A Broad-Scale Characterization of Corn (*Zea mays*)-Soybean (*Glycine max*) Intercropping as a Sustainable-Intensive Cropping Practice

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I hereby declare that I am the sole author of this thesis. This is a true copy of the thesis, including any required final revisions, as accepted by my examiners.

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ABSTRACT

Sustainable-intensification (SI) is known as a strategy to enhance agriculture productivity, while minimizing negative impacts on the environment, and promoting social benefits. The SI concept broadened over the years to cover a wide range of agriculture systems and sustainability issues. Recently, literature reviews revealed that SI research has often failed to address all aspects of the SI concept, specifically social, economic and political dimensions. Influenced by previous SI literature, this dissertation presents original research for conducting interdisciplinary broad-scale SI research. A mixed-method approach influenced by Farming System Research was used, to determine whether modernized corn-soybean intercropping was a suitable SI cropping practice for the southeast Buenos Aires (SEBA) region of the Argentine Pampas. Corn-soybean intercropping was assessed through the incorporation of four studies that each differed in scale, scope and methodology. These studies consisted of the following: i) the socio-ecological regional context; ii) soil greenhouse gas (GHG) emissions derived from corn-soybean intercropping; iii) perspectives from social actors on the adoptability of intercropping in the SEBA region; and iv) an interdisciplinary study that developed a SI framework to characterize and evaluate corn-soybean intercropping for regional suitability.

Studying the socio-ecological context of the SEBA region provided a historical perspective and gave the context of the larger system that the Argentine Pampas production systems are nested within. Identified past events affected regional and field-level decision-making, which impacted novel cropping practice development and implementation. Argentine agriculture policies have frequently changed to meet political platforms, and to regulate social welfare and federal debts. These changes influenced agriculture activities and evolved the Pampean agriculture regime towards modernization and intensification.

The use of intensive agricultural practices throughout the Pampas contributed to an array of environmental issues. In response, agriculture researchers studied corn-soybean intercropping as a strategy to increase production and reduce environmental degradation. One environmental concern that many SI researchers discussed in literature was GHG mitigation. In this dissertation, a greenhouse gas study was performed within the SEBA region at the field scale. The natural science study focused on quantifying, comparing and evaluating carbon dioxide (CO_2) and nitrous oxide (N_2O) soil-surface emissions – obtained weekly from static chambers in field treatments for two growing seasons. The four field treatments examined were two configurations of substitutive corn-soybean intercropping (1:2 and 2:3 configurations) and two corresponding sole crops. CO_2 emissions from the treatments ranged from 3.6 to 86.5 kg CO_2-C ha^{-1} d^{-1}, and did not significantly differ between treatments for both growing seasons.

The 2:3 intercropping treatment had N_2O emissions that were not significantly different from sole crops, ranging from -6.1 to 158.4 g N_2O-N ha^{-1} d^{-1}. The 1:2 intercropping treatment had significantly greater N_2O emissions (ranging from -5.7 to 170.1 g N_2O-N ha^{-1} d^{-1}) compared to the other treatments. During the first growing season (January 2012 - May 2012), the 1:2 intercropping treatment had mean N_2O emissions that was significantly greater ($p < 0.001$; 10.5 ± 1.08 g N_2O-N ha^{-1} d^{-1}± SE) than the means of other three treatments (5.4 ± 0.74 g N_2O-N ha^{-1} d^{-1}). In the second growing season (December 2012 - May 2013), the 1:2 intercropping treatment mean (12.0 ± 1.80 g N_2O-N ha^{-1} d^{-1}) was significantly greater ($p=0.035$) than the sole corn mean (6.3 ± 1.43 g N_2O-N ha^{-1} d^{-1}). An intercropping GHG interpretative (IGI) calculation was developed to evaluate the mitigation potential of intercropping systems in comparison to growing two corresponding crops as sole crops. The IGI values showed that the 2:3 intercropping treatment had greater mitigation potential than the 1:2 intercropping treatment.

At the regional scale, producer and agricultural practitioner perspectives were utilized in an inductive social science study, to determine the adoptability of corn-soybean intercropping as an emerging modernized cropping practice within the SEBA region. Semi-structured interviews with crop producers and unstructured interviews with agricultural practitioners provided insight on cultural, technical, economic, and political factors that affect the real-world logistics of the intercropping practice. Interviews revealed that the intercropping practice had poor adoptability for producers due to: i) national socio-political policies and circumstances; ii) the inability to compete with economic and labour advantages of growing soybean as a sole crop; and iii) the region’s cool climate limited production.

A cross-scale broad-scope framework was developed to characterize corn-soybean intercropping holistically. The framework had a bottom-up structure that differentiated sustainability and intensification components of the cropping practice through indicators, subcategories and categories. SEBA corn-soybean intercropping was characterized as having both sustainability and intensification features, but was a weak representation of SI. Corn-soybean intercropping displayed features within the diversity and complexity category for the sustainability theme, and features within the increased production category for the intensification theme. Results in the short-term economic and socio-political categories impacted corn-soybean intercropping adoptability in the region; these two categories are often underutilized in SI research, yet were revealed to be of great importance within this embedded designed case study. Research gaps were presented in the chemical input mitigation and knowledge intensity categories. Continuing research in these two categories is recommended to strengthen the representation of corn-soybean intercropping as a SI cropping practice.

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LIST OF ACRONYMS AND ABBREVIATIONS

AACREA	La Asociación Argentina de Consorcios Regionales de Experimentación Agrícola - The Argentine Association of Regional Consortiums of Agriculture Experimentation.
AFOLU	Agriculture, forestry, and other land Use
BA	Buenos Aires
BFB	Basic food basket
C	Carbon
C:N	Carbon to nitrogen ratio
CO_2	Carbon dioxide
CO_{2e}	Carbon dioxide equivalent
CONICET	Consejo Nacional de Investigaciones Científicas y Técnicas - The National Scientific and Technological Research Council
CREA	Consorcios Regionales de Experimentación Agrícola - Regional Consortiums of Agriculture Experimentation. (Farm groups affiliated with AACREA)
DAP	Diammomium phosphate – fertilizer
DOY	Day of year
FAA	La Federación Agraria Argentina - The Argentine Agrarian Federation
FAO	Food and Agriculture Organization
FSR	Farming System Research
GDP	Gross domestic product
GHG	Greenhouse gas
GPS	Global Positioning System
HM	Hutchinson and Mosier
IAPI	El Instituto Argentino de Promoción del Intercambio – The Argentine Institute for Promotion of Trade
I.D	Inner diameter
IGI	Greenhouse gas interpretation (ratio value)
INT	Interview
INTA	Instituto Nacional de Tecnología Agropecuaria - National Institute of Agricultural Technology Argentina
ISI	Intensification sequence index
LER	Land equivalent ratio
MAP	Monoammonium phosphate – fertilizer
Mha	Mega hectare (ha x 10^6)
MT	Mega tonnes (Ton x 10^6)
N	Nitrogen
NH_4^+	Ammonium
N_2O	Nitrous oxide

NO_2^-	Nitrite
NO_3^-	Nitrate
O.D	Outer diameter
P	Phosphorus
PFTE	Polytetrafluoroethylene
Ppm	Parts per million (equal to mg/kg or mg/L)
RCBD	Randomize complete block design
RR	Roundup Ready
SC	corn sole cropping treatment.
SEBA	Southeast Buenos Aires
SI	Sustainable-intensification / Sustainable-intensive
SOC	Soil organic carbon
SS	Soybean sole cropping treatment.
SSA	Sub-Sahara Africa
^{T}	Interviews translated from Spanish to English
TCD	Thermal conductivity detector
UDAB	Unidad Demostrativa Agroecológica de Balcarce - Agroecological Demonstration Unit of Balcarce
UIB	Unidad Integrada Balcarce - Balcarce Integrated Unit
WFPS	Water-filled pore space
μECD	micro electron capture detector
1:2	One row corn to two rows soybean - Intercropping planting ratio and cropping treatment.
2:3	Two rows corn to three rows soybean - Intercropping planting ratio and cropping treatment.

LIST OF TERMS AND DEFINITIONS

Agroecology	A form of agriculture that combines agronomy and ecology to maintain yields while attempting to preserve social and environmental well-being by mimicking natural processes, enhancing functional biodiversity, and conserving on-site resources.
Agriculture intensification	A form of agriculture that is focused on agronomy and economics to achieve increased yields per unit of area, time and resource. Resources can be both natural and anthropogenic (i.e. water, solar radiation, cash, labour, fertilizer, agrochemicals).
CO_2 equivalent:	A standard unit for measuring carbon footprint. Each greenhouse gas (GHG; e.g. nitrous oxide or methane) are converted to the warming potential of carbon dioxide (CO_2.). The CO_2 equivalent is expressed as a single number, but that number can consist of many GHGs.
Double cropping	A cropping practice that involves growing two consecutive crops on the same land within the same growing season (i.e. a spring crop then a winter crop).

Farming System Research (FSR)	A flexible approach to evaluate farming systems and practices by understanding environmental problems and social constraints that affected crop production and agriculture technology transfer and adoption. The three core characteristics of FSR include the use of systems thinking, relying on multi/inter-disciplinarily, and the incorporation of social actors.
Greenhouse gases	Main greenhouse gases include carbon dioxide, nitrous oxide, methane, ozone, water vapour, chlorofluorocarbons, and hydrofluorocarbons. These gases contribute to the greenhouse effect within the Earth's atmosphere by absorbing and emitting radiant energy that is within the thermal infrared range.
Holistic	Refers to investigating a complex system by the sum of its parts (e.g. social, economic, political, biophysical components), rather than studying the parts in isolation.
Intercropping	A multi-cropping practice that involves growing two or more crops in proximity of each other for all or part of a growing period.
Intercropping greenhouse gas interpretation (IGI) value	A ratio calculation I created in Chapter 4 to evaluate intercropping GHG mitigation potential in comparison to combined corresponding sole crops. The calculation uses CO_2-C equivalents of cumulative soil greenhouse gas production. The calculation assumes that the combined land coverage of the two sole cropping systems equals that of the examined intercropping system.
Land equivalent ratio	A ratio calculation often used to evaluate the effectiveness of an intercropping design or use of a cultivar within multi-cropping environments. This calculation measures the relative yield of a crop in an intercropping system compared to the relative yield of the same crop in a sole cropping system.
Potential yields	Yield to be expected when the best-adapted variety is used along with best-suited management and in the absence of abiotic and biotic stresses (i.e. fulfilled nutrient and water supplementation and when pests, weeds and diseases are controlled).
Sole cropping	The practice of cultivating one crop in a field throughout a growing period.
Sustainable-intensification	A type of agriculture practice that is defined by Pretty 2008 (p.452) as *Intensification using natural, social (community), and human capital assets, combined with the use of best available technologies and inputs (best genotypes and best ecological management) that minimize or eliminate harm to the environment,* and was applied in this dissertation.
Water-limited yields	Yield similar to potential yield, though under rain-fed conditions. Water stress is not supported by supplemented irrigation.
Yield gap	The difference between the average potential yields and the average yields attained by farmers.

CHAPTER 1

GENERAL INTRODUCTION

1.1. INTRODUCTION

There is consensus that crop intensification should occur on prime agriculture land to ensure future food generation; this is in order to discontinue the extensification and degradation of marginal cropland and fragile natural ecosystems (Caviglia and Andrade 2010; Tilman et al. 2011; Garnett et al. 2013; Pretty and Bharucha 2014; Fischer et al. 2014, 18; Hunter et al. 2018). Crop intensification is defined as increasing crop yield per unit of land, time, and input (Gregory et al. 2002; Struik and Kuyper 2017). There are conflicting perspectives and theories on the impact of intensified agriculture. When intensification is viewed through a Malthusian or Neo-Malthusian lens, agriculture practices and consequent food-output limit population growth (Malthus 1798; Caviglia and Andrade 2010). In these views, non-renewable resources are exhausted and shorter fallow periods lead to environmental degradation enhancing food scarcity, and inevitably causing population decline (Malthus 1798; Turner and Ali 1996; Boserup 2005; Caviglia and Andrade 2010).

In contrast, Boserup (1987) argued that population pressure encourages technological advancements allowing for cropping practices to have shorter or eliminate fallow periods, without depleting resources or degrading the environment. If Boserup is correct, then intensification could be considered sustainable in the context of more effective use of growing seasons, natural resources, and human innovations (Caviglia and Andrade 2010; Droppelmann et al. 2017). Influenced by Boserup's views, researchers in the Argentine Pampas modified corn (*Zea mays*)-soybean (*Glycine max*) summer intercropping to be a modern cropping practice for sustainable-intensification (SI) (Caviglia and Andrade 2010). Intercropping is a multi-cropping practice that involves growing two or more crops in close proximity of one another for all or part of a growing period (Brooker et al. 2015; Fletcher et al. 2016). This doctoral research used natural and social scientific methods to assess if the corn-soybean intercropping practice is a suitable SI strategy, for the southeast Buenos Aires (SEBA) region of the Argentine Pampas.

1.1.1. Assessing sustainable-intensification

In general, SI is known as a strategy to enhance agriculture productivity without negatively impacting the environment, and by promoting social and environmental benefits (Weltin et al. 2018). Sustainable-intensification emerged in the 1990s as a concept directed towards smallholders (Pretty 1997; Struik and Kuyper 2017). Over three decades the concept broadened to cover a wide range of agriculture systems and a variety of sustainability issues (Wezel et al. 2015; Bernard and Lux 2017; Mahon et al. 2017). In the mid-2000s, the concept became of great interests in policy and research discourses (Bernard and Lux 2017; Mahon et al. 2018). Food insecurity as a threat to the global society became more pronounced due to the increasing body of evidence that agriculture intensification contributed to environmental degradation, climate change, and biodiversity losses – and due to the 2007-2008 food price crisis (Petersen and Snapp 2015; Mahon et al. 2017; Weltin et al. 2018). Sustainable-intensification evolved to be all-encompassing, including industrial and smallholder agriculture types and was applied to a wide range of objectives with different scopes, scales, and perspectives (Mahon et al. 2017; Struik and Kuyper 2017; Weltin et al. 2018).

The ambiguous use of the term “sustainable-intensification” has been met with widespread criticism. The concept has been accused of being too vague, an oxymoron, and too difficult to measure (Petersen and Snapp 2015; Gunton et al. 2016; Mahon et al. 2017; Weltin et al. 2018). Researchers were concerned that SI research without appropriate guidelines would lead to greenwashed practices with weak interpretations of the concept, rather than representing a useful paradigm shift in global agriculture (Petersen and Snapp 2015; Altieri et al. 2017; Mahon et al. 2017). Mahon et al. (2017) and Weltin et al. (2018) reviewed agriculture SI literature and assessments from 1990 to 2016; they revealed research was predominantly based at field scale with a productivist bias. The majority of SI research failed to address all aspects of sustainability, specifically social, economic and political dimensions (Mahon et al. 2017; Weltin et al. 2018). Published criticism and reviews on SI influenced this dissertation and other researchers to develop holistic SI frameworks, where holistic is defined as studying elements of a complex systems in an integrated manner (e.g. social, economic, political, biophysical components) – rather than studied in isolation (Sarewitz 2010, 65).

The few recent SI framework vary by rationale, scales, and farm types. An SI framework to holistically assess the performance of innovations for smallholders was created by Musuba et al. (2017) and applied in Malawi. Their assessment was used for innovations at any scale and focused on five domains: productivity, social, economic, human, and environmental. Struik and Kuyper (2017) suggest that smallholder low-input agriculture and modern industrialized agriculture use different assessment processes as their goals differ and there is a stark difference in labour and technology availability and efficiency. Recent, modernized agriculture SI framework have been developed (e.g., by Dicks et al. 2018, Polge and Debolini 2018, Mahon et al. 2018; and Weltin et al. 2018) for regions in Europe.

Each of these frameworks identified a different purpose for assessing SI. Mahon et al. (2018) created framework to identify SI indicators for different spatial scales, and Polge and Debolini (2018) created a similar framework for the landscape scale. Weltin et al. (2018) developed a flexible spatial and temporal scale framework and applied it to determine currently used practices that could be considered SI in four different regions in Europe. At the farm-scale, Dicks et al. (2018) made a framework to identify potential SI cropping practices already used by 14-76% of producers in the UK. In my doctoral research, a broad-scale holistic framework was developed to characterize the SI properties of a specific and emerging cropping practice in the Argentine Pampas - corn-soybean intercropping.

Suggestions on what a broad-scale holistic SI framework should include are emerging (Mahon et al. 2018; Weltin et al. 2018). My dissertation contains original research that provides one path for conducting broad-scale holistic SI research. Moreover, there is no holistic framework for assessing SI of emerging cropping practices for modernized agriculture, nor has modernized corn-soybean intercropping been assessed as an SI practice for a specific location. Mixed methods and the Farming Systems Research (FSR) approach were used to perform this study with multiple scales and scopes. Developing the assessment in a holistic manner involved taking into account the regional context, field-scale biophysical aspects of corn-soybean intercropping, and producers' and experts' perspective of the practice. The research design to assess corn-soybean intercropping was constructed using the principals of FSR, utilizing indicators that were highly recommended for evaluating SI, and by targeting identified research gaps for modernized corn-soybean intercropping. The dissertation is divided into three sections: i) the social and ecological context of the region, ii) greenhouse gas emissions derived from soils under corn-soybean intercropping, and iii) the adoptability of corn-soybean intercropping through the perspectives of social actors. These three studies were used as an empirical foundation to develop a holistic framework for assessing modernized cropping practices as SI. This framework is introduced in Chapter 6 and is applied to modernized corn-soybean intercropping implemented in the SEBA Pampas. The SEBA sub-region of the Argentine Pampas was used primarily for this study, however, politically, economically, and socially contexts of the region were connected at the Pampas and national scales.

1.1.2. Sustainable-intensification in Argentina

The Argentine Pampas is a relevant region to study SI because it contains a large proportion of prime agricultural land that has produced a substantial amount of cereal and oilseeds for Argentina and the world (Fischer et al. 2014, 184; Urcola et al. 2015; FAOSTAT

2017). Soybean is a dominant crop within the Pampas, partly due to the global demand for the crop to be used for livestock feed, processed foods, and biofuel (Richardson 2009). Soybean is intensively produced across the Pampean landscape, resulting in soil organic matter deterioration and biodiversity losses (Calviño and Monzon 2009, 61; Barral and Maceira 2011; Caviglia and Andrade 2010). In response, trials of corn-soybean intercropping initiated in the early 2000s as a strategy to fragment soybean fields, improve soil quality, efficiently use natural resources, and to increase crop production (Cavligia and Andrade 2010).

Corn and soybean are two economically and socially important crops produced in Argentina (Schnepf et al. 2001; Richardson 2009; FAO 2017). The South American nation generated ~ 17.5% of the world's soybean and ~ 4.7% of the world's corn, assigning Argentina as one of the top-four producers and exporters of the two crops in 2016 (FAO 2017). The demand for these two crops is expected to rise from 2007 levels by 60% for corn and 80% for soybean, while, the global population approaches 9.7 billion in 2050 (Fischer et al. 2014; 5). Considering Argentina serves as a global "breadbasket", Pampean producers and researchers are highly interested in determining ways to increase production without negatively impacting environmental and social wellbeing (Cavligia and Andrade 2010; Coll et al. 2012; Monzon et al. 2014). Achieving their goals will be challenging, as they will have to do it with less land, water and nutrients, while managing the effects of current land deterioration and adapting to climate uncertainties (Bernard and Lux 2016).

1.2. RESEARCH CONTEXT

This project was derived from a graduate exchange program organized by Dr. Oelbermann and Dr. Echarte and administered between the School of Environment, Resources, and Sustainability (Formally the Department of Environment and Resource Studies) with the University of Waterloo and the Balcarce Integrated Unit (UIB) research facility affiliated with the

University of Mar del Plata, BA. The UIB facility is located in the SEBA region of the Argentine Pampas. The exchange program involved investigating corn-soybean intercropping at a site established in 2006, located at the UIB facility. The corn-soybean intercropping site was utilized by many researchers over the years to study biophysical components of the cropping practice. The experimental trial set-up of the corn-soybean intercropping site accommodated conventional machinery, and was for studying potential yield and water-limited yields, meaning inputs were added to ensure sufficient nutrients and pest control. I conducted in-the-field biophysical research (natural science) at the UIB corn-soybean intercropping site, utilizing the pre-determined experimental trial set-up, during the summer seasons from October 2011-May 2013. I extended my dissertation to include a social component of intercropping by interviewing agriculturalists within the SEBA sub-region. My research findings (both social and natural) were integrated with results from other Pampean intercropping studies to form an interdisciplinary assessment of SEBA modified corn-soybean intercropping. The dissertation project was funded by the International Development Research Centre (IDRC), the Inter-American Institute for Cooperation on Agriculture (ICCA), the National Science and Engineering Council (NSERC), the Canadian Foundation of Innovation (CFI) agencies, Queen Elizabeth II Graduate Science and Technology Graduate Scholarship, Senate Graduate Scholarship, and, the University of Waterloo Graduate Scholarship.

