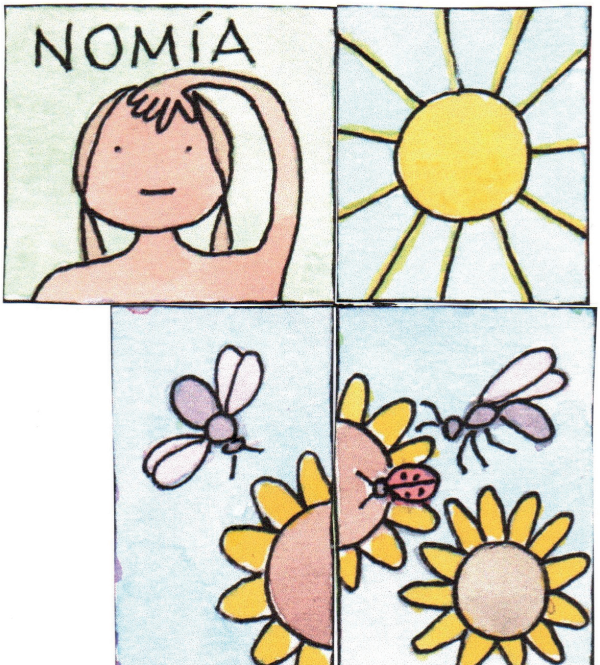
greenhouse contained flower islands of basil (*Ocimum basilicum*), marigold (*Tagetes patula*) and alyssum (*Lobularia maritima*), and another greenhouse served as a control. Introducing flowering plants in tomato greenhouses reduced pest abundance in conventional greenhouses. Organic greenhouses already had high levels of pest suppression, and adding floral resources did not further reduce pest abundance. Organic farms had tomato yields comparable to conventional farms, a lower abundance of pests, less pest injury, and a higher abundance of natural enemies. The three introduced flowering species had a lower abundance of pests than tomato plants in conventionally managed greenhouses. Marigold had a higher abundance of pests than tomatoes in organically managed greenhouses. Overall, alyssum supported a relatively low pest abundance and high abundance of natural enemies and pollinators. The study concludes that floral resources may help reduce pests and, thus, pesticide use in conventional systems. Still, this practice alone is insufficient to effectively maintain pests at low densities. In addition, the study highlights the potential of agroecological and organic management to reduce the reliance on synthetic pesticides without yield reduction while evidencing the context-dependency of the effect of management practices.

In **Chapter 4**, I report the findings of a two-year experiment at an experimental station (2019 and 2020) and a one-year trial on two commercial farms (2020). The experiments focused on onion, a major open-field crop associated with high soil degradation and erosion risks and heavily relying on herbicides for weed control. I assessed the effects of two tillage systems (reduced tillage and conventional tillage) and the application of native effective microorganisms (NEM) in an onion crop grown after a summer cover crop without using herbicides or synthetic fertilisers. I assessed onion crop growth and development, yield, N-status, weed pressure, and soil physicochemical and biological quality. Reduced tillage without agrochemicals reduced the risk of soil erosion and increased soil biological activity and did not negatively impact soil physical conditions for onions. However, reduced tillage resulted in N limitation that reduced onion yield and increased labour demand due to high weed pressure. The results varied among the three experimental sites, particularly for nitrogen limitation and weed pressure. My findings indicate that feasible reduced tillage systems are within reach, but further research is needed to address N limitation and weed pressure.

Chapters 2 to 4 highlighted the need for working at the farm level, starting from a farm-specific diagnosis and actively involving farmers (Chapter 2), and the relevance of considering the context of application (e.g. organic vs conventional farm management in tomato greenhouses in Chapter 3) and the concrete way of implementation (e.g. the green manure biomass quantity and quality in each experimental site in Chapter 4) to design appropriate alternative for each system. Based on the findings of Chapters 2 to 4, I focused in Chapter 5 on the whole farm system level, actively involving farmers in developing a framework to support the transition of vegetable farm systems to agroecology within a co-innovation process.

The Assessment and Diagnostic Framework to Inform Agroecological Transitions (MEDITAE, for its acronym in Spanish) presented in **Chapter 5** is based on six socio-ecological processes underlying the functioning of agroecosystems: nutrient cycling, carbon cycling, plant succession and biotic regulation, water cycling, energy flow, and socio-economic and cultural processes. The core of the framework encompasses, for each process, the description of the main components and interrelationships and a definition of the desirable quality and functioning in an agroecology-based farm system. The analysis of each process is guided by performance indicators, followed by practice-based indicators that may explain these performances. I applied the framework in a co-innovation project with five case study farms. Using the MEDITAE diagnosis framework during the co-innovation work contributed to achieving an agroecological perspective on farm system analysis while raising awareness, promoting learning and creating consensus among the research team, farmers and technical advisors.

In the general discussion in **Chapter 6**, I first reflect on the opportunities and urgency for ecological intensification in vegetable production in Uruguay. Second, I discuss strategies for the transition towards ecologically intensive systems emphasising the need to embark on whole-farm redesign, the contribution of research to this transition and the need for moving beyond the farm-system level. Finally, I discuss the implications of the thesis and pose ideas for future research. I stress the importance of developing actionable knowledge to translate agroecological principles into practices, particularly related to functional biodiversity assessment, design and management and soil health enhancement. In addition, I point out that comprehensive and systemic research approaches, transparency, inter- and transdisciplinary, the promotion of learning processes, and long-term joint work projection are key elements for developing research to support agroecological transitions. Throughout the thesis, as reflected in the chapter's co-authorships and acknowledgements, I worked with many colleagues from multiple disciplines. Agronomy has and brings a necessary common ground to integrate multiple disciplines and co-create new knowledge to face the challenges of supporting changes in agricultural systems. Thus, the research process highlighted the interdisciplinary character of agronomy and contributed to revaluing the role of agronomy in assisting the transition to agroecological systems while also being part of it.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Resumen

La agroecología y la intensificación ecológica se reconocen cada vez más como alternativas más sostenibles al modelo de agricultura industrial intensiva. Sin embargo, los principios rectores de diseño y manejo de los sistemas de producción de base agroecológica suelen ser demasiado generales para traducirse directamente en estrategias y prácticas específicas apropiadas para cada contexto. Esta tesis tiene como objetivo desarrollar conocimientos prácticos y marcos conceptuales que permitan reducir esta brecha y aportar a la intensificación ecológica de los sistemas de producción hortícolas en Uruguay. La tesis comienza con la evaluación de oportunidades para la intensificación ecológica analizando las relaciones entre el uso de insumos y los rendimientos en cinco cultivos hortícolas de relevancia. Luego, se desarrollaron y testearon dos tecnologías para reducir el uso de insumos agroquímicos y promover el funcionamiento de los procesos ecológicos. Por último, desarrollé y apliqué un marco de diagnóstico para apoyar las transiciones agroecológicas durante un trabajo de co-innovación. La metodología empleada en la tesis combinó el análisis de bases de datos y la experimentación en estación experimental y en predios comerciales, centrando el análisis a nivel de cultivo y a nivel predial, aplicando un enfoque sistémico, interdisciplinario y participativo.