1.3. MAIN RESEARCH QUESTION

This dissertation is an embedded designed case study, which refers to the merging of two or more investigations into a single research study with the integrations of both qualitative and quantitative methods (Yin 2003, 55; Patton 2015, 536). Within this case study, both qualitative and quantitative methods were incorporated, as an approach to study the biophysical, social, political, and economic dimensions that can affect the adoption and development of corn-soybean intercropping, as an SI cropping practice. The main research question examined in this dissertation is as follows:

> *Is modernized corn-soybean intercropping a suitable sustainable-intensive cropping practice for the southeast Buenos Aires region?*

Within the context of the main research question ‘suitability’ signifies:

- *the adoptability of the cropping practice to producers in the southeast Buenos Aires region; and*
- *the demonstration of having characteristics of sustainable intensification.*

This main question could be answered a number of ways and at different levels of detail considering agroecosystems are multifaceted. To answer this main question, the conceptual framework for this dissertation used the Farm Systems Research (FSR) approach. Farming Systems Research refers to research that involves assessing farming systems and practices, by understanding environmental problems and social constraints that affected crop production and agriculture technology transfer and adoption (Darnhofer et al. 2012, 5; Fischer et al. 2014; 307). Objectives to answer the main research question were influenced by SI reviews from Mahon et al. (2017) and Weltin et al. (2018). Before mentioning the objectives, the conceptual framework and dissertation foundation are introduced to clarify the research design used to answer the main research question.

1.4. CONCEPTUAL FRAMEWORK

Foundations for the FSR approach was initiated in the 1980s to understand environmental problems and social constraints within developing nations that affected crop production and agriculture technology transfer and adoption (Darnhofer et al. 2012, 5; Fischer et al. 2014, 307). Over time, the FSR focus expanded to include a broader range of objectives and for modernized agriculture systems (Collinson 2000, 51; Klerkx et al. 2012, 460; Fischer et al.

2014; 307). Sustainable-intensification origins and concepts have similarities to FSR. In the 1990s, SI was established to support smallholder livelihoods in Africa by improving the production of underutilized land (Pretty 1997; Weltin et al. 2018). Subsequently, research and development for SI were applied to modernized agriculture systems, as a tactic to manage food insecurities, adapt to climate changes, and minimize agriculture-related environmental degradation, and biodiversity losses (Pretty and Bharucha 2014; Wezel et al. 2015; Weltin et al. 2018).

Farming System Research does not have a specific research design (Darnhofer et al. 2012, 4). Likewise, SI has no predetermined instructions for assessing a given agricultural practice or innovation (Pretty and Bharucha 2014; Petersen and Snapp 2015; Altieri et al. 2017). The lack of specific instructions for FSR and SI is intentional to focus on a goal rather than set targets and to have the flexibility to meet regional suitability, rather than applying one size fits all solutions (Pretty and Bharucha 2014; Struik and Kuyper 2017; Weltin et al. 2018). Moreover, concepts of FSR and SI encourage (but not mandate) the use of holistic perspectives (Darnhofer et al. 2012,7; Mahon et al. 2017).

The FSR approach was chosen for this research because FSR is often used to assess agriculture practice adoption and development, and FSR qualities are similar to the concept of SI. The approach is defined by three core characteristics: utilizing systems thinking, relying on inter/multi disciplinarities, and integrating social actors (Darnhofer et al. 2012; 8).

1.4.1. Three core characteristics of the Farming Systems Research approach

i) Utilize systems thinking: Systems thinking research is distinctive from traditional reductionist research (Darnhofer et al. 2012, 7). Systems thinking focuses on the ‘why’ and ‘how’ it changed rather than the ‘what’ has changed (Patton 2015, 99). Answers to ‘why’ and ‘how’ question involve holistic investigations of a system, by looking at the interrelationships of system parts, how the system works over-time, and how the system interacts within the context of connected systems. Systems (including farming systems) are considered to be sub-systems within nested-set of systems and have permeable boundaries – a change in one sub-system can affect other sub-systems (Darnhofer et al. 2012, 9). Systems of interest are related to a purpose (i.e. main research question and objectives) (Darnhofer et al. 2012, 9). Therefore boundaries and sub-systems interactions are constructed uniquely and depend on researchers goals, experiences, and backgrounds.

ii) Rely on multi/inter-disciplinarity: A farming system whether its crop production, livestock rearing or combination of both, they are the integration of human-made objects combined with natural-made objects. As a result, farming systems relate to many disciplines including those in the biophysical, technical, economic, social, and political sciences. These disciplines integrate into many forms that are considered multi-disciplinary or interdisciplinary. Multi-disciplinary research addresses a question from different domains and different perspectives, but does not integrate the findings (Klien 2010, 17; Stock and Burton 2011; Darnhofer et al. 2012, 15). Interdisciplinary research is encouraged, but less often applied and varies in integration intensity; it is the integration of disciplines by organizing concepts, and methodologies to address "real world" problems and construct new knowledge (Klien 2010, 18; Stock and Burton 2011; Darnhofer et al. 2012, 15).

iii) Integrate social actors: The perspectives and knowledge sharing with producers and stakeholders are critical to understanding how "real-world" situations affect the adoptability of agriculture technologies and practices (Darnhofer et al. 2012, 8). Agricultural innovation is not only about developing the technology, researchers also have to consider the constraints and opportunities of the practice perceived by producers (Alomia-Hinojosa et al. 2018). Producers are the decision makers in their farming systems, and many factors can influence their choices that are not only field-scale or biophysically related (Blackstock et al. 2006; Meijer et al. 2015).

Producers sharing their perspectives can actively shape the research process, and this fuels knowledge transfer processes between researchers and producers (Darnhofer et al. 2012, 7).

1.4.2. Applied FSR framework and research boundaries

These three FSR core characteristics were used to frame the main question by incorporating four chapters that differed in scopes, methods, and scales as illustrated in Table 1.1. This research does not pretend to cover all factors involved in the development and implementation of a cropping practice – as this would require a team of experts and a more substantial investment in time and resources (Darnhofer et al. 2012, 23). Instead, the doctoral research included conducting a regional context historical overview (Chapter 3), a natural sciences study (Chapter 4), and a social sciences study (Chapter 5). These three studies were integrated to create an interdisciplinary study (Chapter 6).

Table 1.1. The scopes, methodologies and scales used in different chapters of this dissertation.

	Chapter 3	Chapter 4	Chapter 5	Chapter 6
Scope	History	Natural Science	Social Science	Interdisciplinary
Methodology	Document Analysis	Experimental Research	Qualitative Assessment	Grounded Theory
Data analysis	Qualitative	Quantitative	Qualitative	Qualitative
Temporal Scale (year)	1800-2014	2011-2013	2011-2013	1990 – 2016
Spatial Scale	Landscape Regional National	Field	Farm Landscape Regional National	Field Farm Landscape Regional National

The combination of these studies makes this dissertation both multidisciplinary and interdisciplinary. Combining social sciences with natural sciences aspects of crop production is recognized as a great challenge because it requires an examination of both quantitative and qualitative components, rather than one or the other (Darnhofer et al. 2012, 17). Natural scientists lean towards quantitative components from the physical dimensions of farming systems and often use reductive methods to obtain results (Darnhofer et al. 2012, 18). Social sciences tend to focus on more qulaitative components that interpret norms, values, reason, and meanings of human nature and activity (Darnhofer et al. 2012, 18). I took on the challenge to build a bridge between natural sciences and social sciences dimensions, to encompass a holistic perspective. Research boundaries were defined to study both natural and social sciences. Figure 1.1 illustrated the disciplinary boundaries used in this dissertation and Box 1.1 provides a detailed overview of Figure 1.1.

The blue highlighted region in Figure 1.1 depicts the disciplinary boundary of this dissertation. The boundary predominantly covers natural science areas, because most research on corn-soybean intercropping was within the natural science disciplines, and my disciplinary background is in natural science. Social actors were included to examine the main question holistically. Producers and agriculture practitioners were interviewed, and they shared their subjective perspectives on economics, policies and technological aspects. To have context of discussions in the interviews, an in-depth historical review was conducted on the Argentine Pampas for agriculture developments and socioecological context. Within the boundaries of this dissertation, specific objectives were created to answer the main research question. Objectives were formulated using research recommendations for SI and research gaps in corn-soybean intercropping.

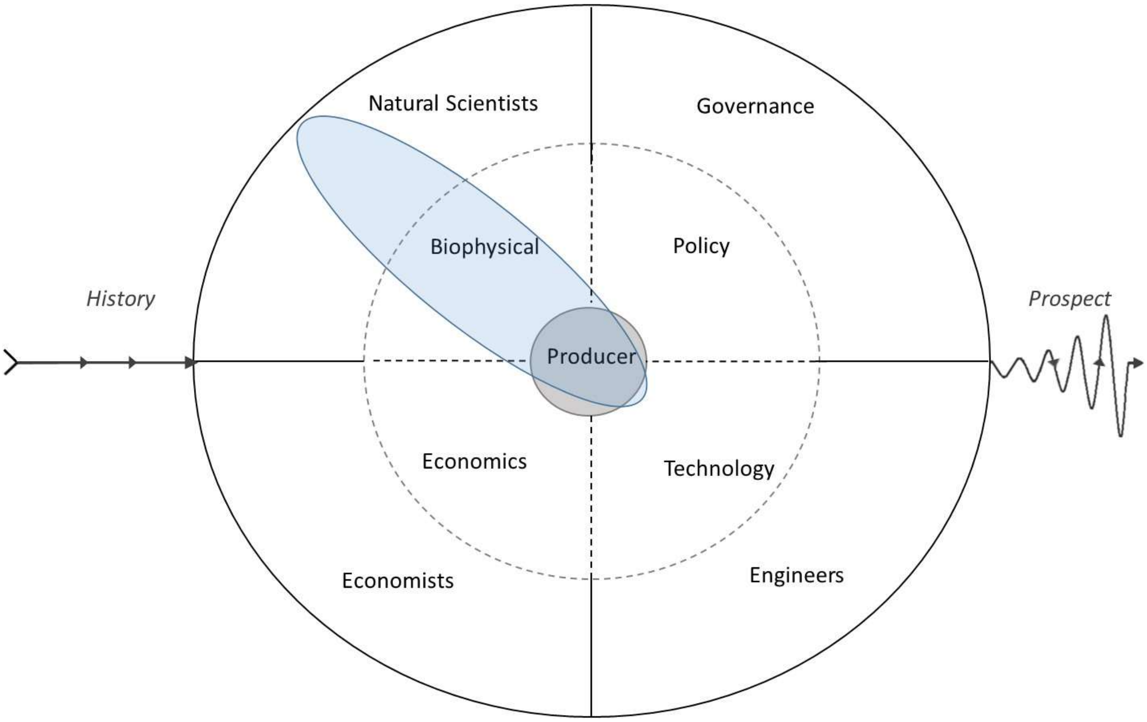

Figure 1.1. Illustration of the many options to study cropping practices and selected disciplinary boundaries. The blue highlighted area is the disciplinary boundary used in this dissertation.

Box 1.1. Agriculture research-producer boundaries and knowledge gaps

In Figure 1.1 producers are represented in the centre (gray circle) of the farming system. Producers are the end-decision makers on how, what, when, and where a crop is produced. The dotted-inner circle represents the multi-facets of a farming system - (biophysical, economics, policy, and technologies). These facets have cause-and-effect relationships with each other, and they influence producers' decisions. These facets are commonly studied and developed in isolation within (sub) disciplines –government, natural scientists, and engineers, economist. The outer circle represents the disciplines, and the solid line between each discipline illustrates disciplinary silos. The arrows labelled "history" and "prospect" represent how past events and future projections have shaped current decisions of researchers and producers. However, these two types of decision makers do not necessarily have the same goals or needs.

The early (1980s) FSR studies showed that producers were not adopting cropping methods promoted by agriculture researchers and extensionists. It was concluded that this happened partly because the novel innovations did not address the needs of the farmers (Darnhofer et al. 2012, 5). The FSR approach was then altered to emphasize the inclusion of social actors (Hart 2000, 45; Darnhofer et al. 2012,5). Research and development in crop production continue to be heavily based on biophysical and technological facets (Mahon et al. 2017; Weltin et al. 2018). Social actors are often excluded in crop production research and development, yet social actors shape how the land is used through decisions that are influenced by circumstances, knowledge, conflict resolution, and collective action (Blackstock et al. 2006; Meijer et al. 2015; Alomia-Hinojosa et al. 2018). The seldom use of social actors has created disconnects between scientists and producers, and this contributes to knowledge gaps and agriculture development problems (Ortega et al. 2016; Waldman et al. 2016; Droppelmann et al. 2017).

Developing a cropping practice that is adoptable to producers involves the consideration of social actors and the real-world impacts they face. A pivotal strategy for gaining this information is through the shared knowledge and perceptions of producers (Weltin et al. 2018). The blue-highlighted research boundary shows that the biophysical dimension of agriculture was used, as well as information from producers. Shared knowledge from producers allowed for insights into technology, economics, and policy facets. Highlighting the entire diagram would require a team of producers, specialized researchers, and inter-and trans disciplinarians.

1.4.3. Sustainable-intensification research reviews that support objectives

Some experts have expressed that SI is difficult to analyze objectively due to being intrinsically vague and multiscalar (Garnett and Godfray 2012; Petersen and Snapp 2015; Hunter et al. 2017), while other experts have encouraged the concept's evolvement and its characteristics (Garnett et al. 2013; Pretty and Bharucha 2014; Rockström et al. 2017). Mahon and Colluegues (2017) systematically reviewed SI literature (composed of 75 articles) to assess the number and type of indicators that have been used to study the concept. The total amount of indicators used to measure SI reached 218. The top four indicators were related to agriculture production outcomes, suggesting that the analysis in the studies were more objective and had a productivist bias. Mahon et al. (2017) recommended that future SI studies include the under-represented, social and political dimensions, apply holistic methods, and develop indicators according to farm type and scales. A more recent systematic review (composed of 349 articles) by Weltin et al. (2018) agreed with Mahon et al. (2017) that SI research required the incorporation of holistic methods.

In contrast to Mahon et al. (2017), Weltin and colleagues (2018) promoted the use of multi-scales. Furthermore, Weltin et al. (2018) found that social and economic dimensions were underrepresented, and the majority of studies were objective and at the field/farm scale. Weltin et al. (2018) explicitly emphasized that SI case studies were context sensitive (regionally and historically); thus critically dependent on situation knowledge from producers and stakeholders. Research findings and recommendations from both Mahon et al. (2017) and Weltin et al. (2018) helped structure the dissertation, and supported objectives used to answer the main research question. The following section displays the four studies within this dissertation and explicates each study's primary objectives, sub-objectives, study rationales, and the method overviews.

1.5. OBJECTIVES AND METHODS OVERVIEW

1.5.1. Study 1. Social-ecological context and historical overview of the Argentine Pampas

Overall objective

1. Provide socio-ecological context of the Pampean agriculture regime.

Specific objectives

1.1. To supply background knowledge and history overview to support perspectives of producers' comments concerning Pampean agriculture regime.

1.2. To reveal past events that influenced Argentina to be interested in increasing production units with SI cropping systems.

Study rationale

The socio-ecological and historical context was investigated because it contributed to the systems thinking and the multi/interdisciplinary components of FSR. Reviewing Pampean agriculture historical background provided familiarity with developments and evolution of its agrarian structure, which in turn aided in distinguishing events that shifted agriculture practices, as well gave insight to the desires for having SI cropping practices in the region. Furthermore, geological settings, historical developments, and current land use practices affect the suitability of a cropping practice to be SI within different places and agriculture systems (Weltin et al. 2018).

Methods overview

English and Spanish literature reviewed included Pampean geography, agriculture history, socio-ecological context, historical agro-political events, and land management transitions within the Argentine Pampas. Data were collected by electronic searches and reputable recommendations. Academic databases included in the review were: Primo, Scholars Portal, Google Scholar, JSTOR, and the National Institute of Agricultural Technology Argentina (INTA). Databases utilized for this study included the Food and Agriculture Organization (FAO), The Argentine Association of Regional Consortiums of Agriculture Experimentation (AACREA), and the Argentina Ministry of Agriculture, Ranching, and Fisheries (MAGyP). Reviewed recommended readings were suggested by Argentinian practitioners, scholars and informants.

1.5.2. Study 2: Evaluating CO_2 and N_2O emissions from corn-soybean intercropping systems during two contrasting hydrological growing seasons in the Argentine Pampas

Overall objective

2. To use natural science methodologies to evaluate and quantify soil emitted carbon dioxide (CO_2) and nitrous oxide (N_2O) from corn-soybean intercropping systems (a potential SI cropping practice).

Specific objectives

2.1. To quantify CO_2 and N_2O soil emissions in corn and soybean sole cropping and corn-soybean intercropping systems during two summer growing seasons.

2.2. To determine differences in CO_2 and N_2O soil emissions between corn and soybean sole cropping and two designs of corn-soybean intercropping.

2.3. To evaluate whether corn-soybean intercropping has the potential to act as a sustainable-intensive cropping practice that mitigates greenhouse gas emissions.

Study rationale

At the field scale, this dissertation focused on the mitigation potential of soil greenhouse gas (GHG) production. Quantitative data from biophysical variables obtained in this study contributed to assessing corn-soybean intercropping in a multi and inter-disciplinary manner. Sustainable-intensification literature strongly emphasized the need for strategies to reduce GHG production within agriculture systems (Tilman et al. 2011; Garnett et al. 2013; Mahon et al. 2017). In the Mahon et al. (2017) review, GHG production was the top suggested outcome indicator for assessing SI. Soil cultivation contributes to the releases of these two gases through land-use change, fertilizer usage and soil degradation. Cultivated lands have the capability of mitigating GHGs and sequestering carbon and nitrogen depending on the cropping and soil management practices used. Diversification and complexity are features of intercropping that are expected to aid producers in adapting to climate shifts and minimize contributions of GHG emissions (Brooker et al. 2015; Droppelmann et al. 2017; Struik and Kuyper 2017).

Few studies have evaluated soil GHG emissions from intercropping, as well intercropping studies vary by sampling durations, site conditions, crop combinations, crop configurations, and input management (Qin et al. 2013; Chapagain and Riseman 2014; Sánchez et al. 2016). Full season observations of soil derived GHG emissions did not exist for corn-soybean intercropping in the Argentine Pampas; intercropping trials are often studied in comparison to sole cropping. This study developed a tool to evaluate GHG emissions between intercropping and sole cropping.

Methods overview

Soil derived GHG emissions from corn-soybean intercropping was studied reductively and objectively. Two configurations of corn-soybean intercropping were compared to two corresponding sole crops in a randomized complete block design (RCBD) during the summer growing seasons for 2011-2012 and 2012-2013. The experimental site was located at the Balcarce Integrated Unit (UIB) research facility (37º 45’S, 58º 18’W), located in the SEBA region. Concentrations of carbon dioxide (CO_2) and nitrous oxide (N_2O), two GHG associated with land cultivation, were collected from the headspace of in-field static chambers. Data collection occurred weekly during the summer growing season. Gas concentrations were analyzed using gas chromatography, and fluxes of the two gases were calculated with the Venterea (2010) chamber bias correction model. Other quantitative data collected included soil moisture and temperature, soil nitrogen concentration, and weather parameters. Data from each treatment were compared within seasons and between growing seasons though parametric statistical analysis ($\alpha = 0.05$) using a Univariate General Linear model, T-test, and linear regression. Moreover, the yield and biomass land equivalent ratios for the two intercropping configurations were presented, and the intercropping GHG interpretation tool was introduced.

Field notes were collected on soil and crop management operations, plant growth stages, and harvest outcomes. The FSR approach is flexible; it encourages cropping research to take place in producers’ fields, though acknowledges implementing research in farmers’ fields is not always possible (Darnhofer et al. 2012, 21). Circumstances related to the practice being in early development limited the ability for corn-soybean intercropping to be studied in a producer’s field. As an alternative, I gained experience on the physical, biological and technical factors that directly related to corn and soybean sole cropping and intercropping cultivation, while working in the experimental field trial.

1.5.3. Study 3: Barriers and opportunities regarding adopting summer intercropping practices in the southeast Buenos Aires Pampa

Overall objective

3. To utilize the perspectives of producers and practitioners from the southeast Buenos Aires Pampas, to clarify adoption limitations and development opportunities for corn-soybean intercropping.

Specific objectives

3.1. To obtain producers' and practitioners' perspectives on the implementation of corn-soybean intercropping in their region.

3.2. To determine how Pampean agrarian structure, agro-economic, political affairs, and field management affects the development and adoptability of corn-soybean intercropping as a modern cropping practice.

Study rationale

The FSR approach promotes the integration of social actors to determine if a practice is regional suitable through adoptability. Moreover, there is recent evidence of low producer adoption rates for SI cropping and management practices (Bautista et al. 2016; Droppelman et al. 2017; Alomia-Hinojosa et al. 2018). Producer perspectives from past studies have revealed social, economic, technical, political, and cultural reasons for not adopting SI practices (Bautista et al. 2016; Droppelman et al. 2017; Alomia-Hinojosa et al. 2018). Latest SI literature has acknowledged the need to integrate producers participation in order for better representation of social, economic, and political dimensions and to conduct purposeful SI research (Mahon et al. 2017; Weltin et al. 2018; Dicks et al. 2018).

This study evaluated perspectives from producers and agricultural practitioners to determine opportunities and barriers for adopting corn-soybean intercropping, as an emerging SI cropping practice. Research on Pampean corn-soybean intercropping was predominantly based on biophysical variables. To my knowledge, producers' perspectives had not been analyzed in determining factors that directly and indirectly affected the adoption of corn-soybean intercropping in Argentina. Barriers and opportunities for the adoption of corn-soybean intercropping ranged from farm to national scale and covered technological, economic, political, social, and ecological dimensions. This study contributed to the dissertation – being a multi and interdisciplinary study – by providing a social-science component to assessing corn-soybean intercropping.

Methods overview

This qualitative inductive study used purposive sampling to gain the perspectives from cash crop producers and agricultural practitioners within the SEBA region of the Argentine Pampas. A total of twenty-four interviews were conducted within three months. Interviews comprised of eighteen semi-structured interviews with crop producers, and six unstructured interviews with agricultural practitioners.

Interviews were audio-recorded in English and in Spanish with the use of a translator. Interviews were transcribed in English, and analyzed using inductive and deductive processes (Patton 2015, 255; Palinkas et al. 2010). Interviews provided insight on cultural, technical, economic, and political factors that affect real-world logistics of corn-soybean intercropping. Situational knowledge was gained from these interviews which gave a stronger orientation to whether the cropping practices was a practical option, to be adopted in the SEBA region (Patton 2015, 367; Weltin et al. 2018).

1.5.4. Study 4: Characterizing corn-soybean intercropping as a sustainable-intensive cropping practice

Overall objective

4. To holistically characterize and evaluate whether corn-soybean intercropping is a sustainable-intensive (SI) cropping practice, by interconnecting research findings from my dissertation and other academic studies.

Specific objectives

4.1. To amalgamate studies within my dissertation and use an interdisciplinary perspective to assess corn-soybean intercropping, as a SI cropping practice.
4.2. To develop a holistic framework to assess and characterize a cropping practice as SI.
4.3. To evaluate whether corn-soybean intercropping is a SI cropping practice in the southeast Buenos-Aires.
4.4. To answer the main question of this dissertation from an interdisciplinary perspective.

Study rationale

Recent literature has recommended that SI agricultural practices be studied with holistic methods and interdisciplinary perspectives (Mahon et al. 2017 and Weltin et al. 2018), similar to what the FSR approach endorses. New frameworks are emerging that utilize recommendation from recent reviews to study small-scale cropping practices and to decipher if practices used in a region are considered SI (Musuba et al. 2017; Dicks et al. 2018; Polge and Debolini 2018; Mahon et al. 2018). I integrated the findings from Studies 1-3 to develop a framework specifically for assessing the appropriateness of classifying a modernized cropping practice as SI, and to distinguish whether the practice is a weak or strong interpretation of the term of SI. The framework was used to assess corn-soybean intercropping within the SEBA region of the

Argentine Pampas. From a review of literature, this is the first study to conduct an all-encompassing assessment on modernized corn-soybean intercropping.

Methods overview

A qualitative interdisciplinary study was constructed using my findings from the three previous studies in this dissertation, in addition to academic literature, and other data resources. The interdisciplinary investigation conducted was broad-scope and methods employed cross-cutting, organizational principals (Klein 2017, 16). A framework was created using grounded theory (Patton 2015, 110), the Jordan and Davis (2015) middle-way concept for SI, and indicators listed in Mahon et al. (2017) systematic research review. Categories and sub-categories emerged through a triangulation process (Patton 2015, 316). A bottom-up (data-driven) process was used within the framework to characterize corn-soybean intercropping, as a SI cropping practice. The framework and characterization process allowed for corn-soybean intercropping to be assessed for its suitability in the SEBA region using an interdisciplinary perspective

1.6. DISSERTATION STRUCTURE

This dissertation combines conventional chapters and publishable articles to bring together an interdisciplinary perspective into one conventional dissertation. In Chapter 2, I review terms and definitions associated with SI and intercropping. Chapter 3 contains the historical context of the study region. This third chapter familiarizes the reader with past and ongoing social and ecological occurrences that related to the main findings in the following study chapters. Chapter 4, 5 and 6 are the main study chapters. Chapter 4 presents the field-scale biophysical investigation that quantifies and evaluates soil GHG emissions from a long-term corn-soybean intercropping and sole cropping research site. Chapter 5 explores the limitations and opportunities of corn-soybean intercropping by qualitatively analyzing perspectives from producers and practitioner located in the SEBA region of the Argentine Pampas. Chapter 6 integrates findings from Chapters 3, 4 and 5 and results from other intercropping studies, to achieve a broad scale and interdisciplinary assessment that characterizes corn-soybean intercropping as an SI cropping practice. Lastly, Chapter 7 concludes the dissertation by summarizing findings from Chapters 3, 4, 5, and 6 and presents an overall conclusion of the main question. This last chapter discusses the research contributions of this dissertation, reflects on the trade-offs when conducting integrated research, and provides recommendations for future research.

CHAPTER 2

CROPPING PRACTICE BACKGROUND

Background on sustainable-intensification and intercropping

2.1. INTRODUCTION

There are different interpretations of the concept of sustainable-intensification (SI), and there are many ways to perform intercropping. The purpose of this chapter is to provide background and clarify terms associated with SI and intercropping. As well, this chapter explicates how SI and intercropping was used in the Argentine Pampas and within the context of this dissertation.

2.2. BACKGROUND ON SUSTAINABLE-INTENSIFICATION

Recent studies by Ray et al. (2013), Hunter et al. (2017), and Berners-Lee et al. (2018) are optimistic that yield improvements will be capable meeting the future demand of 9.7 billion people in 2050, but stress this can only occur with recalibrated SI strategies. The main issue with SI is that there is no common consensus of what it represents (Petersen and Snapp 2015; Wezel et al. 2017; Hunter et al. 2017). Pretty (1997) created the term in the 1990s for smallholders. Later the same author modified the definition to accommodate for a wider-range of agriculture systems; defining SI as:

> *Intensification using natural, social (community), and human capital assets, combined with the use of best available technologies and inputs (best genotypes and best ecological management) that minimize or eliminate harm to the environment.* – Pretty (2008, 451)

Since the publication by Pretty (2008), the number of articles published based on SI exponentially increased from 4 articles in 2009 to 103 articles in 2016 (Weltin et al. 2018). These articles came from all over the world, mostly originated from Europe, Asia, and Africa (Weltin et al. 2018). Authors of these articles had a range of skepticism and support for the SI concept (Garnett and Godfray 2012; Pretty and Bharucha 2014; Weltin et al. 2018; Dicks et al. 2018).

2.2.1. Skeptics of and supporters for sustainable-intensification

Many have criticized the SI concept as being vague and not having guidelines for any particular vision of agriculture production (Garnett and Godfray 2012; Petersen and Snapp 2015; Hunter et al. 2017). These concerns have led to debates on whether the concept is an oxymoron, has a productivist bias, and disguises “status quo” agriculture (Petersen and Snapp et al. 2015; Alteri et al. 2017; Mahon et al. 2017). Advocates for the concept are optimistic that it will start a useful paradigm shift in global agriculture to mitigate food insecurities, environmental degradations, and climate change (Garnett et al. 2013; Pretty and Bharucha. 2014; Rockström et al. 2017). Supporters of the concept agree that SI represents a goal to work towards rather than a strategy with pre-determined targets and prescriptive practices (Pretty and Bharucha 2014; Godfray 2015; Silberg et al. 2017; Struik and Kuyper 2017). The generally accepted SI goal is to produce more food and improve environmental goods and services (Pretty and Barucha 2014; Dicks et al. 2018). Some publications suggest that the political, social and economic implications need to be incorporated to meet all-encompassing goals of SI (Gunton et al. 2016; Struik and Kuyper 2017; Mahon et al. 2017; Weltin et al. 2018). Nevertheless, researchers have suggested frameworks be developed with the considerations of agriculture type (Mahon et al. 2017), multi-dimensions (Weltin et al. 2018), mid-way strategies (Jordan and Davis 2015), and distinctions between weak and strong interpretations (Altieri et al. 2017).

2.2.2. Specifying sustainable-intensification

Recently, Weltin et al. (2018) and Dicks et al. (2018) assessed modern cropping practices for SI within regions in Europe. Both emphasize the importance of regional suitability and middle-way strategies (defined in Box 2.1). Neither assessments went into detail on whether the practices were weak or strong representations of SI. Some cropping practices labelled as SI by these two authors included complex crop rotations, the incorporation of legumes, implementing flower strips, utilizing high-yielding or stress tolerant crop varieties, precision farming, integrated pest management, intercropping, and reduced tillage. The practices chosen depend on an author's selection criteria and goal (Weltin et al. 2018). For example, Dicks et al. (2018) selected practices that "…*might increase yields with no negative environmental or social impact, or reduce pollution with no impact on productivity*." This selection criterion displays favouritism towards agroecology, to avoid productivist biases that were revealed in recent literature reviews (Bernard and Lux 2017; Mahon et al. 2017).

Research and development of SI cropping practices in the Argentine Pampas had social and political incentives to focus on using "*environmental resources (water, solar radiation, nutrients) more intensely, maintaining or increasing crop yield per unit of area and using chemical inputs in a rational way*" (Caviglia and Andrade 2010). From 2003-2015 Pampean producers were not subsidized under the Kirchner-led government. Instead, they were heavily taxed to support national social services (Caviglia et al. 2013). Moreover, incomes in Argentina were affected by high inflation and peso devaluation. Political and economic circumstances influenced Pampean producers' cropping decision (Calviño and Monzon 2009, 55; Chapter 5). Producers had to find ways to increase production efficiency to keep their business viable – double cropping provided some relief to these hardships.

Box 2.1. Middle-way Strategy of combining conventional and agroecology agriculture

Middle-way strategies for modern SI can be perceived as the hybridization of conventional and agroecological cropping practices (Pretty and Barucha 2014; Jordan and Davis 2015). Where conventional cropping practices are considered intensive and productivist, with a focus on agronomy and economics. The main goals of conventional cropping are improving crop yield per area per unit of time with resource efficiency for short-term economic gains (Caviglia and Andrade 2010; Pretty and Barucha 2014). In contrast, and less common in large-scale systems, agroecological cropping practices combined agronomy and ecology with goals of long-term crop production by mimicking natural processes to enhance functional biodiversity, conserve on-site resources and preserve the environment and social wellbeing (Vanloqueren and Baret 2009; Altieri et al. 2017). Intercropping is known as an agroecology practice (Vanloqueren and Baret 2009; Altieri et al. 2017; Bybee-Finley and Ryan 2018), but within this dissertation, the practice was applied using conventional field management methods.

2.2.3. Double cropping as a sustainable-intensification practice in the Argentine Pampas

Double cropping of wheat (*Triticum aestivum*) in the winter and soybean (*Glycine max*) during the summer season was introduced in the Argentine Pampas in the 2000s. By 2008, 20% of the total land cultivated in the Pampas (~30 Mha) was under wheat-soybean double cropping management and was considered a practice that promoted SI (Caviglia and Andrade 2010; Campi 2011, 189). The practice shortened fallow periods and showed the benefits of improving water use efficiency, radiation efficiency, and aid in balancing soil carbon and nitrogen (Monzon et al. 2007). Double cropping increases production by shortening the fallow season from six months (May to October) to three months (May-July); allocating the practice to be valued as 1.5 on the intensification sequence index (ISI) (Caviglia and Andrade 2010). The ISI is one indicator of production intensification and represents the number of crops per year within a sequence (Farahani et al. 1998). The index ranges from 0.5 to 4; the lowest occurring in the western plains of Canada and USA where wheat-fallow is a standard sequence, and the highest ISI unit is 4, occurring in Asia where it is possible to grow rice (*Oryza sativa*) sequentially four times in a year (Farahani et al. 1998; Caviglia and Andrade 2010). Figure 2.1 displays cropping sequences used in the Argentine Pampas and potential practices for increasing the ISI in the region.

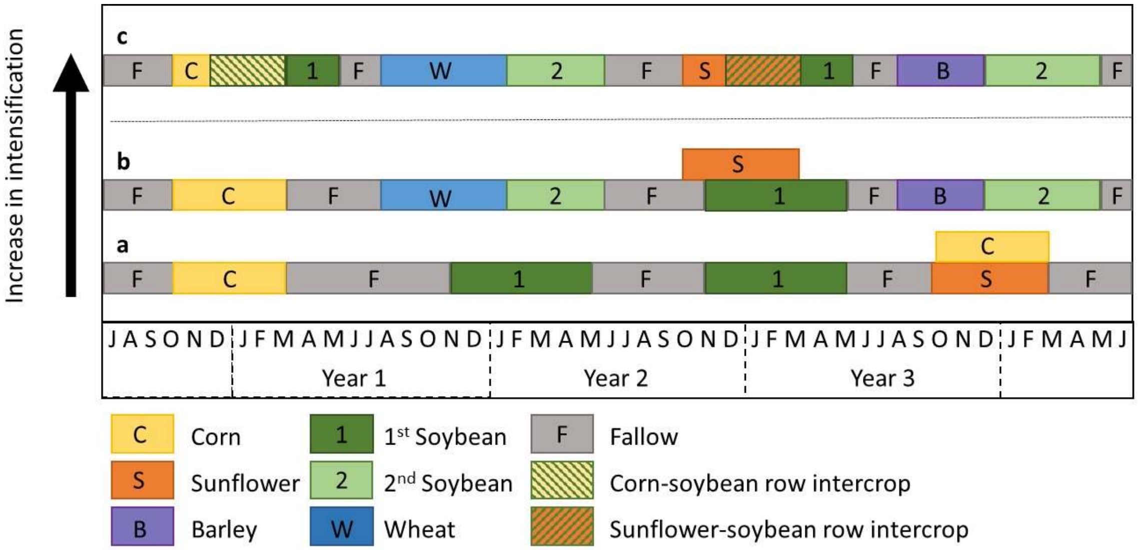

Figure 2.1. Common and proposed cropping sequences in the Argentine Pampas differing in intensification level. Cropping sequences ‘a’ and ‘b’ are commonly used, and ‘c’ is a proposal to increase intensification with the incorporation of summer intercropping. Within four years, the intensification sequence index (ISI) equals 1 for ‘a’, 1.5 for ‘b’, and 2 for ‘c’ (modified from Caviglia and Andrade 2010).

2.2.4. The need for more sustainable-intensification options

Double cropping eased the occurrence of monocropping (growing one crop species in a field consecutively), which is a practice associated with negative impacts on biodiversity and soil quality (Bernard and Lux 2017). However, Pampean double cropping practice continues to promote sole-cropping (growing one crop species in the field within a growing period) with simple crop rotations. Double-cropping is limited to a few winter crops (wheat and barley

[*Hordeum vulgare]*) – and soybean as the summer crop, until more SI cropping practices become available (Andrade et al. 2015).

Soybeans have the flexibility to be planted later in comparison to other regional summer crops – such as corn (*Zea mays)* and sunflower (*Helianthus annuus)*. However, soybean that is planted later to accommodate wheat harvest (a.k.a. second soybean) yields less than soybeans planted earlier in the spring (a.k.a. first soybean) (Caviglia et al. 2011). Compared to growing one crop in a season, double cropping and wheat-soybean relay intercropping are economically advantageous with 58-82% crop production increase (Calviño and Monzon 2009; Caviglia et al. 2011). The disadvantage of these winter crop-soybean cropping systems is that soybean disproportionately covers the rural landscape during the summer period (Caviglia and Andrade 2010; Andrade et al. 2015).

2.2.5. Interests in summer intercropping as a sustainable-intensive cropping practice

Research on corn-soybean and sunflower-soybean summer intercropping in the Argentine Pampas was a response to improve summer crop diversity, and determine other SI cropping practice options (Caviglia, and Andrade 2010; Monzon et al. 2014). Combining corn or sunflower with soybeans improves resource efficiency by allowing a second crop to be harvested on an area, that would otherwise be under fallow from March to May, in a corn or sunflower sole cropping scenario (Caviglia and Andrade 2010; Monzon et al. 2014). The use of intercropping and double cropping has the potential to increase the ISI up to 2, while adding more crop diversity within one growing season (Figure 2.1.c). Modern summer intercropping studies in the Pampas were in the preliminary stages (investigated since 2002). Researchers internationally have frequently suggested modern intercropping as an SI cropping practice (Shennan 2008; Petersen and Snapp 2015; Droppelmann et al. 2017; Struik and Kuyper 2017; Weltin et al. 2018). However, determining the logistics and crop combinations for each region still need to be refined (Vanloqueren and Baret 2009). The following section discusses the key components of intercropping research and management.

2.3. FUNDAMENTALS OF INTERCROPPING

Intercropping is more commonly used within smallholder agriculture in subtropical and tropical regions, as a strategy to use low capital investments, efficiently produce on small parcels of land, and minimize crop failure risks (Altieri et al. 2017; Kermah et al. 2017). Intercropping is less common in temperate regions due to the widespread use of modern varieties, mechanization, and input technologies specialized for sole cropping (Prithiviraj et al. 2000; Lithourgidis et al. 2011; Ehrmann and Ritz 2014). Within the last two decades, modernized intercropping is a subject of growing interest, at least in the research community (Lithourgidis et al. 2011; Brooker et al. 2015; Fletcher et al. 2016). A selection of intercrop combinations recently studied in temperate regions is displayed in Table 2.1. Some reasons to why there is research interest in intensifying land sustainably though modernizing intercropping include: producing more on prime arable land; reducing fertilizer and pesticide requirements; improving diversity and soil structure; and continuing advancements in field mechanization and agroecological engineering (Brooker et al. 2015; Altieri et al. 2017; Bybee-Finely and Ryan 2018).

A barrier to intercropping research involves the dedication of extra time and resources needed to investigate the practice. Within a season, often there is only enough time and resources to examine a few design variations, crop combinations, or crop varieties in a given intercropping study trial (Shennan 2008; Kermah et al. 2017). There are multiple temporal and spatial ways to design an intercropping system, adding to why research on this subject lack conformity (Vandemeer 1992, 3; Connolly et al. 2001; Bybee-Finley and Ryan 2018). The following subsections summarize the different intercropping styles, spacing and density options, and configurations designs. The differences between intercropping designs affect how crops interact below and above ground, and this impacts overall field performance.

Table 2.1. Examples of temperate intercropping studies from 2009-2018.

Crop Combination		Temperate Region	Reference
Soybean	Corn	Argentina, USA	Monzon et al. 2014
	Sunflower	Argentina; Germany	Schittenhelm 2010; Coll et al. 2012
	Sorghum (*Sorghum bicolor*)	Germany	Schittenhelm 2010
	Wheat	Argentina, USA,	Caviglia et al. 2011
Pea (*Pisum sativum*)	Barley	Canada; France; Denmark	Sahota and Malhi 2012; Chapagain and Riseman 2014; Bedoussac et al. 2015;
	Wheat	France	Bedoussac et al. 2015
	Oats (*Avena sativa)*	Germany; Finland; Austria	Kontturi et al. 2011; Jannoura et al. 2014; Neugschwandtner and Kaul 2014
	Canola	Canada	Sahota and Malhi 2012
Faba bean (*Vicia faba*)	Barley	Denmark	Bedoussac et al. 2015;
	Wheat	Denmark; UK	Barker and Dennett 2013; Bedoussac et al. 2015
	Canola	France	Jamont et al. 2013
Canola (*Brassica napus)*	Wheat	Canada	Hummel et al. 2009
	Pea	Australia	Fletcher et al. 2017
Red clover (*Trifolium pratense)*	Wheat	Canada	Gaudin et al. 2014

2.3.1. Intercropping temporal designs

Simultaneous and relay are the two main temporal designs used in intercropping. Simultaneous intercropping refers to planting two crop species at the same time. Relay intercropping designs involve staggering planting dates (Bybee-Finely and Ryan 2018) and as a consequence is more logistically complex than simultaneous intercropping (Caviglia 2009). Often relay intercropping is used to improve crop production performance or to lengthen a growing season in regions with climate restrictions (Prithivitaj et al. 2000; Coll et al. 2012). The cooler temperatures of southeast Buenos Aires (SEBA) region of Argentina influenced experimentation on modified relay intercropping of wheat (or barley)-soybean, and summer relay intercropping for corn-soybean and sunflower-soybean crop combinations (Monzon et al. 2007; Coll et al. 2012; Monzon et al. 2014).

Modified relay intercropping involves planting a summer crop into an existing maturing winter crop. For example, soybean is planted into heading wheat up to five weeks before the wheat is harvested (Caviglia et al. 2004). This type of intercropping is advantageous when there is time or climate restraints that limited the ability to perform soybean-wheat double cropping (Caviglia 2009; Fletcher et al. 2016). Summer relay intercropping involves planting both crops in the spring with staggering dates that are weeks to a month apart (Monzon et al. 2014). Staggering summer intercropping planting dates ensure crop species are sown during their ideal times, and to prevent critical growth periods of the two crops from overlapping (Prithivitaj et al. 2000; Coll et al. 2012; Bybee-Finley and Ryan 2018). In SEBA Argentina, corn was sown before soybean when intercropped. Corn was ideally sown in October and harvested in March (Coll et al. 2012; Andrade et al. 2012). Soybean as a sole summer crop (i.e. first soybean) yielded best when planted in mid-November, when the soil was warmer (Coll et al. 2012). In a double cropping scenario, soybeans (i.e. second soybean) planting occurs as late as January (Calviño et al. 2003). When soybean is intercropped with corn, planting is delayed until late November to early December, and then harvested in May (Coll et al. 2012).

2.3.2. Intercropping spatial designs

Intercropping spatial designs vary in pattern, configuration, spacing and density. The main patterns for annual intercropping are mixed, strip, and row (Bybee-Finley and Ryan 2018). Mixed intercropping involves growing two or more crops in close proximity without a distinctive arrangement. Strip intercropping refers to growing two or more crops in narrow, adjacent strips that allows crop species to interact but are wide enough to allow independent cultivation with modern equipment. Row cropping does not permit independent cultivation, because crops are planted in alternating rows to promote more agronomic interactions (Bybee-Finley and Ryan 2018). The corn-soybean intercropping practice evaluated in this dissertation was in the row formation.