En el **Capítulo 2**, estudié la relación entre el uso de insumos de plaguicidas y nutrientes, y el rendimiento en cinco cultivos hortícolas relevantes (tomate de ciclo corto y largo, cebolla, boniato y frutilla) mediante el análisis de una base de datos de 82 predios y 428 cuadros de cultivo generada en proyectos desarrollados entre 2012 y 2017 en el sur de Uruguay. Las relaciones entre el uso de insumos y rendimiento fueron débiles o no significativas, evidenciando ineficiencias y un uso excesivo de insumos. Para los cinco cultivos analizados, se identificaron predios que lograron altos rendimientos con bajos niveles de uso de insumos, cuestionando la creencia de que es necesario un alto uso de agroquímicos para una alta productividad. Los niveles de rendimiento y de uso de insumos no estuvieron relacionados con la dotación de recursos de capital del predio. En términos generales, el manejo de los insumos no estuvo asociado a criterios agronómicos o de buenas prácticas de manejo, sino a la experiencia personal, la tradición de manejo o la intuición. Los productores seguían una "rutina de manejo" consistente en todos los cuadros de cultivo y a lo largo de los años, independientemente de las condiciones específicas de crecimiento de los cultivos. A partir de estas conclusiones, discuto que existe un amplio margen para reducir el uso de insumos agroquímicos sin pérdida de productividad. El aprendizaje a partir del estudio de los casos con desempeño positivo, en combinación con el rediseño de los sistemas prediales, con servicios de extensión de alta calidad, y con la generación y el uso de conocimientos y tecnologías desarrolladas para cada contexto específico, puede guiar a los productores en la utilización de prácticas

de manejo más sostenibles y apoyar un proceso de transición. En los siguientes capítulos de la tesis, a partir de los resultados del Capítulo 2 y basado en el intercambio con los productores y sus asesores técnicos, contribuí a la generación de conocimientos y tecnologías de manejo contexto-específicas.

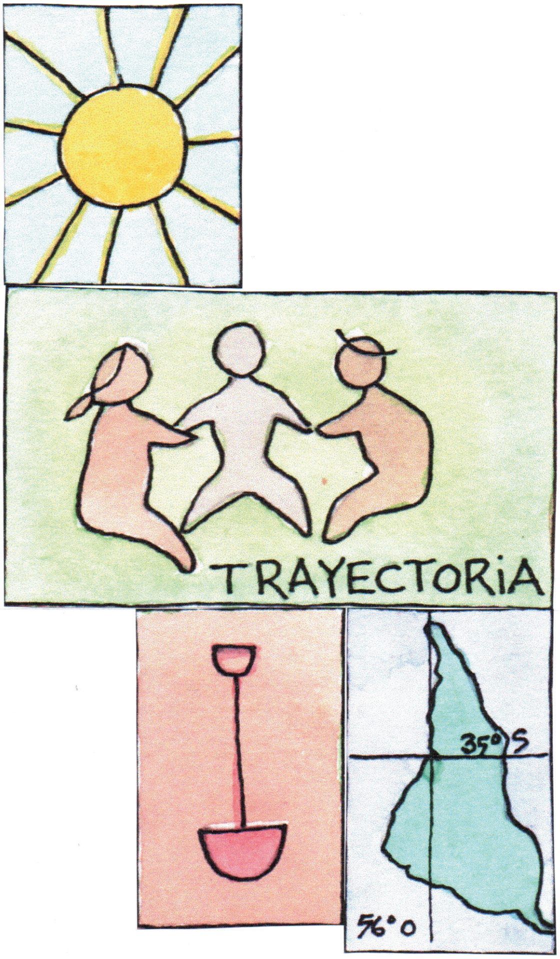
En el **Capítulo 3**, evalué el potencial de la introducción de recursos florales para mejorar el control biológico de plagas en el cultivo de tomate en invernáculo. El tomate es el principal cultivo de invernáculo en Uruguay y depende en gran medida del uso de insecticidas para el control de plagas. Realicé un experimento durante dos años en cuatro predios orgánicos y cuatro predios convencionales en el sur del Uruguay. En cada predio, un invernáculo contenía islas florales de albahaca (*Ocimum basilicum*), tagete (*Tagetes patula*) y alyssum (*Lobularia maritima*), y otro invernáculo sirvió de control. La introducción de plantas florales redujo la abundancia de plagas en los invernáculos convencionales. Los invernáculos orgánicos ya presentaban altos niveles de supresión de plagas, y la adición de recursos florales no redujo aún más la abundancia de plagas. Los predios orgánicos tuvieron rendimientos de tomate similares a los convencionales, una menor abundancia de plagas, menor daño por plagas y una mayor abundancia de enemigos naturales. Las tres especies de plantas florales presentaron una menor abundancia de plagas que las plantas de tomate en los invernáculos con manejo convencional. El tagete presentó una mayor abundancia de plagas que el tomate en los invernáculos manejados de forma orgánica. En general, el alyssum tuvo una abundancia de plagas relativamente baja y una gran abundancia de enemigos naturales y polinizadores respecto a las demás especies. El estudio concluye que la introducción de recursos florales puede ayudar a reducir las plagas y, por tanto, el uso de pesticidas en los sistemas convencionales. Sin embargo, esta práctica por sí sola es insuficiente para mantener bajas densidades de plagas eficazmente. Adicionalmente, el estudio demuestra el potencial del manejo agroecológico y orgánico para reducir la dependencia de los plaguicidas sintéticos sin reducir el rendimiento, al tiempo que evidencia que el efecto de las prácticas de manejo depende del contexto específico de aplicación.

En el **Capítulo 4**, presento los resultados de experimentos en manejo de suelos desarrollado durante dos años en una estación experimental (2019 y 2020) y un año en dos predios comerciales (2020). Los experimentos se centraron en el cultivo de cebolla, un cultivo de relevancia, realizado a campo o cielo abierto, asociado a altos riesgos de degradación y erosión del suelo, y que depende en gran medida del uso herbicidas para el control de las malezas. Evalué los efectos de dos sistemas de laboreo (laboreo reducido y laboreo convencional) y la aplicación de microorganismos eficientes nativos en el cultivo de cebolla implantado tras un cultivo de cobertura de verano sin utilizar herbicidas ni fertilizantes sintéticos. Se evaluaron el crecimiento y desarrollo del cultivo de cebolla, el rendimiento, el contenido de N en planta, la presión de malezas, y la calidad fisicoquímica y biológica del suelo. El tratamiento de laboreo reducido disminuyó el riesgo de erosión del suelo y aumentó la actividad biológica del suelo, sin afectar negativamente las condiciones físicas del suelo para las plantas de cebolla. Sin embargo, redujo el rendimiento de cebolla asociado a una limitación de N, y aumentó la demanda de mano de obra debido a la elevada presión de malezas. Los resultados variaron entre los tres sitios experimentales, particularmente en lo que respecta a la limitación de N y la presión de malezas. Se concluye que si bien la tecnología de laboreo reducido en horticultura y sin uso de agroquímicos está al alcance, se requiere más investigación que permita mejorar el manejo asociado a las limitaciones de N y la presión de malezas.

Los capítulos 2 a 4 ponen de manifiesto la necesidad de trabajar a nivel del sistema predial, partiendo de un diagnóstico específico de cada predio e involucrando activamente a los productores (capítulo 2), y la relevancia de considerar el contexto de aplicación (por ejemplo, el manejo orgánico frente al convencional en los invernáculos de tomate en el capítulo 3) y la forma concreta de aplicación (por ejemplo, la cantidad y calidad de biomasa del cultivo de cobertura en cada sitio experimental en el capítulo 4) para diseñar alternativas adecuadas para cada sistema. Basándome en las conclusiones de los capítulos 2 a 4, en el capítulo 5 me centré en el estudio del sistema predial como un todo, involucrando activamente a los productores en el desarrollo de un marco de diagnóstico para apoyar la transición agroecológica de los sistemas de producción hortícola durante un proceso de co-innovación.