Row intercropping includes two different total population density designs – additive and substitutive. The additive design has a constant density of one species and is combined with a range of densities of another species. The substitutive design maintains the total density and varies the row ratio of different crop species to each other (Vandermeer 1992, 16; Bybee-Finley and Ryan 2018). The crop row-ratio can have different configurations. Within this dissertation, the focus was on two row-substitutive corn-soybean intercropping designs that differed by configuration – one row of corn to two rows of soybean (1:2) and two rows of corn to three rows of soybean (2:3). Two configurations were examined in the experimental trials because both complementary and competitive effects within an intercropping system can be influenced by spatial design and relative crop species frequency.

2.3.3. Complementarity mechanisms

In an intercropping scenario, species are capable of exploiting resources within their surroundings more effectively than sole-cropping. Complementarity production mechanisms between intercrops allow for the more efficient use of resources, such as, nutrient, water, and space (Martin et al. 1991; Fletcher et al. 2016; Bybee-Finley and Ryan 2018). Resource partitioning and facilitation are the two mechanisms that contribute to complementarity effects within an intercropping system. Resource partitioning occurs when crops with different traits efficiently utilize available resources when grown together, rather than when grown separately

(Bybee-Finley and Ryan 2018). Intercropping crops with different rooting depth, phenology, and canopy structure can minimize competition and increase resource partitioning (Kermah et al. 2017; Bybee-Finley and Ryan 2018). For example, corn fibrous-type roots grow at a deeper depth than soybean's nitrogen-fixing taproots when intercropped (Gao et al. 2010). The variations in root structure, phenology and depth, allows corn and soybeans to obtain resources from different sources.

Facilitation is the mechanism where one crop species improves the environmental conditions or provides needed resources to another cropping species (Bybee-Finley and Ryan 2018). For example, soybean (and other legumes) has mutualistic symbiosis with nitrogen-fixing bacteria and mycorrhizal fungi (*vesicular-arbuscular mycorrhizal)* that can supplement corn with nitrogen, phosphorus, and other ions that can have limited mobility (i.e. zinc, copper, molybdenum) for plant uptake (Martin et al. 1991; Ghosh et al. 2007; Zhao et al. 2009). Facilitation can occur indirectly between two crops. Some examples include improved water use efficiency, soil quality, and pest control. When two crops have high water demands at different times in the season or obtain water from different soil depths, it reduces water loss from leaching and evaporation (Coll et al. 2012; Fletcher et al. 2016). For corn-soybean intercropping, the incorporation of cereal and legumes residues maintains soil structure, by balancing carbon and nitrogen, and providing a steady release of nutrients for plant uptake and microbial communities (Oelbermann and Echarte 2011). Above the ground, differences in canopy structures provide habitat for predatory insects that regulate herbivore pests (Martin et al. 1989; Shennan 2008; Sharaby et al. 2015; Lopes et al. 2015). The design of an intercrop will affect whether or not the system provides environmental benefits or reap greater production than sole-cropping. When intercropping systems produce less than sole cropping, it is related to competition between crops, where one is dominant, and the other crop is suppressed (Martin et al. 1998; Coll et al. 2012; Bybee-Finley and Ryan 2018).

2.3.4. Crop competition

Great consideration is needed for temporal and spatial elements of intercropping designs to avoid crops competing for resources and compromising yields (Silberg et al. 2017; Bybee-Finley and Ryan 2018). As mentioned earlier, staggered planting can help prevent resource competition between crops during crucial development stages. The ideal inter and intra-crop spacing prevents crop-crop competition, but use resources effectively enough to subdue weed growth (Snapp et al. 2010; Brooker et al. 2015; Kermah et al. 2017). This balance can be difficult to achieve (Struik and Kuyper 2017).

In the case of corn-soybean intercropping in the temperate regions of Argentina, corn is the dominant crop and soybean is the suppressed crop (Andrade et al. 2012; Monzon et al. 2014). Corn is planted earlier, tall in stature, and a heavy water consumer. Soybean is shaded by corn until the cereal is harvested, and this has a negative effect on soybean's overall growth (Coll et al. 2012). There are preferred traits for both crops to avoid corn dominance over soybean. Intercropping traits for corn include higher leaf tilt angle, lower leaf area, short stature, early maturing, and improved water-use efficiency (O'Leary and Smith 1999; Hauggaard-Nielsen et al. 2001). Traits for intercropped soybean comprise of determinate growth, earlier photosensitive maturing, later or longer flowering period, medium competitive root system, high radiation absorption capacity, and earlier establishment of symbiotic nitrogen fixation (Hauggaard-Nielsen et al. 2001; Valenzuela et al. 2009; Brooker et al. 2015).

2.3.5. The land equivalent ratio

The land equivalent ratio (LER) is often used to evaluate the effectiveness of an intercropping design or use of a cultivar within multi-cropping environments (Fletcher et al. 2016; Bybee-Finley and Ryan 2018). This calculation measures the relative yield of a crop in an intercropping system compared to the relative yield of the same crop in a sole cropping system (Vandermeer 1992, 19). The LER equation (Willey and Osiru 1972) is shown below:

$$LER = \frac{a_i}{a_s} + \frac{b_i}{b_s}$$ **Equation 2.1**

where "a" and "b" represent the yield or biomass per unit area of the two crops in an intercropping or sole cropping systems, and the subscripts "i" and "s" indicate the crops being intercropped or sole cropped, respectively.

The LER is the sum of two partial LERs. The partial LERs represent the ratio of yields (or biomass) of crops 'a' and 'b' grown as intercropping relative to sole crops. Partial LERs provide insight into competitive and complementary interactions when a crop is grown as an intercrop, as opposed to a sole crop. The summed LER value describes the amount of land that would be needed to obtain the yield or biomass of each crop species in an intercrop, if cultivated as a sole crop (Bybee-Finley and Ryan 2018). If the LER ratio is > 1, intercropping performed better than sole crops of its component species. An LER < 1 indicated that intercropping performed equally or less than in a sole cropping scenario (Vandermeer 1992, 19; Bybee-Finley and Ryan 2018). The LER is a useful tool to determine land use efficiency and evaluate yield and biomass progress. However, analyzing LER values need to be used with caution because the LER uses relative sole crop yields, not the average achievable yields of sole crops (Connolly et al. 2001). Moreover, the value of an LER from an additive design will more likely be higher than an LER from a substitutive design because the additive design has a higher planting density confounding the LER value (Connolly et al. 2001; Bybee-Finley and Ryan 2018).

Along with the LER calculation, other intercropping calculations are displayed in Vandemeer (1992). The calculations for intercropping were predominantly based on agronomic and ecological aspects by looking at productivity, income, input costs, resource efficiencies, and pest control. Within this dissertation, I suggest a tool to evaluate the environmental aspects of intercropping. The tool developed is for evaluating soil greenhouse gas emissions from an intercropping system compared to two corresponding sole crops (Chapter 4). The purpose of the developed tool was to aid researchers in finding strategies that reduce the environmental footprint of crop cultivation.

2.3.6. Interests in corn-soybean intercropping

Corn-soybean and sunflower-soybean were the two main substitutive relay-row summer intercropping crop combinations studied in SEBA. From an environmental perspective, corn-soybean intercropping had a couple of main advantages over sunflower-soybean – increasing diversity and soil quality. Soybean encroachment and the lack of crop diversification throughout the Argentine Pampas was a concern for agriculturalist and researchers (Calviño and Monzon 2009, 61; Barral and Maceira 2011; Coll et al. 2012; Bouza et al. 2016). In 2012 the cultivated area in the SEBA region of the Pampas during the summer was dominated by soybean covering 67%, followed by sunflower covering 27%, then corn covering 6% of cropland. (Coll et al. 2012). Corn-soybean intercropping had the potential to increase summer cereal coverage throughout the landscape by incorporating corn with commonly cultivated soybean.

The additions of cereal residues contribute to balancing the carbon content of soil throughout the region. Both soybean and sunflower are oilseeds and have residues with a low carbon to nitrogen (C:N) ratio (C:N ~ 13-25) (Stevenson et al. 1999, 200; Coll et al. 2012). These low carbon residues are conducive to decomposition and promote a net low carbon input (Caviglia and Andrade 2010). Carbon reductions in soils lead to deterioration, by interrupting soil biological processes, weakening soil structure, and enhancing carbon losses through erosion or emissions (Chen et al. 2004, 9; Coll et al. 2012; Oertel et al. 2016). Combining corn with soybean as an intercrop is a strategy to regulate soil carbon content by providing a mixture of high and low C:N residues to the soil within the same growing season (Regehr et al. 2015;

Olbermann et al. 2017). Cereal residues such as corn contain a higher C:N ratio (60-80) and are more resistant to decomposition and persist in soil for an extended time, slowly forming aggregate and sequestering carbon (Stevenson et al. 1999, 200; Chen et al. 2004, 6).

Corn-soybean intercropping has the potential to increase yields and landscape diversity, improve efficiency-use of natural resources, and promote carbon storage making this practice a candidate for SI from a biophysical perspective. The regional suitability and socio-economic factors also dictate whether a practice is suitable for SI or not. The following chapter provides the socio-ecological context and the historical developments that have played a part in forming the current Pampean agriculture model.

CHAPTER 3

HISTORICAL CONTEXT

Social and ecological context of the Argentine Pampas

3.1. INTRODUCTION

Simon Kuznets, a 1971 economist Nobel Prize recipient has remarked:

> *"There are four kinds of countries in the world: developed countries, undeveloped countries, Japan and Argentina."* (as cited by The Economist 2014).

Argentina is known for its volatility. In the past century, Argentina has swung between economic prosperity and collapse, unlike Japan that has been known for its rapid growth and industrialization (Jacobs 2012). During these fluctuations, agriculture in Argentina was directly impacted. This is notable because Argentina's agriculture sector has not only directly provided for the nation, it is also a primary contributor to the nation's Gross Domestic Products (GDPs) by exporting agricultural goods (Jacobs 2012). As a result, Argentina has a prominent role in international markets (Schnepf et al. 2001; Lence 2010). The success of the agriculture sector aids Argentina's economy allowing positive economic growth, or more recently, keeping the country afloat while in deep debt.

Pampean agriculture production of arable crops (specifically corn [*Zea mays*] and soybean (*Glycine* max) is a main fund conduit, and intuitively the Argentinian government has intervened with policies and regulations to gain revenue (Rojas 2002; Richardson 2009; Lence 2010). As an outcome, agriculture producers are pressured to produce more; inherently impacting producers crop management practices and decisions (Campi 2011, 18).

Agriculture systems in the Argentine Pampas have been altered throughout the decades, highly influenced by past events closely related to economics, politics and technology

(Campi 2011, 18). In order for agriculture researchers to develop crop management practices that are both sustainable and intensive, the capacity of natural resources, economic status, and implemented policies need to be considered as these factors have previously affected past agriculture models' success and deterioration. This extensive site description contains three sections: 3.2 describes the geography of the Pampas, and why its biophysical characteristics have allowed for agriculture success. 3.3 is an overview of the socio-economic and agriculture land management history of Argentina between 1800-2014. This section illustrates the strong dependence the nation has on its agriculture sector, and how agriculture shifts in the Pampas were influenced by national and international events. 3.4 summarizes the landscape changes and historical events that modernized Pampean agriculture, which has evoked interest in cropping practices that promote sustainable-intensification (SI).

The purpose of this chapter is to provide context to the Pampean agriculture system further supporting: i) producers comments in interviews in Chapter 5 and 6; ii) why Argentina is determined to increase production units, and iii) the focus on certain crops to aid in the adoption of cropping practices for SI.

3.2. GEOGRAPHY OF THE PAMPAS

The Pampas is one of the most agriculturally productive areas of the world covering 750,000 km^2 of South America, situated in the countries of Uruguay, Brazil and Argentina (Figure 3.1). The Pampas have vast, gentle, sloping plains that are rich in nutrients and organic matter, with a warm temperate climate (Caviglia and Andrade 2010; Campi 2011, 65). Approximately a sixth of Argentina's total area of 2,780,400 km^2 (278 Mha) is covered by the Pampas (Caviglia and Andrade 2010), located at (28-40°S and 57-66°W) within the provinces of Buenos Aires, Entre Rios, Santa Fe, Cordoba, and La Pampa (Campi 2011, 65; Pérez et al. 2015).

The Argentine Pampas are generally described as having warm summers (December – April) best suited for corn, soybean, and sunflower (*Helianthus annuus)* cash crops. The winters are mild (May-September) allowing for livestock to continue to graze, and for southern regions to grow cold-tolerant crops such as wheat (*Triticum aestivum)*, barley (*Hordeum vulgare)*, rye (*Secale cereal*), oats (*Avena sativa)*, lentils (*Lens culinaris*), and canola (*Brassica napus*; Campi 2011, 65).

Figure 3.1. The general coverage area of the South American Pampas (shaded in green).

The large area that the Pampas cover is heterogeneous with respect to landscape, soil and climate. Average rainfall declines from the northeast (annual mean 1200 mm) to the southwest (annual mean 400 mm) (Caviglia and Andrade 2010). As well, heavy monsoonal rainstorms called "pampeanos" occur more often in the northwest and become more evenly distributed in the southeast (Caviglia and Andrade 2010). Average annual temperatures are

13.5°C in the south and 18.5°C towards the north of the Pampas (Caviglia and Andrade 2010). Soils are predominantly Luvisols consisting of loess, but soil texture is sandy to sandy loam in the southwest, and clay to clay loam to the northeast (Caviglia and Andrade 2010). Fertility of soils (organic matter, nitrogen content, granular structure) decreases from the humid east to the sub-arid west (Viglizzo et al. 1997).

Viglizzo et al. (1997) distinguished five agro-ecologically homogenous biomes, which are Mesopotamian, Rolling, Central, Flooding and Southern (Figure 3.2). The Rolling Pampas are considered the most productive as the deep well-drained soils and climate allows for continuous cropping (Viglizzo 1997; Viglizzo et al. 2005). Most of the Central Pampas can be cultivated; however, soils become sandier to the west creating erosion issues (Viglizzo et al. 2005). The Mesopotamian and Flooding Pampas are common areas for beef production as there are water drainage and salinity limitations (Viglizzo et al. 2005). The Southern Pampas has the Tandilla hills that create slopes in the landscape; this area's agroecological features are best suited for double cropping summer and winter annual crops (Barral and Maceira 2012).

The Pampas is fundamental for meat and grain production in Argentina, with the highest output derived from the province of Buenos Aires (SIIA 2014) due to prime agroecological features and transport accessibility. Numerous agro-industries and ports for exports sit along the Río Paraná, the mouth of Río del Plata and the Atlantic coast, which are accessible by roads (and previously railroads) reducing the cost of transporting commodities (Morello et al. 2000; MAGyP 2014). Domestic consumption is considerably local as approximately 60% of the country's population lives in the Argentine Pampa provinces, with 46% residing in the Buenos Aires province, and approximately 20% living in the greater Buenos Aires city area (Censo 2010).

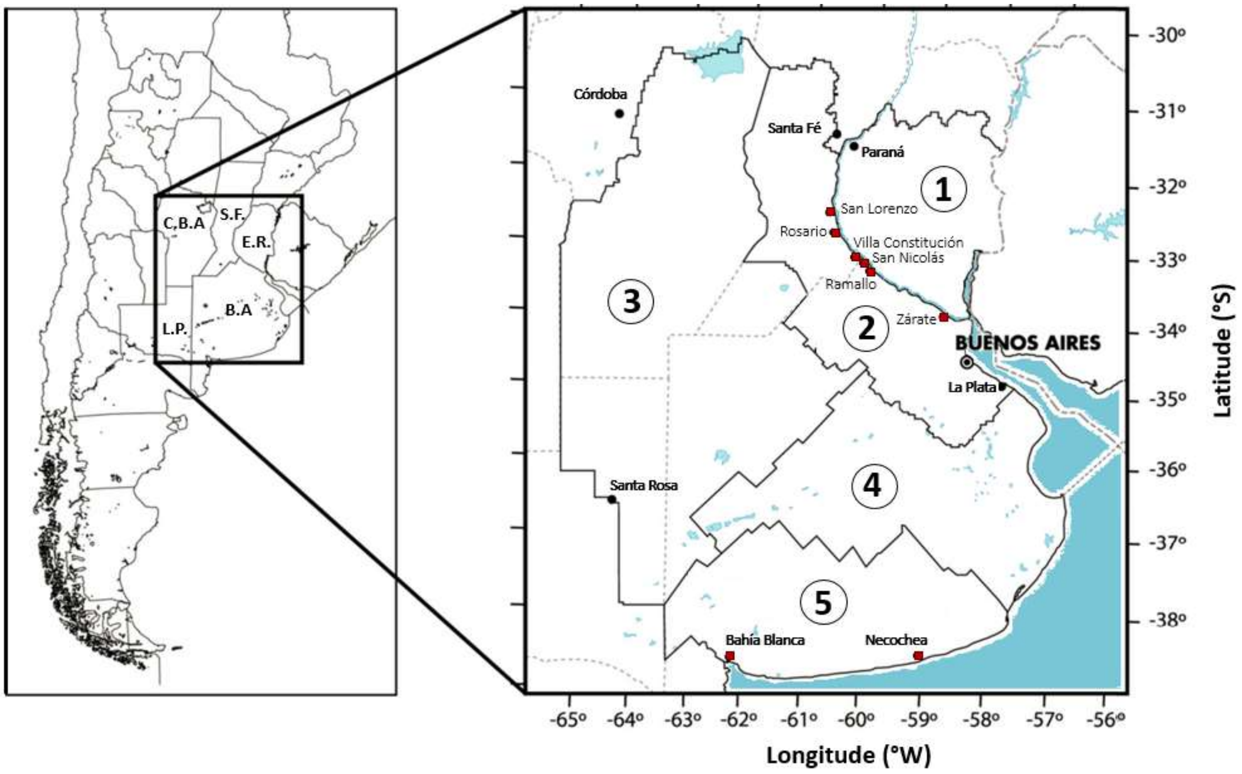

Figure 3.2. Argentine Pampas provincial and agro-ecoregion boundaries. Left map the provincial boundaries: (B.A.) Buenos Aires, (L.P) La Pampa, (C.B.A) Córdoba, (S.F.) Santa Fé, and (E.R.) Entre Ríos. The right map displays the five agro-ecoregions: (1) Mesopotamian, (2) Rolling, (3) Central, (4) Flooding, and (5) Southern. Red squares represent grain ports. The edited figure is sourced from Pérez et al. (2015).

3.3. SOCIO-ECONOMIC HISTORY OF AGRICULTURE IN THE ARGENTINE PAMPAS

3.3.1. Agriculture expansion into the Buenos Aires Pampas (1800-1915)

Agriculture developed slowly in the Buenos Aires Pampas. Originally, the region inhabited the Querandí Indigenous peoples, who subsisted mainly on animal fat from rhea, guanaco, and deer (Rock 1987, 8). In the 1600s, Gauchos (a mix of Spaniard and Indigenous descent) also roamed the region hunting wild cattle, to be sold and exported for meat, hide and tallow (Rock 1987, 24). A century later wild cattle population declined, prompting Gauchos and migrants to settle on the outskirts of the city of Buenos Aires to manage sheep and cattle operations, and to cultivate small plots of land (Rock 1987, 46). These occupied lands were confiscated in the 1830s to become land titles for estates (Rock 1987, 107). By the 1840s, these estates were sold (total of 8.5 Mha) to a few hundred powerful landlords (Rock 1987, 154; Rojas 2002, 20). Most of the bought land was reserved for ranching, with some plots leased by agriculture smallholders (Rock 1987, 115).

Agriculture development reached a turning point in the 1860s. Those governing Argentina wanted to expand settlements into the Pampas territory to increase revenue from the exportation of livestock and agriculture goods; as well to "clear the way" to claim the Patagonia region (Rock 1987,154; Rojas 2002, 20). Profits from the estate sales financed the "Conquest of the Wilderness" campaign, where a military expedition subdued, displaced, and killed Indigenous groups throughout the Pampas and surrounding regions (Rock 1987, 154). This land (30.4 Mha) taken from Indigenous groups, was used as pasture for sheep and cattle for the remainder of the 19th century (Slatta 1983, 2). As land expansion for agriculture was underway, the Republic of Argentina secured political structures to establish a capitalistic economy advancing agricultural and industrial sectors (Rojas 2002, 21). External capital and labour were received through massive immigration of southern Europeans (i.e. Spanish, Italians, Germans, and French) who sought high wages due to Argentina's labour scarcities (Rojas 2002, 21; Barksy and Gelman 2009, 167). Foreign investments supported the establishment of settlements through infrastructure and railroads construction. Railroads were essential for transport to create industry and national markets, and to distribute agricultural products (Rojas 2002, 22; Barksy and Gelman 2009, 171; Campi 2011, 55).

The Buenos Aires province became the foundation of Argentina's export economy (Rojas 2002, 20). Argentina agriculture economic model was heavily based on agricultural land expansion, extensively managing livestock, and rotating annual crops (Barksy and Gelman 2009, 174; Campi 2011, 75). Coincidently the Pampas was extraordinarily fertile allowing minimal management efforts to obtain efficient yields for meat production, and cereal and oilseed crops, mainly wheat, corn, and flaxseeds (Lewis 2002, 63; Rojas 2002, 21; Barksy and Gelman 2009, 191; Campi 2011, 24). Foreign demand and domestic industry altered the Pampas to be one of the world's leading crop-producing regions, making Argentina a competitor in the international markets. The nation's trade surplus multiplied over 13 times between 1865 and 1914 (Rojas 2002, 21) identifying Argentina as one of the world's top ten richest countries per capita (Rojas 2002, 44).