El Marco de Evaluación y Diagnóstico para Impulsar Transiciones Agroecológicas (MEDITAE) presentado en el **Capítulo 5** se basa en seis procesos socioecológicos que subyacen al funcionamiento de los agroecosistemas: el ciclaje de nutrientes, el ciclaje de carbono, la sucesión vegetal y la regulación biótica, el ciclaje de agua, el flujo de energía y los procesos socioeconómicos y culturales. El corazón o núcleo del marco abarca la descripción de los principales componentes e interrelaciones y una definición de la calidad y el funcionamiento deseables de cada proceso en un sistema predial agroecológico. El análisis de cada proceso es guiado mediante el uso de indicadores de funcionamiento o desempeño, seguidos de indicadores de prácticas de manejo que pueden explicar este desempeño. El marco fue utilizado durante un proyecto de co-innovación en cinco predios comerciales tomados como estudios de caso. La utilización del marco MEDITAE durante el trabajo de co-innovación contribuyó a lograr una perspectiva agroecológica en el análisis del sistema predial, al tiempo que sensibilizó, promovió el aprendizaje y facilitó la creación de consensos entre el equipo de investigación, los productores y los asesores técnicos involucrados.

En la discusión general del **Capítulo 6**, primero reflexiono sobre las oportunidades y la urgencia de la intensificación ecológica en la producción hortícola en Uruguay. En segundo lugar, discuto estrategias para la transición hacia sistemas ecológicamente intensivos, haciendo hincapié en la necesidad de emprender un rediseño global de los sistemas prediales la contribución de la investigación en esta transición, y la necesidad de avanzar más allá de este nivel predial. Por último, discuto las implicancias de la tesis y planteo ideas para futuras investigaciones. En este sentido, resalto la importancia de desarrollar conocimientos prácticos que permitan traducir los principios agroecológicos en prácticas concretas, sobre todo en relación a la evaluación, el diseño y el manejo de la biodiversidad funcional y la mejora de la salud del suelo. Además, señalo que un abordaje holístico y sistémico, la transparencia, la inter y transdisciplinariedad, la promoción de procesos de aprendizaje y la proyección del trabajo conjunto en el largo plazo, son elementos clave para desarrollar una investigación que promueva y apoye las transiciones agroecológicas. A lo largo de la tesis, como se refleja en las coautorías y agradecimientos, trabajé con muchos colegas de múltiples disciplinas. La agronomía implica y brinda un terreno común, necesario para integrar múltiples disciplinas y co-crear nuevos conocimientos que permita afrontar el desafío de apoyar la transición de los sistemas agrarios. Así, el proceso de investigación desarrollado resalta el carácter interdisciplinar de la agronomía y contribuye a revalorizar el rol de la agronomía en apoyar, al tiempo que es parte, la transición hacia sistemas agroecológicos.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Acknowledgements

This, "My" PhD, is the result of the work of many people. At this point, I want to express my gratitude to all of you for joining and supporting me on this journey.

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Thank you to my colleagues and co-authors of the thesis chapters: Leticia Bao, Paloma Bertoni, Magdalena Rieppi, Florencia Alliaume, Gabriela Illarze, Guillermo Galván, Margarita García, Pablo González, and José Pedro Dieste from the Faculty of Agronomy, Natalia Bajsa and Tania Trasante from IIBCE, and Juan Carlos Gilsanz from INIA. Thanks to all the CRS staff who participated in the development of this work. Special acknowledgements to Natalia Curbelo, Oscar Costa, Néstor Laxalt, and Fabián Milsevich for your dedication, commitment, and support. Thank you all for your work and contributions and for your positive energy, which culminated in this final product and strengthened our growth and project as a team.

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Special thanks to my colleagues and friends from the horticulture group at the Faculty: Paula Colnago, Guillermo Galván, Fernanda Zaccari, Sebastián Peluffo, Carlos Barros, Margarita García, Luis Aldabe, Héctor Gonzalez, Mariana Arias, Paloma Bertoni, Marcela Gonzalez. You made my PhD possible, taking on additional tasks so I could make progress. My PhD is yet another result of this long history of teamwork.

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Thanks to the HortEco team, I enjoyed our workshops and learning about other realities. Thanks to the colleagues at FSE Group at WUR who warmly welcomed me and made me feel at home on every visit. Special thanks to Pablo, Bettina, Qingbo, Roos, Lenora and Carl for sharing every stay in the Netherlands with me and my family.

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About the author

Mariana Scarlato García was born in Montevideo, Uruguay, on July 26, 1985. Since 2005 she has been in a couple with Ignacio, with whom she has three children: Ema, Julia and Martín. Since 2014, she has lived on a farm in Canelones, in southern Uruguay.

From an early age, under the influence of her parents, she became involved and interested in agronomy in its broadest sense, closely linked to ecology, production, environment, and people. She studied at the Faculty of Agronomy of the Universidad de la República in Uruguay from 2004 to 2010, where she graduated as an agronomist engineer. Later, from 2012 to 2015, she completed a Master´s degree in Agricultural Science at the same institution. From 2006 to 2009, she worked at an educational farm with kindergarten and primary school children. From 2009 to 2012 and from 2014 to 2018, she worked as a part-time research assistant for different research projects at the Faculty of Agronomy, where she also had the opportunity to start teaching. From 2012 to 2015, she worked as a part-time researcher at the National Institute of Agricultural Research of Uruguay. From 2008 to 2017, she also worked as a technical advisor with family farmers and farmer´s organisations in southern Uruguay. In 2017, she started a 'sandwich' PhD programme within the former Farming Systems Ecology group of Wageningen University. In 2019, she jointed the Horticulture Group of the Faculty of Agronomy as a permanent lecturer. From that date to the present, she works at the Department of Plant Production of the Faculty of Agronomy at the South Research Station (´Centro Regional Sur´) as a lecturer and research assistant.

List of publications

Scientific articles

Scarlato, M., Bao, L.; Rossing, W.A.H.; Dogliotti, S.; Bertoni, P.; Bianchi, F.J.J.A. 2023. Flowering plants in open tomato greenhouses enhance pest suppression in conventional systems and reveal resource saturation for natural enemies in organic systems. *Agriculture, Ecosystems and Environment.* 347, 108389. https://doi.org/10.1016/j.agee.2023.108389

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Scarlato M., Colnago P. 2023. Strategies and tools for the transition to agroecological-based vegetable production systems. *Agrociencia Uruguay.* 27, Supplement e1207. https://doi.org/10.31285/AGRO.27.1207

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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 project proposal (6 ECTS)

- Ecological intensification pathways for vegetable production systems in South Uruguay

Post-graduate courses (5.7 ECTS)

- Introduction to R for statistical analysis; WUR (2018)
- Linear models; WUR (2020)
- Generalized linear models; WUR (2020)
- Mixed linear models; WUR (2020)
- Advances in intercropping: principles and implementation; PE&RC, WUR (2021)
- How bugs support sustainable crop production and biodiversity; PE&RC, WUR (2023)

Deficiency, refresh, brush-up courses (2 ECTS)

- Functional diversity for sustainable crop production; WUR (2018)
- Agrobiodiversity; WUR (2018)

Invited review of journal manuscripts (5 ECTS)

- Agrociencia Uruguay: onion cover crop reduced tillage (2021)
- Agricultural Systems: co-design agricultural practices (2021)
- Agrociencia Uruguay: pesticides use production systems (2022)
- International Journal of Pest Management: biological control agricultural practices (2022)
- Agronomy Research: greenhouse tomato management pollinators (2023)

Competence strengthening/skills courses (4.1 ECTS)

- Scientific writing; WUR (2018)
- Presenting with impact; WUR (2018)
- Intensive writing week; Radboud University (2021)

Scientific integrity/ethics in science activities (0.75 ECTS)

- Research data management; WUR (2018)
- Ethics in plant and environmental sciences; WUR (2020)

PE&RC Retreat, PE&RC day, and other PE&RC events (2.4 ECTS)