3.3.2. Economic prosperity and world wars (1915-1955)

Since the early 1900s, Argentina's economic well-being was dependant on the Pampas to supply international markets with corn, flaxseed, meat, and wheat (Rojas 2002, 38; Barsky and Gelman 2009, 311). After the Great War, global yields saturated the market lowering international prices, devastating Argentina's economy (Lewis 2002, 88; Barksy and Gelman 2009, 267). During this period, landowners shifted land between ranching and cultivating depending on market conditions. Ranching was low cost and low risk with little capital and labour investments. Land renters tried to improve profits by cultivating land intensively and finding strategies to lower the cost of production (Lewis 2002, 64; Campi 2011, 69). Renters were focused on profitability as it became increasingly difficult to pay land dues or to receive advanced loans for food and supplies. The rural population declined as smallholders and farm labourers migrated from the countryside to the outskirts of cities looking for urban employment (Barksy and Gelman 2009, 318). In attempts to maintain the rural populations, a law was passed to support smallholder producers by freezing rent fee for four years (Barksy and Gelman 2009, 319).

By the 1930s, droughts in North America and areas of Europe, boosted Argentina to become the eleventh largest exporter, with 96% of their export goods derived from the agriculture sector – partitioned as 40% meat and 60% grains (Barksy and Gelman 2009, 311).

Their economy declined by 1942 when international prices fell by 41%, leading many Argentinians to bankruptcy (Barksy and Gelman 2009, 319). These financial lows contributed to the subdivision and deconcentrating of farm properties. Landowners sold sections of properties as currency inflation, and rent freezes decreased receivable income (Barksy and Gelman 2009, 320; Gras 2009, 348; Campi 2011, 107). From 1914 to 1947 ownership of land doubled, and family farms provided 80% of agriculture commodities to the domestic market (Rojas 2002). Small and medium-scale family farms managed low input cattle-annual crop rotations on properties averaging 247.6 ha (Barksy and Gelman 2009, 322).

The occurrence of the Second World War halted Argentina's export developments by severely restricting foreign trade. The Argentinian government-initiated tariffs, exchange controls, import restrictions and substitution, and taxes on agriculture exports, to prevent overproduction and fluxes in commodity prices to protect domestic consumers (Cavallo and Mundlak 1982; Rojas 2002, 60; Barksy and Gelman 2009, 357). Diversions of investments from agriculture advancements and rural development shifted to labour-intensive manufacturing industries and urban services, such as, transportation, energy, communication, food processing, labour unions, and social services to improve the quality of life in urban areas (Cavallo and Mundlak 1982; Barksy and Gelman 2009, 365). Argentina became a welfare state as a strategy to be self-sufficient and to avoid downfalls from international influence, such as, future wars (Cavallo and Mundalk 1982, 20). A country that was once a very open economy transformed into one of the world's most closed economies.

During the1940s, Argentina contained the largest middle social class on the continent; however, politics were biased against the agriculture sector (Cavallo and Mundlak 1982, 20). Producers were prevented from selling directly to the international market, which had commodity prices increasing by 11% per annum. Instead producers sold to the domestic market that increased only by 5.9% per annum (Cavallo and Mundlak 1982, 20; Rojas 2002, 66), or to the Argentine Institute for Promotion of Trade (IAPI established in 1946); a government division which bought cereals and meats from the producers at a set price and sold the commodities when international prices were high (Rojas 2002, 65; Barksy and Gelman 2009, 361). The profits gained by the IAPA funded industry projects and welfare services, along with controlling inflation and food prices (Rojas 2002, 65; Barksy and Gelman 2009, 363).

Argentina's crop production marginalized in the world's economy; the rural population declined by 26% from 1946 to 1950 and agriculture productivity decreased by 0.2% annually (Cavallo and Mundlak 1982, 20). Agriculture wages grew by 5.4% annually, displaying the labour scarcity from urban migration; urban wages continued to grow by 2% annually (Cavallo and Mundalk 1982, 20). Exports were reduced as domestic consumption increased rapidly with improved living conditions; 80% of both meat and cereal products were nationally consumed (Rojas 2002, 65). As Argentina depreciated its agriculture sector, other countries invested in their agriculture to modernize with the green revolution movement (Cavallo and Mundlak 1982, 91; Rojas 2002, 78).

European countries rebuilt their agriculture regime and prioritized protecting their farmers and economies. European and North American countries applied new agriculture technologies that increased yields and overall production, such as, using petroleum powered machinery, plant genetics, fertilizers, and agrochemicals (Cavallo and Mundlak 1982, 91; Rojas 2002, 78). Argentina lost their foreign investors and trading partners. Specifically, Great Britain stopped investing and trading with Argentina to favour business with Commonwealth countries, with the USA to pay debts, and with Asia when the Panama Canal opened (Rojas 2002, 65; Barksy and Gelman 2009, 363). The restriction of external flows of goods, labour, and capital, limited Argentina's accessibility to new yield-increasing technologies. This resulted in stagnant agriculture production following the deterioration of their transport system and infrastructures, such as, warehouses, silos, and bulk facilities at ports (Rojas 2002, 115; Barksy and Gelman 2009, 363; Campi 2011, 119).

3.3.3. Opening the ports to the Green Revolution (1956-1965)

Argentina's deteriorating agricultural sector during the 1950s resulted in a production gap. For example, Argentina's corn yields were 55% of those obtained in the USA (Campi 2009, 126); outcomes that triggered initiatives to transform the Pampean agricultural model. The National Agriculture Technology Institute (INTA 1956) government agency and agricultural companies worked closely with producers to determine cropping techniques that were best adapted to the Pampa environment. These stakeholders further collaborated to distribute new seed hybrids for corn and wheat that were better yielding, along with new crops: sorghum, sunflower, and soybeans (Barsky and Gelman 2009, 396; Campi 2011,190; Manuel-Navarrete and Gallopín 2012). Soon after, farmer groups known as CREA (Regional Consortium of Agriculture Experimentation) were formed. These groups consisted of producers who discussed ways to increase productivity, reduce costs, and to receive higher profits. The high participation in these groups encouraged producers to crop-share as opposed to traditional leases (Campi 2011, 158).

During the formation of agricultural groups, substantial changes to economic policies occurred to regulate high inflation rates triggered by high wages, an overvalued currency, and an economy based on exports that were also central to domestic consumption (Rojas 2002; Barksy and Gelman 2009, 392). Taxes remained but trade barriers lowered; the peso was put against foreign currency, and foreign borrowing was restored giving producers financial support. Investments in electricity and petroleum infrastructure, road extension, and agro-industry were promoted (Rojas 2002, 81). Infrastructure investments, set policies, and a flourishing domestic industry allowed producers to modernize.

Tractors and mechanical harvesters were quickly adopted as field labour was scarce, and the increase of power per hectare lowered production costs (Campi 2011, 154). Modern mechanization influenced increased field output, by permitting consistent seeding density and depth and shortening the time required for planting and harvesting (Campi 2011, 157). Even though temporary and permanent labour requirements decreased, some small firms invested in agriculture machinery and employed people with good technical skills and cultivation knowledge to become contractors (Barsky and Gelman 2009, 497). Contractors were outsourced labour that plowed, conventionally tilled, planted, and harvested fields mechanically, allowing machinery access that was affordable to small and medium producers (Campi 2011, 172). The increase in agriculture capital expanded cultivated land coverage and improved yields; agriculture products amounted to 90% of their total exports (Lence 2010, 413; Campi 2011, 150). However, liberal trade policies weakened local industry – including agriculture products – as imports were cheaper to buy than domestic products.

3.3.4. Presidential turmoil (1966-1989)

Argentina has had a succession of military coups, the first from 1930-1932, then followed 1943-1946 and 1955-1958. Acknowledging the past military coups aids in understanding the decades of drastic changes in Argentina's policies and economy (Rojas 2002, 75). Repeated military coups occurred from 1966-1973 and 1975-1983. In seventeen years (1966-1983) there were twelve presidents, a high turnover of leaders during a critical time where considerable attention was required for the nation's economy (Rojas 2002, 89). Instead, military presidents' central concerns were to maintain power, by making short-term solutions for price stability and deficit reduction (Lewis 2002, 136; Rojas 2002, 80). Military governments attempted various programs to reduce inflation, such as, cutting many social services and wages, and devaluing the currency (Rojas 2002, 90; Romero 2013, 173). Inflation was a consistent issue that accelerated sharply to 300% from 1975 to 1979 (Rojas 2002, 90). Public debt increased as international banks loaned funds to Argentina to cover budget deficits and to pay interests on accumulated loans (Rojas 2002, 80).

Frequent changes in governmental power in the late 1960s to early 1980s did not prevent the Pampa's participation in the Green Revolution. The strong foundation of agricultural groups, research institutions and companies, and the introduction of herbicides and fertilizers supported yield progress and alternations to the Pampean landscape. By 1974, Argentina agricultural output reached the same output from 33 years previously, which was 24 million tonnes (Campi 2011, 148). The rate of agricultural production continued to increase by an annual average of 4.5% until 1985 (Campi 2011, 150). In the 1980s, agricultural export taxes accounted for nearly one-third of Argentine federal tax receipts; it was the first decade where production grew simultaneously for both livestock and crop cultivation (Deese and Reader 2007, 10).

Sub-regions of the Pampas were allocated for grain cultivation and other areas for livestock and mixed agriculture, a process that detached and specialized Pampean agricultural systems (Campi 2011, 151). Livestock and mixed agriculture were designated to flood-prone regions of the Pampas (Deblitz and Ostrowski 2004), while, prime arable land was dedicated for cultivation. By 1985, the cultivation of wheat, corn, sunflower, sorghum, and soybeans increased to 95% (previously 70% in the 1950s); barley, rye, and flaxseed lost relevance to the Pampas (Prentice and Storey 1989; Campi 2011, 151). The development of short-season wheat in the 1980s benefitted the southeast region of Buenos Aires, where previously the area was considered marginal land, since the cropping season entailed a longer cycle for wheat (Barsky and Gelman 2009, 433; Campi 2011, 176).

Agricultural production in the Pampas decelerated by 1985. The use of intensive tillage and simplified rotation practices encouraged soil erosion, which degraded the chemical, physical and biological features of the Pampas, resulting in limited production. Moreover, the modern agricultural model had revealed economic vulnerabilities from agricultural price falls, limited financing, and unstable macroeconomics (Campi 2011, 172; Viglizzo and Frank 2006). Democracy was restored, though economic collapse quickly ensued. The national debt accumulated to over $40 billion USD plus interest and the country was bankrupt (Rojas 2002, 99). Industry and social mobility declined, and over 400,000 companies of various sizes were bankrupt (Rojas 2002, 92). Food shortages, tragic peso devaluation, and hyperinflation reaching an estimated 12,000% per annum lead to a series of riots in 1989 (Rojas 2002, 102).

3.3.5. Convertibility to transgenes (1990-2000)

The 1990s were devoted to restructuring Argentina's economy for prolonged economic growth by controlling accumulated external debt and hyperinflation from the previous decades. The 1991 Convertibility Plan changed Argentina's political regime to neoliberalism (Manzanal 2008, 2; Gras and Hernández 2014, 339). The peso was at par with the USD dollar, as a strategy for domestic currency acceptance, since Argentinians started to demand payment in USD currency (Rojas 2002, 110; Campi 2012, 183). Regressive and value-added tax policies were applied to control tax evasion and increase public revenues. The grain and meat markets were deregulated, reducing the gap between national and international commodity prices (Manzanal 2008, 7). Privatization occurred in the natural resource, transport, energy, communication, and financial sectors (Rojas 2002, 114). Public institutions were dismantled, diminishing equal education, health, and housing (Manzanal 2008, 3). Privatization and foreign investments were encouraged (Rojas 2002, 106). The Convertibility Plan negatively affected Argentina's poorest population, but reduced inflation sharply, improving the quality of life for the rest of Argentina's social classes (Manzanal 2008, 2).

Smallholder domestic producers struggled to compete beside larger producers and importers due to the reduction in farm subsidies, trade protection, increased interest rates on agricultural loans, and value-added taxes (Manzanal 2008, 9). The systematic discrimination and exclusion towards small-scale agricultural systems reduced crop diversity and production of regional crops (i.e. flaxseed and vegetables; Manzanal 2008, 5). Smallholders who could not compete sold or leased their properties to the larger producers. From 1988 to 2002, the number of farms decreased by 21% (105,948 to 134,112 farms) and the average farm size increased by 25% (382 to 510 ha; Gras and Hernández 2014, 343). Some who leased or sold their land conformed by becoming contractors who sowed, sprayed and/or harvested owned and leased land (Gras and Hernández 2014, 343). Contractors significantly increased agriculture productivity by changing the organization of land, capital, and human resources related to agrochemical and biotechnologies, making the incorporation of new technology profitable (Barsky and Gelman 2009, 496; Gras and Hernández 2014).

The peso at par with the USD dollar caused an influx of imported machinery and agro-supplies allowing for modernization in agriculture and industry (Rojas 2002, 107; Manzanal 2008, 8; Campi 2011, 185; Nogués 2011). Soil structure improved as modified and new machinery allowed for producers to adopt no-tillage. Soils were nutrient replenished using fertilizers (McKell and Peiretti 2004). Similarly to other nations, synthetic fertilizers became an essential input in the Pampas. From1990 to 2007 total nitrogen inputs increased eight-fold from 0.10 MT to 0.94 MT, contributing to the doubling of grain production (Campi 2011, 210; IFASTAT 2018). The agricultural system in the Pampas shifted from extensive to intensive, promoting the production of wheat, soybean, corn and beef for export (Gras and Hernández 2014, 341). Argentina was open to agro-technology projects and programs from agricultural companies, such as, Monsanto, Syngenta, and Bayer (Gras and Hernández 2014, 344). In 1991, the National Advisory Committee of agricultural biotechnology institution was created to supervise transgenic seed programs (Gras and Hernández 2014, 343). By 1996, Argentina was one of the first countries to readily adopt transgenic Round-up Ready (RR) soybean combined with glyphosate herbicide (Round up ®). Soybeans became easier to manage, and the international market expressed a high price and high demand for the crop. Within four years, 90% of the soybean sowed in Argentina were of the glyphosate-tolerant variety (Pengue 2005; Campi 2011, 201). The combination of short-season wheat and soybeans intensified land-use for grain production in the Southern Pampas agro-ecoregion through the practice of double cropping (Caviglia and Andrade 2010; Campi 2011, 195).

Argentina's economy grew 50% from 1990 to 1998 (Campi 2011, 189), but its growth and the Convertibility Plan was short-lived; the nation entered a three-year-long recession in 1999 (Nogués 2011). Argentina trade advantage diminished with the fixed exchange rate and by currency devaluation of competitors Brazil and Mexico (Rojas 2002, 133). Progressively the fixed exchange rate reduced imports costs, weakening national industrial infrastructure, and ultimately reduced employment and tax revenues (Rojas 2002, 119). Economic and political instability ensued, with feverous government spending, growing external public debt and receiving various international loans, bonds and I.O.Us, particularly large loans from the International Monetary Fund (Rojas 2002, 122; Hornbeck 2010).

3.3.6. The great depression of the millennia (2001-2003)

The Convertibility Plan ended with an economic collapse at the end of 2001 (Rojas 2002, 118). To balance national budgets and to minimize bad credit ratings, governments froze spending, increased taxes, imposed pay cuts, reduced retirement benefits, and enforced conversion of all USD dollar bank deposits to pesos at an exchange rate below the market level (Rojas 2002, 123). The economy declined 20% from 1998-2002 (Rojas 2002, 135) with unemployment reaching 21.5% (Manzanal 2008, 2). Bank accounts were frozen to an initial spending limit of $250 ARS per week to prevent Argentinians withdrawing all their savings or relocating money abroad (Romero 2013, 334). Fifty percent of Argentinians were considered financially poor, and 25% of the population were living in extreme poverty conditions (Rojas 2002, 102). In 2002, Argentina's government defaulted on $132 billion USD in public debt; the peso was no longer fixed to the USD dollar, and poverty and food shortages worsened before Argentina's recovery (Rojas 2002, 102; Romero 2013, 337).

The peso devalued to a third of its previous value providing a favourable situation for agriculture (Barksy and Gelman 2009, 484). The comparative advantage for agricultural exports, a depreciated real exchange rate and an increase in commodity prices, and support from agricultural companies and institutions made agriculture a lucrative business (Barksy and Gelman 2009, 484; Gallo 2012). The favourable external conditions for agriculture aided in managing the national crisis; the government was shut off from international financing and was in urgent need to raise funds to mitigate poverty (Gallo 2012; Romero 2013, 348).

New polices arrived in 2002 to mitigate the negative social impacts of the crisis by protecting and stabilizing the domestic food prices, in light of inflation and increased international prices (Barksy and Gelman 2009, 484; Calvo 2014). Domestic food prices were controlled, and food processing was subsidized, export barriers were put in place for commodities that contributed to the basic food basket (BFB) and export taxes were reissued (sunflower and soybean at 13.5%, and wheat and corn at 10%; Nogués 2011, Calvo 2014). The BFB included a set of products that were consumed by Argentinians and that satisfied caloric and nutrient intake recommendations at the lowest possible cost (Graciano and Risso-Patrón 2011). Corn and wheat were included in the BFB; once enough corn and wheat were collected for the domestic market (amount varied per year), the remaining quantities were permitted for export. Levies created price and market uncertainties for producers; as a consequence, growing soybean equated to financial stability, as the oilseed had no export restrictions and was not a part of the traditional diet (Richardson 2009; Nogués 2011; Calvo 2014).

3.3.7. Golden grains (2003-2014)

Taxes paid by agriculture accounted for 45% of the total taxes collected by the Argentinian government from 2002-2005 (Lence 2010, 413). The rural sector was expanded to pay dues and provide national welfare services. From 2005 to 2010, the Argentinian government negotiated with financial lenders to repay 66.3% less than the original bonds. Ninety-three percent of the bondholders accepted the offer (Hornbeck 2010). By 2006 Argentina paid 9.8 billion USD; the full debt owed to the IMF (Hornbeck 2010; Gallo 2012).

Peso devaluation and high inflation continued into the 2010s; there were allegations that the government doctored inflation statistics; for example, from 2010-2011 the government calculated an 8% inflation rate, while private sources estimated consumer inflation rate to be 25-30% (Gallo 2012). The differences between the two inflation estimations made it difficult for Argentinians to save and inflated the cost of goods, including food.

Argentina paid off these debts, controlled inflation, and alleviated urban poverty using an aggressive financing strategy that put agricultural producers, who were mainly those from the Pampas, in a disadvantageous position (Nogués 2011; Gallo 2012; Calvo 2014). Import substitution was re-established, and agricultural export taxes increased through 2002-2008. In 2008, the government attempted to raise soybean taxes to 46% and failed due to producers' display of outrage over the new taxation scheme (Richardson 2009). At the end of 2008, export taxes settled at 20% for corn, 23% for wheat, 32% for sunflower, and 35% for soybean (Nogués 2011).

Soybean had the highest taxes because the oilseed generated the most export revenue. For example, exports of raw soybeans, and soy products (oil and meal) generated 26% of the Argentina's export revenue in 2007; while corn, wheat and meat generated 8% each (Gras and Hernández 2014) The international price for soybean stayed relatively high as soybean products were highly demanded in China (Nogués 2011; Gallo 2012; Romero 2013, 356; Sensi et al. 2013). Export levies continued for corn and wheat to control production and prices of the commodities. The federal government chose where and when corn and wheat were exported, otherwise, the two commodities were sold in the domestic market at a non-competitive price (Richardson 2009). The threat of increasing grain taxes, the non-competitive domestic market, and inconsistent export quotas caused tension between the government and agriculture producers (Gallo 2012).

Producers protected themselves from external market fluctuations and governmental policies through cooperative management by creating network-systems that integrated production, commercial and financial partnerships, while outsourcing labour and machinery via contractors (Domínguez and Sabatino 2006; Gras and Hernández 2014, 346). These network systems were termed sowing pools or trust funds and included varying types of producers from large agro-companies to family businesses. These network partnerships were more economically diverse and flexible compared to land ownership when considering cost efficiency, risk management, innovative arrangements, and technological updates (Barsky and Gelman 2009, 498; Gras and Hernández 2014, 347).

Modifications of the agriculture regime since the 1990s drastically transformed the Pampean landscape, to concentrate on a few commodities – corn, wheat, and soybeans. Decades of government inconsistencies, economic instability, and constant agricultural innovations influenced the formation of the Pampean agriculture technological package (also known as the soybean package) that producers reliably used. This package consisted of:

i. Field contractors;
ii. No-tillage land management;
iii. New machinery and technology (i.e. larger field machinery, GPS, mobile phones);
iv. Fertilizers (i.e. Urea, DAP, MAP);
v. Herbicides (specifically glyphosate)
vi. Transgenic seeds (particularly for soybean and corn);
vii. Double cropping (specifically wheat-soybean);
viii. Corporative management
ix. Frequent soybean cultivation (Campi 2011, 190).

The widespread use of the technological package doubled production from 1990-2014 (Campi 2012, 189; yieldgap 2014; FAOSTAT 2017). Increased production was due to both intensification and expansion of cultivated lands (Barral and Maceira 2011; Fischer et al. 2014, 253; yieldgap 2014). Corn production increased at a rate of 0.60% per year (1990-2010) from yield improvements, while soybean production advanced 1.5% per year due to land expansion.