- PhD Workshop carousel (2018)
- PE&RC First years weekend (2018)
- PE&RC Last year retreat (2022)
- Symposium the anthropocene biosphere transforming for sustainable futures (2022)
- Mini symposium crop diversification new perspectives beyond agronomy future (2022)
- Masterclass the anthropocene biosphere transforming for sustainable futures (2022)

Discussion groups/local seminars or scientific meetings (8.4 ECTS)

- Discussion group vegetable production systems; Facultad de Agronomía, Uruguay (2017-2021)
- Reading sustainable foodscapes; FSE (2018)
- Jornadas de investigación de la facultad de Agronomía (2018)
- Scientific meetings of HortEco project (2018-2021)
- Scientific meetings and workshops project mejora de la calidad del suelo y reducción del uso de agroquímicos en sistemas hortícolas: el cultivo de cebolla como modelo (2019-2021)
- Seminar transición agroecológica, producción, comercialización, sistemas participativos de garantías (2020)
- Workshop promoviendo la transición hacia sistemas alimentarios agroecológicos: producción y comercialización de hortalizas en Chile y Uruguay (2020)
- Congreso latinoamericano de agroecología; SOCLA (2022)
- Discussion group biodiversity in agroecosystems; PE&RC, WUR (2022-2023)

International symposia, workshops and conferences (7.9 ECTS)

- International symposium for farming system design; Uruguay (2019)
- Current issues on research for development of sustainable food systems; FA-UY FSD Congress (2019)
- Seminar transiciones agroecológicas producción, comercialización y sistemas participativos de garantías: intercambio de experiencias entre Uruguay y Chile; CH-UY-WUR (2019)
- Congreso Latinoamericano de Agroecología; SOCLA, UY-ARG (2020)
- International forum estrategias agroecológicas para el control de plagas y enfermedades en la producción de alimentos ; Perú (2022)

- I simposio peruano en seguridad alimentaria SIPSA; CEICIVET y Facultad de Ciencias Veterinarias de la Universidad Nacional de Cajamarca; Perú (2022)

Societally relevant exposure (1.7 ECTS)
- HortEco web page (2019)
- 1ª Muestra nacional de agroecología posters, Uruguay (2019)
- Primera cata nacional de tomate presentation (2020)
- Jornada destacada en horticultura presentation (2020)
- Radio en perspectiva interview (2022)
- Radio informe granjero interview (2022)
- La diaria interview (2022)
- The CAR-INIA las brujas Uruguay presentation (2022)
- ExpoMelilla, Uruguay posters, talk (2022, 2023)

Lecturing/supervision of practicals/tutorials (3 ECTS)
- Analysis and design of vegetable farm systems; Uruguay (2018-2020)
- Organic agriculture; Uruguay (2018-2021)
- Agroecology; WUR (2018, 2022)
- Vegetable production; Uruguay (2019, 2023)
- Intensificación ecológica para sistemas agrícolas sustentables; Chile (2022)

BSc/MSc thesis supervision (6 ECTS)
- Influence of organic and conventional practices on functional biodiversity composition in vegetable open fields in Uruguay
- Promoting natural biological control and pollination by introducing flowering plants in open tomato greenhouses in Uruguay
- Natural enemies, pollinators and pests in semi-natural landscape elements
- Habitat functionality for ecosystem services of pest control and pollination: a study case in Uruguay
- Infraestructura ecológica asociada a los predios hortícolas y su rol en el control natural de plagas
- Comparación de diferentes sistemas de producción en el cultivo de tomate en invernadero a través de indicadores de sustentabilidad
- Evaluación y desarrollo de propuesta para mejorar la sostenibilidad de un predio hortícola orgánico: profundización del enfoque agroecológico
- Efectos de un preparado de microorganismos eficientes y el laboreo reducido, sobre la actividad biologica del suelo
- Efectos del laboreo reducido sobre la calidad y dinamica de nitrogeno en el suelo