Transgenic soybean was considered a low-risk crop, requiring minimal inputs and was adaptable to various soil and climate conditions, making the oilseed the basis for the new Pampean agricultural model (Caviglia and Andrade 2010; Martínez et al. 2013). The ports were always accepting soybeans, and the international price stayed relatively high (Campi 2011, 225; Nogués 2011).

Environmental and social issues presented themselves after a decade of using the technological package for predominantly soybean cultivation. Soybeans encroached and altered the Pampean landscape. The area dedicated to soybeans increased from 5 million ha to 19 million ha from 1993-2010, covering over half of the cultivated Pampean region. (Gras and Hernández 2014; Yieldgap 2014). During that same period, the area dedicated to corn increased from 2 million ha to 5 million ha, and the area for sunflowers decreased from 6 million ha to 4.5 million ha (Gras and Hernández 2014; yieldgap 2014). Other production systems such as dairy, fruit trees, horticulture, and cattle were displaced to other provinces bordering the Pampas (Pengue 2005; Barksy and Gelman 2009, 487). Eventually, soybean production expanded outwards to the northern provinces of Argentina competing with cotton, sugar, and tobacco (Pengue 2005; Campi 2011, 221; Gras and Hernández 2014, 344).

Frequent soybean cultivation resulted in fields being exposed to simplified rotations or monocropping (Barral and Maceira 2012). These intensive practices were associated with reduced soil organic matter content, increased weed tolerance to herbicides (Cavligia and Andrade 2010), the rise in greenhouse gas emissions per hectare (Viglizzo 2011; Bouza 2016), and biodiversity losses (Margosian et al. 2009; Medan et al. 2011; Bouza 2016). The reductions in soil organic matter and loss of biodiversity influenced researchers in the early 2000s, to find new cropping practices that encouraged both sustainability and intensification. Practices that were being tested since the 2000s included: summer intercropping (e.g. corn-soybean and sunflower-soybean); and double cropping with the use of winter legumes (e.g. corn and hairy vetch) (Andrade et al. 2015).

3.4. CONTEXT SUMMARY

The extraordinary fertile soils of the Pampas have been a contributing resource for generating Argentina's GDP for over a century. Revenue from Pampean agriculture production has largely supported the social well-being of Argentinians and paid off excessive national debts. Governments changed agriculture policies repeatedly to meet prevalent issues that occurred throughout the years. These changes both negatively and positively affected agriculture production and evolved the Pampean agriculture regime to what it is today. Tables 3.1 to 3.5 display social events and production trends that occurred at different time periods discussed in this chapter. The regional context presented and summarized in this chapter supports the social, economic and political findings associated with corn-soybean intercropping that are discussed in Chapters 5 and 6.

The combination of chronic economic instability and the lack of a long-term platform for agricultural policies encouraged producers to focus on short-term profitability, to ensure personal financial security. Years where implemented policies were highly restrictive for producers (i.e. the 1940s) or when economic collapses ensued (i.e. 1985-1989), producers focused on reducing economic risks and using agricultural practices that required minimal inputs. These production strategies along with events that took place resulted in reduced or stagnated production (Campi 2012, 114, 150). Production increased during years of economic liberalization and when polices permitted flow of new technologies and machinery to enter the country (i.e. 1955-1965, 1991). Learning from past events, producers who remained in the industry this past decade used cooperative management, as a strategy to contend economic and policy fluctuations. Labour was outsourced to contractors, the land was commonly rented, and producers developed partnerships with other producers, companies, and investors for flexible risk management and cost efficiencies.

Technological advancements introduced into Argentina has significantly increased production; however, widespread management choices of these technologies resulted in environmental consequences. Argentina's agricultural production lagged in the 1940s to 1950s, while other countries were investing in technology from the Green Revolution. The Pampean agricultural model was restructured in order for Argentina to be once again a competitor in the international markets. The introduction of fuel-powered machinery, specialization techniques, new seed varieties, and new crops rejuvenated the agricultural sector. The restructured agricultural model was a success until the mid-1980s; when it was evident that production declined due to soil degradation from intensive tillage. A decade later, soil quality issues were resolved by improving soil structure with no-tillage and replenishing nutrients with fertilizers. Argentina was inviting to foreign investors and was one of the first countries to use genetically modified technologies. The technological package created in the 2000s doubled production with the introduction of glyphosate-tolerant crops and double cropping techniques.

Concurrently, research that revealed environmental consequences has had greater exposure. Land use change in the Argentine Pampa has contributed to biodiversity losses. Increased fertilizer usage has resulted in greater soil greenhouse gas emissions. Agrochemical contamination increased with the use of no-tillage, and soybean encroachment has shown evidence of degrading soil organic content, increasing the prevalence of herbicide-resistant weeds, and displacing other crops and agricultural industries (Viglizzo et al. 2011; Bouza 2016). Researchers and producers were challenged to find new techniques and practices that can grow crops in a more environmentally sustainable manner, while continuing to increase production. One imminent solution was to utilize corn-soybean intercropping, as a sustainable-intensive cropping practice. The 4th chapter of this dissertation introduces an empirical aspect of modernized corn-soybean intercropping in the Argentine Pampas, from a natural sciences' perspective. Chapter 4 covers a field-scale quantitative study that evaluates greenhouse gas mitigation potential of corn-soybean intercropping in the Pampas, to determine if the practice is a strategy to reduce the carbon footprint of cropping activities.

Table 3.1. Summary of events in Argentina and in the Buenos Aires Pampean agriculture sector between years 1860-1929.

Time Period	Social occurrence	Government intervention	Agriculture Impact	Field Management	Main Agroecosystem Attributes
1860-1929	Mass displacement and killing of Indigenous Peoples Mass immigration of Europeans to Argentina Migration of people settling in the B.A. Pampas. World War I Economic prosperity	Conquest of the Wilderness Expanding Argentina's frontier Foreign investment in capital and infrastructure.	Low capital Limited labour Establish transport accessibility Rural infrastructure establishment Industrial establishment (meat packaging, flour mills, & food processors)	Extensive pasturelands Plowing and low inputs owned with small leased land parcels Horse & steam mechanization Manual labour Management influenced by country of origin	Ranching of sheep & cattle Export of animal hides, tallow, wool, & meat. Land breaking for crop production Rotated Annual crops – wheat, flax, rye Shifted between ranching and cultivating with market conditions. Horticulture production for self-sufficiency High prevalence of manual labour Short term leases on small parcels of land (3-4 years) Extensive agriculture Trial and error plant selection to improve crop quality Majority of arable crops exported Food consumed in Argentina was grown domestically

Table 3.2. Summary of events in Argentina and in the Buenos Aires Pampean agriculture sector between years 1930-1955.

Time Period	Social occurrence	Government intervention	Agriculture Impact	Field Management	Main Agroecosystem Attributes
1930-1955	World War II Loss of trading partners International market crash Severe droughts	Welfare state Formation of IAPI Tariffs on Agriculture exports Exchange controls Import restrictions & substitutions Use of agriculture taxes fund for welfare services.	Late entrance in Green Revolution Less investment in agriculture and more in urban areas Migration to urban centres resulting in farm labour shortages Small producers supported by government Large estates divided & sold into smaller fragments	Land-intensive practices plowing & tillage Crop rotations Animal - annual crop integrated agriculture production Farm owned & operated High demand for manual labour	Land vulnerable to soil degradation & erosion Land splitting and deconcentration increased the number of small and medium-sized owned & operated farms Increased crop diversity in the landscape Mixed agricultural systems – crop & livestock Agriculture production stagnated mainly focused on feeding the domestic population Main arable crops: wheat, corn, flaxseed, rye, barley 80% of meats & grains were consumed domestically

Table 3.3. Summary of events in Argentina and in the Buenos Aires Pampean agriculture sector between years 1956-1989.

Time Period	Social occurrence	Government intervention	Agriculture Impact	Field Management	Main Agroecosystem Attributes
1956-1989	Flourishing domestic industry Dirty War Falkland's War Military coup High political turnover Hyperinflation Domestic food shortage High prevalence of poverty in the nation	Agriculture taxes Trade barriers lowered foreign borrowing restored Access to credit Argentina Bankruptcy Excessive usage of International loans	Agroindustry &agriculture research promoted Creation of INTA Farm groups established (CREA & FAA) Development of short cycle wheat Access to agrochemicals: fertilizer, herbicides & fungicides	Intensive use of plowing & tillage Crop rotations Use of gas-powered machinery Land expansion Use of improved hybrid seeds Use of herbicides & fungicides Introduction of sorghum, sunflower, & soybeans to fields Separation of cattle & annual crop production Decrease demand for manual labour	A diverse range of producers small to large scale Increasing input use of agrichemicals Emphasis on growing crops &/or ranching in best suited/ designated regions Increased agriculture production More consistent crop development & yields Main arable crops in Pampas: wheat, corn, sunflower, sorghum, & soybeans Producers participated in share-cropping rather than traditional cropping Land degradation & erosion concerns due to intensive practices Majority of Argentina's agriculture production was exported Insufficient supply of affordable food for the domestic market resulting in national food shortages

Table 3.4. Summary of events in Argentina and in the Buenos Aires Pampean agriculture sector between years 1990-2000.

Time Period	Social occurrence	Government intervention	Agriculture Impact	Field Management	Main Agroecosystem Attributes
1990-2000	Democracy restored Debt accumulated to over 40 billion Recession High unemployment rate	1991 Neoliberalism Convertibility plan Peso at par with the dollar Regressive tax Value-added tax Deregulation of meat and grains Privatization foreign investments Quota elimination	Small producers outcompeted by large-scale capitalistic producers Agroindustry promoted The influx of imported machinery with modifications for No-till International agriculture companies and biotechnology welcomed	No-till Farmer sowing pools Use of field contractors Limited manual labour required Dependence on gas-powered machinery Use of transgenic seeds, herbicides, pesticides, and fertilizers Simplified rotations Double cropping Specialization Small-scale producers sell or lease to larger producers.	Fewer landowners with increased area owned. Large-scale producers benefit from new policies Crop diversity reduced The shift from extensive to intensive production Specialization of wheat, soybean, corn and beef Labour outsourced with contractors Fertilizer usage increased exponentially 90% of soybeans grown were transgenic Majority of arable crops exported Food consumed in Argentina was grown domestically and imported

Table 3.5. Summary of events in Argentina and in the Buenos Aires Pampean agriculture sector between years 2000-2014.

Time Period	Social occurrence	Government intervention	Agriculture Impact	Field Management	Main Agroecosystem Attributes
2000-2014	Argentina's Great Depression High unemployment Food shortages Increased commodity prices in international markets High International demand for soybean 25% inflation rate unrecognized by the government Devaluation of peso	Civilian money spending frozen & restriction for purchasing foreign currency Converted USD dollar bank deposits to devalued pesos Defaulted on $132 billion USD debt Negotiated a repayment that was 66.3% less to lenders Paid off IMF debt Import substitution re-established Agriculture taxes increased Export barriers on wheat & corn Use of agriculture taxes to repay debts & fund welfare services. Agrofood Strategic plan	Advance agriculture production-networks Comparative advantage for agriculture exports Pampa producers heavily taxed. Export barriers implemented on BFB commodities Price uncertainties for wheat & corn Large support from agriculture companies Increased promotion for yield improvement research Beef migrate to northern & western provinces Crop production expanded to marginal lands	Transgenic soybeans main summer crop Use of larger, more versatile, & technology-advanced machinery (i.e. GPS, real-time yield estimate) ~90% use no-till Contractors with large machinery/ computerized technology/ cellphones/ GPS Use of transgenic seeds, herbicides, pesticides, & fertilizers Simplified rotations & double cropping Network partnerships Specialization Large areas of land cropped intensively The emergence of precision agriculture Research on summer intercropping commenced	Increasing yield through best-utilizing resources & concentration rather than land expansion Intensive crop production using double cropping Soybeans dominate Pampa landscape & reduce the production of other summer crops 95-99% of soybeans used are transgenic RR variety; 90-95% of corn was transgenic Bt variety Horticulture, dairy, orchards, & beef sectors displaced from Pampas. Domination of corporate managed networks, land leasing, & outsourced labour Argentina's yield similar to competitors (closing yield gap) Majority of arable crops are exported Food consumed in Argentina grown domestically Agriculture sector contributes 1/5 of Nation's GDP with 28% derived from exported soybean products. The main crop grown (soybean) was not consumed domestically.

CHAPTER 4

NATURAL SCIENCES STUDY

Evaluating CO_2 and N_2O emissions from corn-soybean intercropping systems during two contrasting hydrological growing seasons in the Argentine Pampas

4.1. INTRODUCTION

By the year 2050, the anticipated 9.7 billion global population is expected to have the highest demand growth for corn (*Zea mays*) and soybean (*Glycine max*), in comparison to other staple crops to accommodate feedstock and biofuel needs (Fischer et al. 2014, 5). The demand for these two crops is expected to increase by 80% for corn and 60% for soybean from 2007 to 2050 (Fischer et al. 2014, 8). Argentina was one of the top-four global producers and exporters of both soybean and corn in 2016 (FAOSTAT 2017). Producers from Argentina and other major cereal and oilseed exporting countries will need to further intensify crop production through yield progression, rather than by area expansion, to meet future demand (Fischer et al. 2014, 8). Concomitantly, crop producers will be challenged to grow more, using fewer resources and adapt their production to climate uncertainties (Fischer et al. 2014, 3; Mahon et al. 2016).

4.1.1. Crop production impacts and contributions to climate change

Climate change affects crop production in numerous ways, some examples include shifts in: i) average temperatures, precipitation, and weather extremes; ii) carbon dioxide (CO_2) and ground-level ozone concentrations; and iii) pest and disease incidences (Lin et al. 2008; IPCC 2013; Fischer et al. 2014, 422). Agriculture is an anthropogenic source of climate change through activities (i.e. land-use change, livestock production, soil erosion, urea and liming applications to soil) that weaken carbon sinks and emit greenhouse gases (GHGs) to the atmosphere. In 2010, 24% of globally emitted GHGs –CO_2, nitrous oxide (N_2O), and methane – were derived from the Agriculture, Forestry, and Other Land Use (AFOLU) sector (IPCC 2013; EPA 2017). Latin America and the Caribbean contributed 7% of GHG emissions in 2008 (Calvin et al. 2016) – within this percentage, 40% was from the AFOLU sector – more than double the global fraction of AFOLU emissions (Calvin et al. 2016). More specifically, agricultural activities in Argentina during the year 2000, contributed 44.3% to the national total of GHG emissions (282 MT CO_2 equivalent) – 98.7% of these agriculture emissions were sourced from land cultivation (Fundación Bariloche 2007; World Bank 2015). From 2000 to 2014, Argentina's total GHG emissions increased by 25%, with 38% of the increase directly related to land-use change and the forestry sector (Climate Watch 2017).

Both soybean and corn production in Argentina contributes to GHG emissions. Encroachment of soybean cultivation has led to deforestation and disturbed pastures, and the continuous use of soybean monocropping has deteriorated soil health (Caviglia and Andrade 2010; Coll et al. 2012; Novelli et al. 2017). Altering landscapes for frequent soybean production degrades soil organic matter, promoting the release of CO_2 to the atmosphere and hinders carbon (C) sequestration (Oertel et al. 2016). Nitrogen (N) fertilizer usage is the primary source (~50%) of global anthropogenic nitrous oxide emissions; N_2O is a potent GHG and is a stratospheric ozone-depletion substance (Dobermann and Cassman 2005; Shcherbak et al. 2014; Oertel et al. 2016). Unlike soybeans and other legumes, corn cannot provide its own nitrogen, requiring nitrogen fertilization. Excess nitrogen interacts with soil conditions resulting in reactions that release N_2O from the soil (Oertel et al. 2016).

The pressure to increase crop production is expected to encourage intensive cropping practices and steadily increase nitrogen fertilizer use (FAO 2017). Already Argentina's use of urea as a nitrogen fertilizer has increased by five-fold from 0.07 MT in 1990 to 0.45 MT in 2007, contributing to doubling grain production (Campi 2011, 210; IFASTAT 2018). Many agricultural experts call for the use of sustainable-intensification (SI) cropping practices as a strategy to mitigate agriculture-related GHGs, minimize environmental degradation, and to ensure food security for future populations.

Sustainable-intensification is a concept that was defined by Pretty (2008, 451) as "*Intensification using natural, social (community), and human capital assets, combined with the use of best available technologies and inputs (best genotypes and best ecological management) that minimize or eliminate harm to the environment.*" Sustainable-Intensification is considered a broad and vague concept. In respects to describing field-scale agronomic aspects of SI for cropping practices, it is the intention of utilizing time, renewable resources, and new technologies to increase crop output by shortening the fallow period without degrading environment qualities (Kershen 2013, Caviglia and Andrade 2010, Andrade et al. 2015).

Researchers in the Argentine Pampa studied intercropping as a potential SI strategy (Caviglia and Andrade 2010; Coll et al. 2012; Monzon et al. 2014). Intercropping is the cultivation of two or more crops simultaneously or on the same field during all or part of the life cycle of each crop (Brooker et al. 2015; Fletcher et al. 2016). Traditional smallholder farmers use intercropping to grow more in a small area, reduce yield loss risks, and improve input efficiency (Boudreau 2013; Altieri et al. 2017). For mechanical conveniences, modern cropping systems most commonly use sole cropping in a rotation or as mono-cropping. Sole cropping is not efficient at using time (longer fallow periods) and natural resources (i.e. water, nutrients, and radiation) (Fletcher et al. 2016; Bybee-Finley and Ryan 2018).

Corn-soybean intercropping was one of the intercropping combinations that underwent experimental trials in the Argentine Pampas. Positive indicators of crop intensity and soil conservation were applied to these intercropping trials by measuring crop eco-physiological interactions, yield and biomass production, and soil characteristics (Coll et al. 2012; Cambreri 2013; Monzón et al. 2014; Oelbermann et al. 2015; Regehr et al. 2015; Bichel et al. 2016;

Bichel et al. 2017). There are no official indicators required to measure SI of cropping practices. However, the Mahon et al. (2017) systematic review of SI literature identified 218 suggested indicators; GHG emissions (a negative indicator) being the most recommended indicator after soil organic matter (a positive indicator that is affiliated with the production of soil derived GHGs). This chapter used GHG emissions as an SI indicator to quantify and evaluate soil emitted CO_2 and N_2O from corn-soybean intercropping and rotated sole cropping field trials, in the southeast Buenos Aires (SEBA) region of the Argentine Pampas. The following sections detail the mechanisms that produce GHGs from cultivated soils, and how intercropping has the potential to mitigate GHG soil emissions.

4.1.2. Carbon dioxide and nitrous oxide emissions from cultivated soils

Microbial activity and chemical decay processes are the main mechanisms that produce CO_2 and N_2O by influencing carbon and nitrogen cycles (Oertel et al. 2016). Soil emitted CO_2 is predominantly from the burning and decomposition (autotrophic and heterotrophic respiration) of plant litter and soil organic matter (Lal 2007; Bond-Lamberty and Thomson 2010; Oertel et al. 2016). Changes in the rate of organic carbon input and losses, directly affect soil nitrogen turnover, and in turn influence N_2O exchange between soil and the atmosphere (Li et al. 2005; Oertel et al. 2016). When there are greater amounts of mineral nitrogen compared to easily metabolized carbon ($C:N < 15$), nitrogen is mineralized (the release of NH_4^+ from decomposed organic matter). Mineralization stimulates soil microbial activity to convert nitrogen into N_2O through predominantly nitrification (oxidation of NH_4^+ to NO_3^- via NO_2^-) and denitrification processes (reduction of NO_3^- to N_2O and N_2) (Chapuis-Lardy et al. 2007; Oertel et al. 2016). Nitrification and denitrification microbial processes are controlled by oxygen concentrations, pH, temperature, rainfall, and soil water content. Hence, climatological parameters and land-use information are paramount in soil GHG studies (Butterbach-Bahl et al. 2013; Oertel et al. 2016).

Soil nitrification activity releases N_2O as a by-product and predominantly occurs when water filled soil porosity (WFPS) is between 30-60% (Bateman and Baggs 2005; Oertel et al. 2016). Soil denitrification is stimulated under anaerobic conditions when WFPS is > 60% (Bateman and Baggs 2005). During denitrification, N_2O is an intermediate and depending on environmental conditions, denitrification can sequester nitrogen, or it can be a source of N_2O (Oertel .et al. 2016; Chapius-Lardy et al. 2007). Under drier soil conditions (WFSP<30%), low levels of N_2O emissions can occur through nitrification and/or denitrification processes depending on anaerobic microsites and the microbial species composition occurring in the soil (Bateman and Baggs 2005; Ji et al. 2015; Oertel et al. 2016).

Cropping and land management practices that are known to promote CO_2 and N_2O emissions are plowing or intensive tillage, extended bare-field fallow periods, continuous monocultures, soil drainage, excessive use of nitrogen fertilizers, and burning or removal of biomass (Lal 2007; Novelli et al. 2017). In Argentina, continuous and frequent use of soybean monocropping was commonly implemented in fields (Barral and Maceira 2012; Monzon et al. 2014; Urcola et al. 2015). Soybean residues degrade quickly due to its low C:N ratio creating a greater risk of organic carbon losses and soil erosion during winter fallows (Caviglia and Andrade 2010; Novelli et al. 2017).