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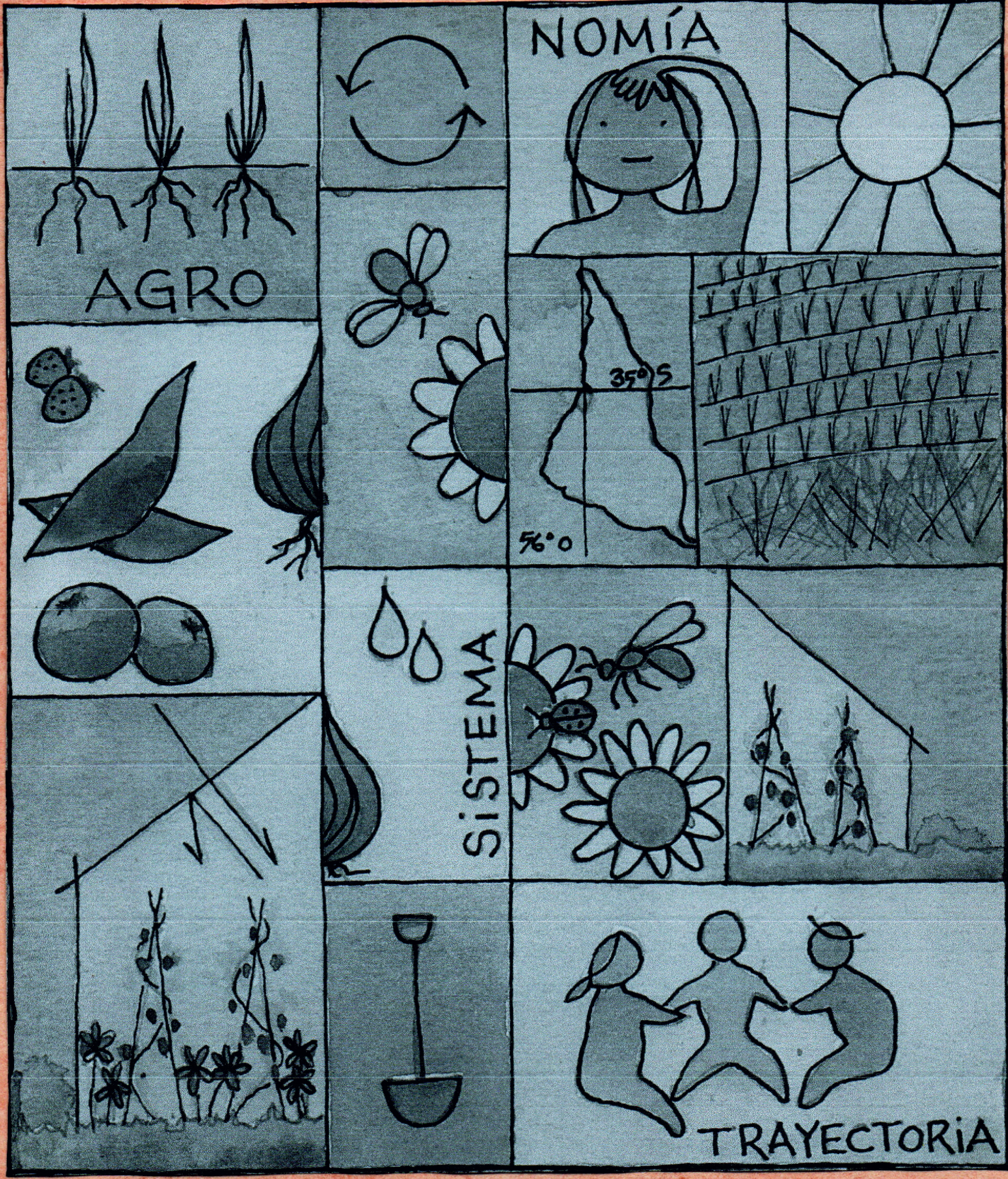
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