4.1.3. Intercropping as a GHG mitigation practice

Cultivated soils are a source of GHGs, but can be a sink for carbon and nitrogen when these elements are regulated using suitable cropping and land management practices. It was estimated that cultivated soils have lost 50-75% of their soil carbon pool due to historical land use change and cultivation practices (Lal 2007). In temperate regions of Argentina, soil organic carbon (SOC) losses were estimated to be 35% within the upper 15 cm soil layer (Álvarez 2001). These past SOC losses present an opportunity to utilize cropping strategies that sequester carbon, for cultivated soils to reach their carbon storage capacity and to lower agriculture's carbon footprint (Snyder et al. 2009; Oertel et al. 2016; Sánchez et al. 2016). Reduced or avoiding tillage, optimized fertilization and increased crop intensity were three strategies recommended to regulate carbon and nitrogen dynamics, mitigate GHGs, and sequester carbon (Sánchez et al. 2016; Novelli et al. 2017). Increasing crop intensity (growing more from a unit area on a yearly basis) was a priority for developing new cropping practice development in the Argentine Pampas, to increase both crop diversity and production (Coll et al. 2012). Cropping practices that were considered to increase cropping intensity were: i) growing two cash crops in a year by intercropping or double cropping (Caviglia et al. 2004; Monzon et al. 2014; Novelli et al. 2016); and ii) incorporating cover crops during the winter or inter-seeded with summer crops (Andrade et al. 2015). Growing more than one crop within a year adds more and diverse residue inputs to the soil which in turn, improves carbon and nitrogen regulation by protecting SOC reserves, stabilizing decomposition rates, reducing heterotrophic respiration, and reducing fertilizer needs (Oertel et al. 2016; Sánchez et al. 2016; Novelli et al. 2016).

A study by Sánchez et al. (2016) estimated that crop rotations have the potential to sequester 0.08-1.6 t CO_2 ha^{-1} year; improving carbon storage with increased rotation complexity and crop diversification. From the same study, intercropping practice were estimated to sequester at least 0.01-0.03 t CO_2 ha^{-1} year, though minimal information was available to calculate this estimate. Intercropping studies on this subject are limited, and highly variable due to crop species combination, spacing, density and configuration used in intercropping designs, (Qin et al. 2013; Chapagain and Riseman 2014; Sánchez et al. 2016; Jalilian et al. 2017). For instance, Chapagain and Riseman (2014) found that non-fertilized pea-barley intercropping sequestered -33% (-4.4 t CO_2 ha^{-1} $year^{-1}$) to +10% (+7.3 t CO_2 ha^{-1} $year^{-1}$) more carbon than sole cropped barley, depending on whether the intercropping system was a mixed or row design.

Cereal-legume is a common intercropping combination (Bedoussac et al. 2015; Bybee-Finley and Ryan 2018). Legumes (i.e. peas and soybean) obtain nitrogen from the atmosphere reducing competition for soil derived nitrogen that cereals (i.e. wheat [*Triticum aestivum*], barley [*Hordeum vulgare*], and corn) require (Bybee-Finley and Ryan 2018). Additionally, cereal-legume intercropping simultaneously adds residues with contrasting C:N ratios to the soil. These residue mixtures can better regulate microbial activity with changing environmental conditions (Dyer et al. 2008; Bichel et al. 2017; Regehr et al. 2015). More specifically, soybean residue C:N ratio ranges from 13 to 25, and corn stover C:N ratio is substantially higher ranging from 60 to 80 (Stevenson et al.1999, 200). Improved nitrogen allocation and diversifying carbon and nitrogen inputs were two main reasons to propose corn-soybean intercropping to be a GHG mitigation cropping practice.

In the temperate region of China, Tang et al. (2017), Huang et al. (2017) and Shen et al. (2018) found that fertilized row corn-soybean intercropping systems had significantly ($p<0.05$) or numerically lower N_2O emissions compared to corn sole crops. In the SEBA region of the Argentine Pampas, Dyer et al. (2010) conducted a preliminary study to quantify soil emitted GHGs from a recently established corn-soybean intercropping field trial. Their findings did show that corn-soybean intercropping had numerically lower CO_2 and N_2O emissions than corresponding sole cropping systems. However, this study was based on five days of measurements for less than half the total growing season. This small observation period may have associated biases considering soil GHG fluxes can vary seasonally. For example, soil CO_2 emissions are subjected to 10-95% variation throughout a given growing season (Hanson et al. 2000). Variations in CO_2 and N_2O fluxes are due to temporal nutrient supply, seasonal effects, changing environmental conditions, and crop development (Dobbie et al. 1999; Rochette et al. 1999; Hanson et al. 2000; Oertel et al. 2016).

4.1.4. Study Objectives

To extend the work of Dyer et al. (2010), I conducted a two-year in-field soil chamber-based study that measured soil emitted CO_2 and N_2O weekly for six months, in a five-year established corn-soybean cropping systems experimental site located in the southeast Buenos Aires Argentine Pampas.

The objectives were to:

i. quantify CO_2 and N_2O soil emissions in corn-soybean sole cropping and intercropping systems during two summer growing seasons;
ii. determine if differences in CO_2 and N_2O soil emissions exist between corn-soybean sole cropping and two designs of corn-soybean intercropping; and
iii. evaluate whether corn-soybean intercropping has the potential to act as a SI cropping practice that mitigates greenhouse gas emissions.

This study investigated soil emitted CO_2 and N_2O from rotated corn-soybean sole cropping and two configuration types of corn-soybean intercropping. The examination of tow intercropping treatments occurred because crop configuration (especially in multi-cropping systems) can influence microclimate, residue input, resource facilitation, and competition effects (Vandemeer 1992, 33; Echarte et al. 2011; Brooker et al. 2015).

4.2 METHODS

4.2.1. Field experimental site, plot, and treatment descriptions

Soil chamber-based field experiments were conducted at the Balcarce Integrated Unit (UIB) agriculture research facility, Buenos Aires, Argentina (37°45'S, 58°18'W) during two summer growing seasons from November 25, 2011 to May 7, 2012 (Day of year [DOY] 329-128) and December 11, 2012 to May 14, 2013 (DOY 346-134). These two periods are distinguished as 2011-2012 and 2012-2013 throughout this chapter. The site was 130 m above sea level, and had a warm temperate climate with 860 mm mean annual precipitation and 14.3°C mean annual temperature (Oelbermann et al. 2015). The soil at the site was a Luvic Phaeozem (FAO Soil Taxonomy) – Typic Argiudoll (Caviglia et al. 2004) with a loam texture consisting of 41.1% sand, 35.8% silt, and 23.1% clay (Domínguez et al. 2009), and had a depth of 1.4 m (Cambareri 2013). The research site was part of a long-term comparative study (established in 2006) that investigated corn-soybean rotations and intercropping production (Oelbermann and Echarte 2011). The site had a 2% slope and was previously used for crop and pasture experiments; from 2005-2006, the area was cultivated with sunflowers (*Helianthus annuus)* using reduced tillage methods (Oelbermann et al. 2015).

The corn-soybean research site had a randomized complete block design with four treatments and three replications per treatment (Figure 4.1). There were four cropping practice treatments: two treatments were sole cropping systems and two treatments that were summer substitutive row-relay intercropping systems. The two sole cropping treatments were sole corn (SC) and sole soybean (SS) that alternated plots per growing season. The two corn-soybean intercropping systems differed by crop configuration. The 1:2 intercropping system (1:2) had the configuration of one row of corn and two rows of soybeans. The other intercropping system had the configuration of two rows of corn and three rows of soybeans (2:3). Intercropping treatments by configuration were designated to the same plots every growing season. The dimensions of the rotated sole cropping plots were 11.5 x 7.3 m and the dimensions of the intercropped plots were 11.5 x 8.8 m. Crop spacing, density, and management decisions – since the experiment trial establishment in 2006 – was based on adapting intercropping to modern cropping systems, and to obtain potential and water limited yields (Echarte 2011). Crop spacing and density were selected for mechanization accessibility, limiting resource competition between crops, and permitting synthetic inputs (Echarte et al. 2011). The corn density in SC, 1:2, and 2:3 treatments were 8.0, 4.3, and 5.3 plants per m^2, respectively; soybean crop density was 29 plants per m^2 in

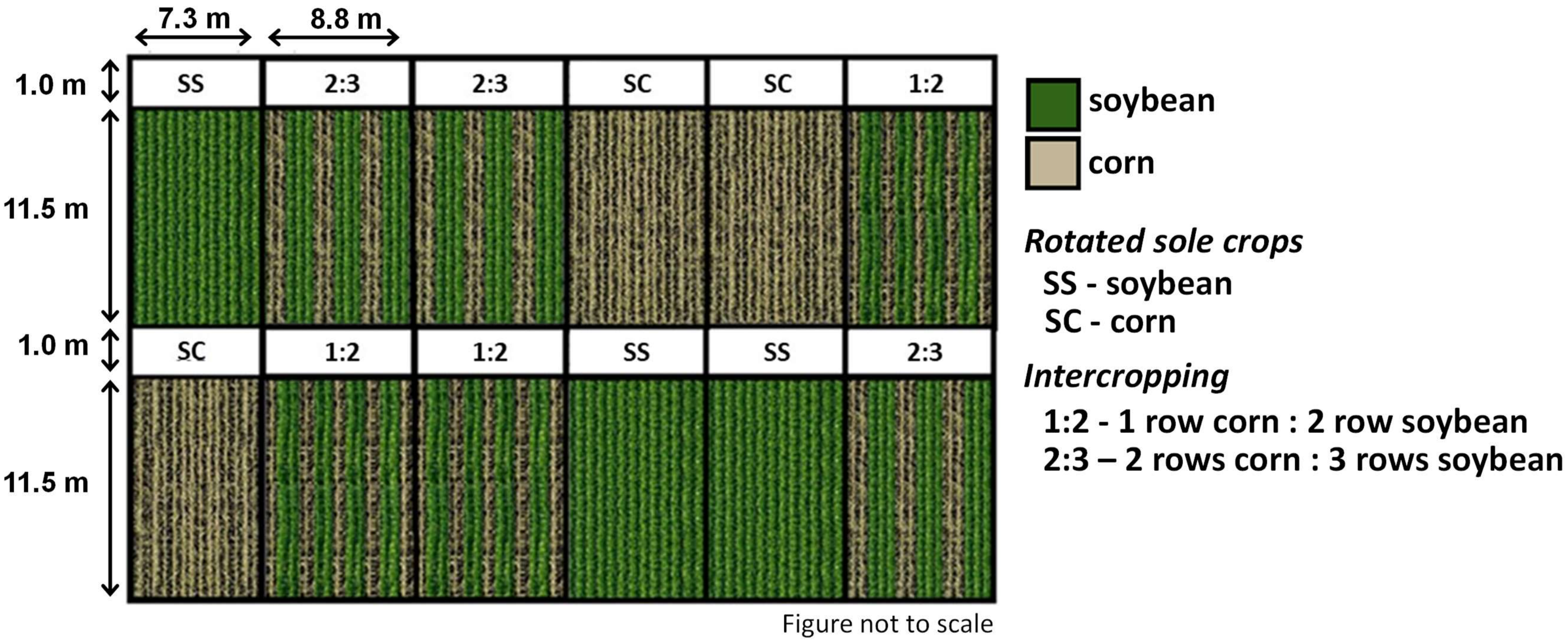

Figure 4.1. Field experiment setup and plot layout at Balcarce Integrated Unit agriculture research facility, Buenos Aires, Argentina, 2011-2012. Two 1.0 m buffers were created for accessibility to each plot.

SS, 1:2, and 2:3 treatments. All treatments had a 0.52 m inter-row and the rows were planted in the northeast to southwest direction.

All plots at the site were managed with minimal tillage (disc and spike harrow) and were rain-fed. Diammonium phosphorus (DAP) fertilizer was added to all plots at a rate of 33 kg P ha^{-1} as the soil was mildly acidic and had low available phosphorus (Oelbermann et al. 2015). Nitrogen was applied in the form of urea by hand in a band formation near corn stems in SC, 1:2, and 2:3 plots at a rate of 150 kg N ha^{-1} when corn was at the 6th leaf stage on dates November 29, 2011 (DOY 333) and December 19, 2012 (DOY 354). Planting dates and crop varieties used for each growing season are displayed in Table 4.1. Soybeans were inoculated with *Bradyrhizobium japonicum* before sowing and were planted approximately a month after corn. Staggered planting dates of soybean and corn were used to prevent both plants competing for resources at critical plant growth stages (Andrade et al. 2012; Coll et al. 2012). Both corn and soybean varieties were glyphosate (N-phosphonomethyl glycine) resistant in order to manage weeds manually with spray applications throughout the season. In the 2012-2013 season, corn was planted on October 23, 2012 (DOY 297) unknowingly with non-glyphosate resistant corn seed. Experiments were delayed to replant corn on November 27th, 2012 (DOY 332), and sow soybeans on December 21st, 2012 (DOY 356). A shorter season soybean variety was sown for growing season 2012-2013 due to the later planting date.

Table 4.1. Dates of sowing and harvesting of corn and soybean varieties used per season from November 2011 to May 2013, in sole crop rotation and intercropping comparative plot study at UIB, Balcarce, Argentina.

Season and Crop	Crop Variety	Sowing Date	Harvest Date (DOY)
2011-2012			
Corn	PIONEER 38A57RR	October 20, 2011 (293)	Feb 29, 2012 (60)
Soybean	NIDERA 4613	November 22, 2011 (326)	May 5, 2012 (126)
2012-2013			
Corn	I-550MGRR2	November 27, 2012 (332)	May 15, 2013 (135)
Soybean	NIDERA 4613	December 21, 2012 (356)	May 15, 2013 (135)

4.2.2. In-field soil respiration chamber design

Cylindrical static chambers were used to measure seasonal CO_2 and N_2O concentrations. Static chamber design consisted of a collar inserted into the soil to reduce lateral flow. The chamber seals to the collar during sampling (Collier et al. 2014), and a vent was featured on the chamber to reduce internal pressure anomalies (Pumpanen et al. 2004). Static chambers trap gas emitted from the soil surface, and gas concentrations are collected from the chamber's headspace over a designated time-span (Collier et al. 2014). Fluxes for CO_2 and N_2O are calculated by the rate of change in the accumulation of gas concentrations, of a known time-span and known headspace volume (Pumpanen et al. 2004; Rochette and Hutchinson 2005; Collier et al. 2014).

The design of the chamber was influenced by recommendations from the Trace Gas Protocol Development Committee-United States Department of Agriculture (Parkin et al. 2004) and by materials locally available in Argentina. Chamber collars were constructed with white PVC pipe (15 cm I.D x 15.5 cm O.D x 25 cm height). The chamber lids were fitted PVC Caps wrapped with insulating reflective silver bubble wrap and silver aluminum foil tape. Increasing the reflectivity of the chambers reduces ambient and internal chamber temperature and pressure differences during sampling (Rochette and Bertrand 2008; Parkin and Venterea, 2010). The sampling port was added using a tightly fitted PFTE Butyl septa (2 cm diameter; Fisher Scientific, Mississauga, Canada). Approximately 2 cm from the sample port, a pressure vent was added using a Bev-a-line IV tubing (6 mm I.D and 10 cm long, Fisher Scientific, Mississauga, Canada). Both the sampling port and vent tubing were secured to the lid with silicon. Foam lining (1 cm width) taped along the inside edge of the lid ensured a snug fit to the chamber collar to prevent leakage during deployment.

There were two collars per plot equalling six collars per treatment. Collars were placed systematically in the middle of crop inter-rows within 2 m of plots' borders to facilitate time-based sampling. In the intercropping plots, chambers were placed in inter-rows between corn and soybean. Collars were added to plots one week prior to initial chamber headspace sampling, to allow the soil system to stabilize after collar insertion disturbances (Rochette and Hutchinson 2005). Collars were inserted to 10 cm soil depth and levelled; soil collars were not removed until the end of the field season. Chamber height was measured after insertion into the soil, to obtain individual chamber volume required for calculating CO_2 and N_2O fluxes.

Chambers were sampled for N_2O and CO_2 concentrations from pre-fertilization to crop harvest once a week, to observe soil emitted CO_2 and N_2O fluctuations. Fifty milligrams of urea was added inside the soil collars in SC, 1:2, and 2:3 treatments by hand. Urea was added to the chambers to ensure soil in chambers was exposed to the fertilizer, since collars can act as a physical barrier. All chambers were sampled during midday hours from 10:30 h to 12:30 h to be representative of the average daily CO_2 and N_2O fluxes (Davidson et al. 1998; Rochette and Hutchinson 2005). Chamber lids were deployed for a total of 30 minutes, where 20 mL of chamber headspace samples were collected at 0, 15 and 30 minutes using a 20 mL Bicton Dickinson (BD) syringe and 25G ½ BD needles. Chamber headspace samples were stored in pre-evacuated 7 mL vials (Exetainer $^{®}$, Labco Ltd., High Wycombe, UK). Full vials were stored in a dark cabinet, at room temperature, until air transported and delivered to the University of Waterloo, Canada, for gas concentration analysis.

4.2.3. Chamber CO_2 and N_2O headspace concentration analysis

At the University of Waterloo, vials of CO_2 and N_2O gas concentrations were quantified using a gas chromatograph (Agilent 6890) that possessed a thermal conductivity detector (TCD) and a micro electron capture detector (μECD). Standards of 100 ppm, 1000 ppm, and 10 000 ppm of CO_2 and 0.04 ppm, 1 ppm, and 10 ppm N_2O were used to calibrate the gas chromatograph (Praxair Canada Inc.). Blanks consisting of ultra-high purity helium (Praxair Canada Inc.) were analyzed every 12 samples, and standards were analyzed every 24 samples.

4.2.4. N_2O-N and CO_2-C chamber flux calculations

Flux calculations for static chambers are based on the estimation of the specified gas concentration over time (dC/dt). There are a variety of methods to calculate dC/dt. The most common methods are the Linear model, Hutchinson /Mosier (HM) model (Hutchinson and Moiser 1981), and the Quadratic model (Wagner et al. 1997); with the incorporation of correction factors for environmental and chamber biases (Rochette and Eriksen-Hamel 2008; Venterea and Baker 2008; Parkin and Venterea 2010; Venterea 2013). In this study, the three-point N_2O and CO_2 fluxes were calculated using a hybrid scheme of HM model and Linear methods in order to match flux curve shape with the best-suited calculation method (Dyer et al. 2012; Venterea 2013; Cambareri 2016). The nonlinear HM model calculates fluxes by the following equation (Hutchinson and Mosier 1981):

$$F = (C_1-C_0)^2 / [t \times (2 \times C_1-C_2-C_0)] \times \ln [(C_1-C_0) / (C_2-C_1)] \qquad \textbf{Equation 4.1}$$

where F is the calculated flux (nL L^{-1} h^{-1}), C_0, C_1, and C_2 represents the chamber headspace gas concentrations (nL L^{-1}) at sampling times 0, 1 (0.25 h), and 2 (0.5 h), respectively, and t is the interval between gas sampling points (0.25 h). Compared to other conventional flux calculations (Linear and Quadratic models), the HM model is least biased to gas fluxes that have a convex downward curvature that often occurs due to gas concentration build up over time (Hutchinson and Mosier 1981; Livingston and Hutchinson 1995; De Klein and Harvey 2012, 99). However, the HM model is restricted by equally spaced time points and is more sensitive to measurement error (Hutchinson and Mosier 1981; De Klein and Harvey 2012, 99). In order to apply the HM model, flux data needed to be equal to 1 when entered in the equation below:

$$[(C_1 - C_0)/ (C_2 - C_1)] = 1 \qquad \textbf{Equation 4.2}$$

When N_2O and CO_2 fluxes did not meet Equation 4.2, the Linear model was used because it was less biased for convex-upward curvature (Venterea et al. 2009; De Klein and Harvey 2012, 99). The Linear model calculates flux using the slope of gas concentration versus time using the Microsoft Excel LINEST function (Venterea et al. 2009; De Klein and Harvey 2012). Both the HM model and Linear models were calculated with Venterea's (2010) publicly shared simplified flux calculation spreadsheet for chamber bias correction (CBC) method in Excel found at the USDA (2017). The HM model and Linear model included: i) the aforementioned chamber bias correction; ii) chamber design factors - chamber area (cm^2), volume (cm^3) and height (cm); iii) gas transport theory – molecular mass of CO_2 ($\mu g\ mol^{-1}$) or N_2O ($ng\ mol^{-1}$), molecular volume ($cm^3\ mol^{-1}$) at chamber temperature (°C), and atmosphere barometric pressure (atm); and iv) soil property factors – bulk density ($g\ cm^{-3}$), soil moisture ($cm^3\ cm^{-3}$), soil temperature (°C), soil pH, and clay fraction. Calculated flux output units for N_2O were ng N_2O-N $cm^{-2}\ h^{-1}$ and µg CO_2-C $cm^{-2}\ h^{-1}$ for CO_2. Carbon dioxide and N_2O flux units were converted to kg CO_2-C $ha^{-1}\ d^{-1}$ and g N_2O-N $ha^{-1}\ d^{-1}$ for better result interpretation. Cumulative CO_2 and N_2O emissions were calculated for each treatment by the summation of mean CO_2-C fluxes and N_2O-N fluxes that were converted to CO_2-C equivalents. Cumulative CO_2 and N_2O emissions were obtained by linear interpolation between sampling dates, with an assumption that fluxes were representative of the average daily CO_2 and N_2O flux.

Static chamber measurements are susceptible to environmental, sampling and analytical errors (i.e. contamination from laminar flow, human error, and vial or chamber leakage) (Davidson et al. 2002; Rochette and Hutchinson 2005). Errors were recorded during field measurements and throughout lab analysis resulting in 5.8% of the total 1200 CO_2 flux data to be removed. N_2O concentrations were not analyzed until January 22, 2012, due to technical issues with the µECD. Vials of gas obtained prior to January 22, 2012, were only analyzed for CO_2, resulting in 40.4% and 3.1% of N_2O flux data missing in 2011-2012 and 2012-2013 from total data set of 1200, respectively (see Appendix 9.1).

4.2.5. Contextual environmental measurements

Daily precipitation and daily mean air temperatures, humidity, and atmospheric pressure were obtained from the UIB weather station located northeast and less than 500 m from the study site. In addition, the air temperature and chamber temperatures were obtained during each sample session using a traceable expanded range thermometer (Fisher Scientific, Pittsburgh, PA). Closed in-chamber temperatures were obtained by inserting a sensor through a vent for the 30-minute sampling duration, and measurements were manually recorded.

During chamber sampling, soil temperature (°C) and moisture content (cm^3 cm^{-3}) were measured with a WET Sensor (Delta-T Devices Ltd. Cambridge, England) beside (~10 cm distance) each chamber at 0-7 cm soil depth. The WET sensor malfunctioned and required repairs from January 12th (DOY 12) to January 31st, 2012 (DOY 31). When the WET sensor was being repaired, soil moisture content was measured by weight loss basis (oven dry 24 h at 105°C), from 0-5 cm soil samples collected beside each chamber using a Dutch style soil augur (7-cm I.D) (Sheppard and Addison 2008,43). Soil temperature was temporarily obtained by inserting a sensor, from a traceable expanded range thermometer into the soil at where the moisture samples were taken.

In 2011-2012 and 2012-2013, duplicate bulk density samples were collected at 5-10 cm depths, in each plot using a soil bulk density sampler (Model 0200, ICT International, Australia). Bulk density soil cores were weighed and recorded for wet and oven dried (105°C for 48 h) weights. Bulk density was calculated using the soil dry-weight divided by the volume of the cylinder (88.5 cm^3). Bulk density was used to calculate: i) gas fluxes from each chamber; ii) soil water-filled pore space (WFPS) per chamber; and iii) nitrate content per hectare. The mean summary of soil bulk density, and carbon and nitrogen parameters are shown in Table 4.2. Previous work by Regehr (2014) concluded that the topsoil of each treatment had a statistically similar bulk density, pH (5.6) and C:N ratio.

In 2012-2013, soil concentrations of ammonium (NH_4^+) and nitrate (NO_3^-) were obtained to provide information on the microbial processes that could affect N_2O fluxes. Composite soil samples of five subsamples per plot at 0-15 cm depth were collected using a Dutch style soil augur (7-cm id). In December, soil samples were collected at pre-fertilization, the day of fertilization, three days post fertilization, and nine days post fertilization. From January to May, soil samples were collected monthly. Soil subsamples of 10 g were used to determine soil water content by weight loss (oven dry at 105 ºC for 24 h). Another set of soil subsamples of 20 g were shaken for 0.5 h (200 rpm) with the addition of 100 mL of 4% K_2SO_4 solution; then were centrifuged (19,500 ×g for 5 min). Soil solutions were preserved with 0.04 mL of phenylmercury acetate (10 mg/ L of deionized water) and stored in a refrigerator at 4°C until analysis. Analysis of soil NH_4^+ and NO_3^- concentrations was conducted by the UIB lab services via Kjeldhal micro-distillation (Bremner 1965; Sbaraglia et al. 1988) using a Tecator Kjeltec 1030 autoanalyzer (Tecator AB, Hoganas, Sweden).

Table 4.2. Soil parameters (0-10 cm depth) obtained from the corn-soybean cropping system experimental trials at UIB, Balcarce, Argentina during 2012-2013.

	Cropping system treatments			
	Rotated sole crops		Intercropping	
Parameters	Corn	Soybean	1:2 configuration	2:3 configuration
Bulk density (g/cm^3)*	1.29 ± 0.02	1.31 ± 0.02	1.30 ± 0.02	1.31 ± 0.02
Soil organic carbon content (%) †	3.06 ± 0.19	3.29 ± 0.19	3.09 ± 0.19	3.19 ± 0.19
C:N ratio†	13.16 ± 0.18	13.55 ± 0.18	13.31 ± 0.18	13.31 ± 0.18

** Bulk density samples are averaged from 2011-2012 and 2012-2013 at 5-10 cm soil depth.*

† *Soil organic carbon content and C:N ratios derived from Regehr (2014, 49).*

4.2.6. Statistical analysis

All statistical analyses were conducted with SPSS (IBM SPSS Science Inc., v. 25.0, Armonk, NY) and used the standard critical threshold of $p < 0.05$. Statistical tests were performed on four variables: CO_2 fluxes, N_2O fluxes, soil WFPS, and soil temperature to determine differences of treatments between growing seasons and treatments within growing seasons and sampling dates. Carbon dioxide and N_2O were the main variables for evaluations; however, soil moisture and soil temperature can influence GHG emissions (Oertel et al. 2016). These environmental variables can differ between sole cropping and intercropping systems due to moisture competition and shading between crops of same or different species (Caviglia et al. 2004).

The 2012-2013 season had sowing delays and used a different soybean variety resulting in two seasons with different field preparation methods. The comparison between field seasons conveyed differences in GHG fluxes due to differences in weather conditions and planting times – two factors that commonly occur in cropping systems. When 2011-2012 and 2012-2013 seasonal N_2O fluxes were compared, data starting from January 22nd (DOY 22) was used in 2012-2013 to prevent comparison sample size biases; considering 2011-2012 had missing N_2O data from Nov 25, 2011 to Jan 17, 2012 (DOY 329-17).

Data series were assessed for normality by observing skewness and kurtosis, and conducting Shapiro-Wilk tests ($p>0.05$). The majority of individual sampling dates had parametric data. At the seasonal scale, variable data were non-parametric, except for WFPS data for 2012-2013. Data heteroscedasticity was evaluated with Levene's non-parametric test on ranked data ($p>0.05$) – seasonal scale data that were non-parametric, showed to be heteroscedastic – while the majority of individual sampling dates was homoscedastic. Heteroscedasticity occurred at the seasonal scale because temporal and spatial variabilities existed in flux data (De Klein and Harvey 2012, 108). For the seasonal data to meet parametric test assumptions, data were transformed using a two-step transformation that applies fractional ranks then uses the inverse normal distribution function (Templeton 2011). The individual sampling dates that did not meet parametric test assumptions were transformed using the two-step transformation approach.

All transformed data met the assumptions to use parametric tests. Two-mean comparisons of the same treatment between 2011-2012 and 2012-2013 seasons were analyzed using an Independent Sample T-test. Treatments within seasons and treatments within individual sampling dates had more than two means, and accordingly, they were tested using the Univariate General Linear Model. Since sample sizes were not always equal, Scheffé post-hoc was used for data with equal variances (Levene's test with a p value > 0.05) and the Tamhane T2 post-hoc was performed on comparisons with unequal variances. Regressions models were fitted (linear and exponential) to explain GHG variance relationships with soil conditions; CO_2 fluxes and N_2O fluxes were the dependent variables, and soil moisture, soil temperature, and soil moisture × soil temperature were the independent variables.

4.3. RESULTS AND DISCUSSION

4.3.1. Seasonal contrasts and soil conditions during the two-year study

Sole cropping and intercropping systems were subjected to contrasting hydrological seasons during the two-year study. Season 2011-2012 was abnormally dry, while the following 2012-2013 season had frequent rainfall (Figure 4.2). From November 2011 to May 2012, the total precipitation was 14.5% below the fifteen-year seasonal mean (683 mm). Infrequent precipitation and dry conditions occurred from December 23rd, 2011 (DOY 357) to January 19th, 2012 (DOY 19), and January 24th, 2012 (DOY 24) to February 16, 2012 (DOY 47). These dry periods ensued when corn was in its late vegetative to anthesis growing stages, a period when corn is most sensitive to nutrient and moisture stress (Andrade and Ferreiro 1996; Calviño and Monzon 2009, 62). Dry conditions caused corn from all treatments to reach physiological maturity by late February; a month earlier than anticipated. During the same period, soybeans were in early vegetative growth stages and started to bud by February 2012; soybeans were less impacted by the dry periods and reached maturity in mid-April.

In 2011-2012 soil WFPS was significantly lower than 2012-2013 season (T_{1121} = 12.96, p <0.001; Table 4.3). In 2011-2012, intercrops had lower seasonal soil moisture content than sole crops; the 2:3 intercrop had significantly drier soils (25.3 ± S.E.0.98%, $F_{1, 3}$ = 5.39, p=0.001) compared the other cropping treatments (combined WFPS mean of 29.9 ± 1.04%; Table 4.3). Significantly lower moisture occurred in the 2:3 intercropping treatment during episodes of low precipitation and canopy development growth stages, suggesting greater water competition interactions compared to the 1:2 intercropping and sole crop systems (Figure 4.3, Appendix 9.1). The frequent rainfall during the 2012-2013 season resulted in the WFPS means between treatments to not be significantly different; the combined WFPS mean was 38.2 ± 0.52% (Figure 4.2 and Figure 4.4).

The overall soil mean temperature (25.6 ± 0.32 °C) for the 2011-2012 season was significantly warmer (t_{1172}=8.2, p < 0.001) than the 2012-2013 season (22.0 ± 0.29 °C; Table 4.3). Within seasons, soil temperature means between treatments did not significantly differ. On an individual date basis within seasons, soil temperature was significantly different between treatments predominantly during vegetative growth stages of the crops, with intercropping as the intermediates (Figure 4.5, Figure 4.6, and Appendix 9.1).

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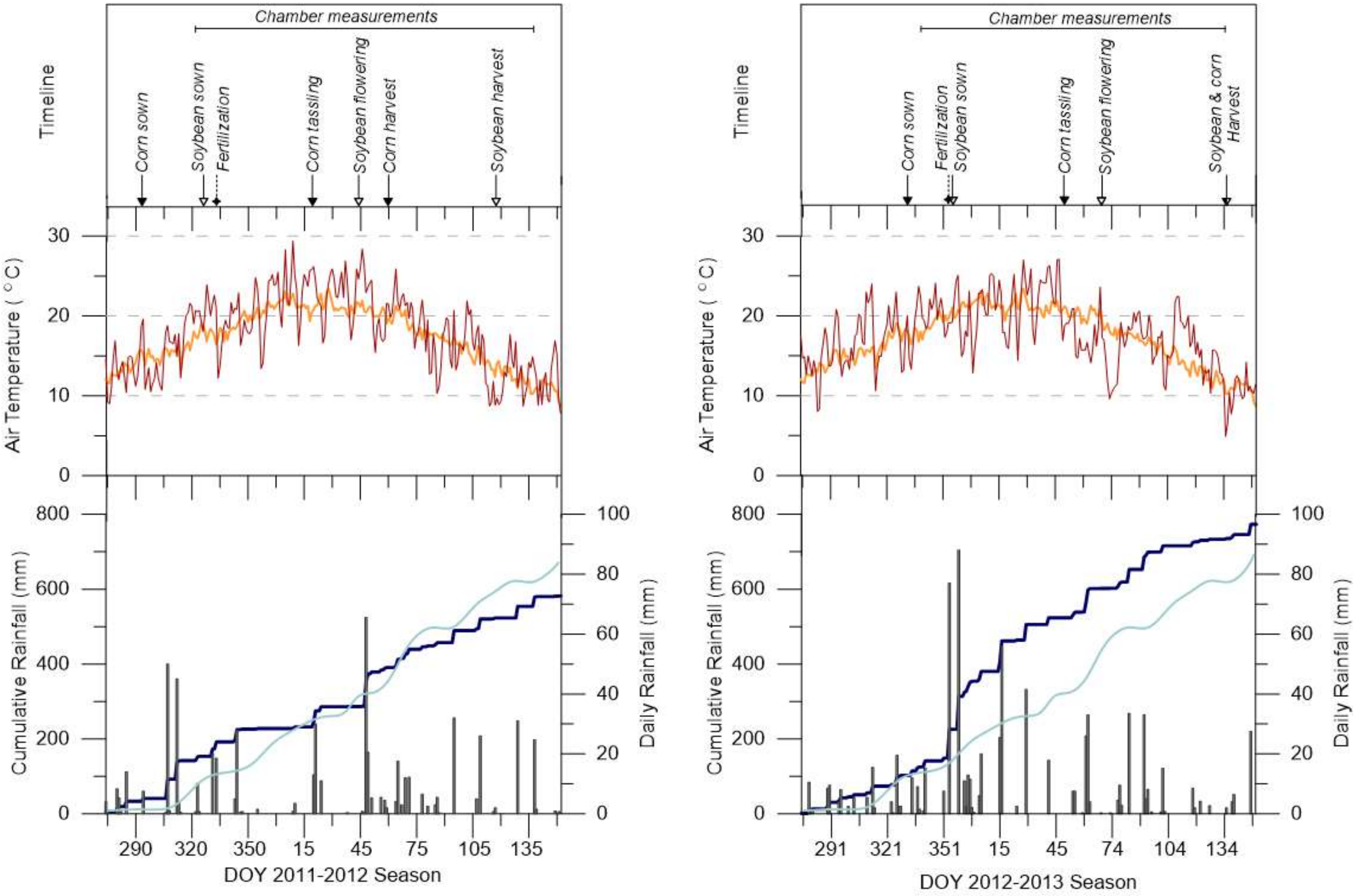

Figure 4.2. Summarized climate and timeline data for the corn-soybean cropping system experiment at UIB. The DOY represents the day of year. The orange line is the 15-year average air temperature, and the dark red line is the daily air temperature. Daily rainfall is shown as a bar graph, the dark blue line is the cumulative seasonal rainfall, and the light blue line is the cumulative fifteen-year average rainfall.

Table 4.3. Descriptives, general linear model univariate analysis of treatments, and season comparison independent T-test summaries for soil water-filled pore space (WFPS), soil temperature, soil emitted carbon dioxide (CO_2) and nitrous oxide (N_2O).

	Season 2011-2012					Season 2012-2013					Season comparison	
		Descriptives		Univariate GLM*			Descriptives		Univariate GLM		T-Test	
Treatment	N	Mean	S.D	F	P	N	Mean	S.D	F	P	T	P
Soil WFPS (%)												
All treatments	573	28.7^{A}	12.44	5.39	**0.001**‡	550	38.2^{B}	12.24	0.71	0.545	12.96	**0.001**
sole corn	144	30.7^{a,A†}	13.63			137	37.0^{d,B}	12.37			4.31	**<0.001**
sole soybean	141	29.6^{a,A}	11.23			138	38.9^{d,B}	12.87			6.45	**<0.001**
1:2 intercrop	144	29.3^{a,A}	12.48			138	37.9^{d,B}	11.82			5.95	**<0.001**
2:3 intercrop	144	25.3^{b,A}	12.74			137	38.8^{d,B}	11.90			9.74	**<0.001**
Soil temperature (°C)												
All treatments	623	25.6^{A}	8.11	0.34	0.797	551	22.0^{B}	6.88	1.27	0.283	8.17	**<0.001**
sole corn	156	25.2^{a,A}	7.82			138	21.4^{d,B}	6.71			4.52	**<0.001**
sole soybean	156	25.9^{a,A}	8.68			138	22.8^{d,B}	7.47			3.39	**0.001**
1:2 intercrop	156	25.6^{a,A}	8.01			138	22.4^{d,B}	6.67			3.66	**<0.001**
2:3 intercrop	155	25.7^{a,A}	7.96			137	21.3^{d,B}	6.61			4.80	**<0.001**
CO_2 emissions (kg CO_2- C ha^{-1} d^{-1})												
All treatments	613	29.7^{A}	15.02	2.60	0.051	553	25.0^{B}	12.71	1.63	0.181	5.55	**<0.001**
sole corn	156	27.7^{a,A}	14.51			141	24.3^{d,B}	12.57			2.03	**0.044**
sole soybean	150	29.9^{a,A}	13.00			134	26.3^{d,B}	11.91			2.43	**0.016**
1:2 intercrop	152	32.7^{a,A}	15.51			138	25.6^{d,B}	13.96			3.93	**<0.001**
2:3 intercrop	155	28.9^{a,A}	16.50			140	23.8^{d,B}	12.26			2.69	**0.007**
N_2O emissions (g N_2O-N ha^{-1} d^{-1})												
All treatments						558	8.1	17.03	3.06	**0.028**		
sole corn						142	6.3^{d}	17.04				
sole soybean						135	6.1^{d,e}	8.77				
1:2 intercrop						139	12.0^{e}	21.21				
2:3 intercrop						142	7.9^{d,e}	17.88				
N_2O emissions (g N_2O- N ha^{-1} d^{-1}) – January to May												
All treatments	372	6.7^{A}	8.44	7.19	**<0.001**	397	3.3^{B}	5.23	4.18	**0.006**	5.88	**<0.001**
sole corn	93	6.7^{a,A}	9.14			101	1.8^{d,B}	2.70			4.00	**<0.001**
sole soybean	92	4.4^{a,A}	5.85			97	4.0^{e,A}	4.66			0.32	0.748
1:2 intercrop	92	10.5^{b,A}	10.38			98	4.7^{d,e,B}	7.63			4.49	**<0.001**
2:3 intercrop	95	5.2^{a,A}	6.39			101	2.8^{d,e,B}	4.30			2.95	**0.004**

* F critical value = 2.60; T critical value = 1.65; p = 0.05 significance. † Dissimilar uppercase letters indicate significant differences for seasonal T-test comparison. Dissimilar lowercase letters indicate significant differences between treatments within a season. ‡ Bold font represents significant differences between treatments within a season and for season comparison.

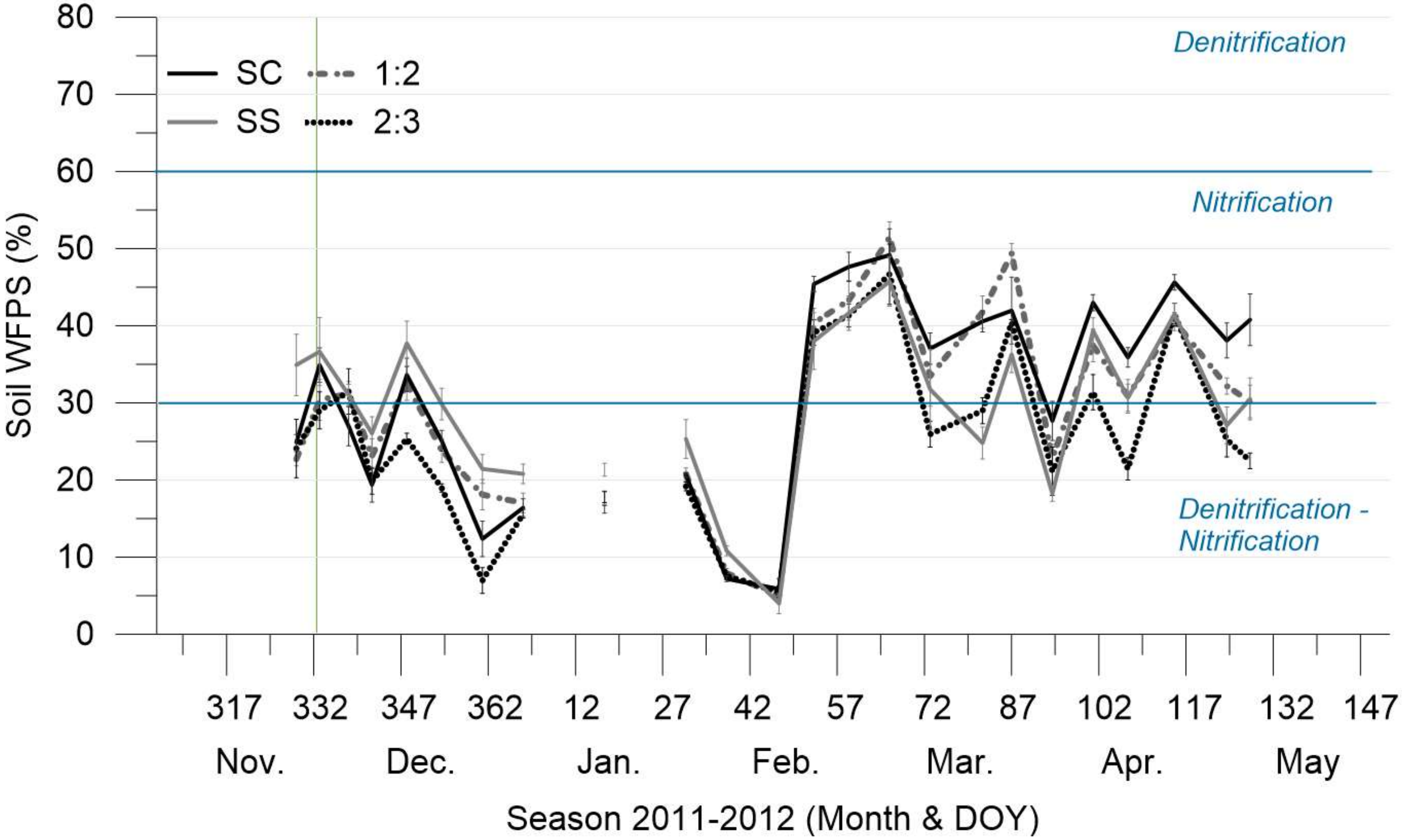

Figure 4.3. Mean water-filled porosity space (WFPS) and its standard error (bars) at 0-7cm depth in corn-soybean intercropping and rotated sole cropping treatments at UIB, Balcarce, Argentina, during 2011-2012 summer growing seasons. The green vertical line marks the date when urea was applied to SC, 1:2 and 2:3 cropping system treatments. The blue lines separate moisture conditions that best-suited denitrification and/or nitrification activity.

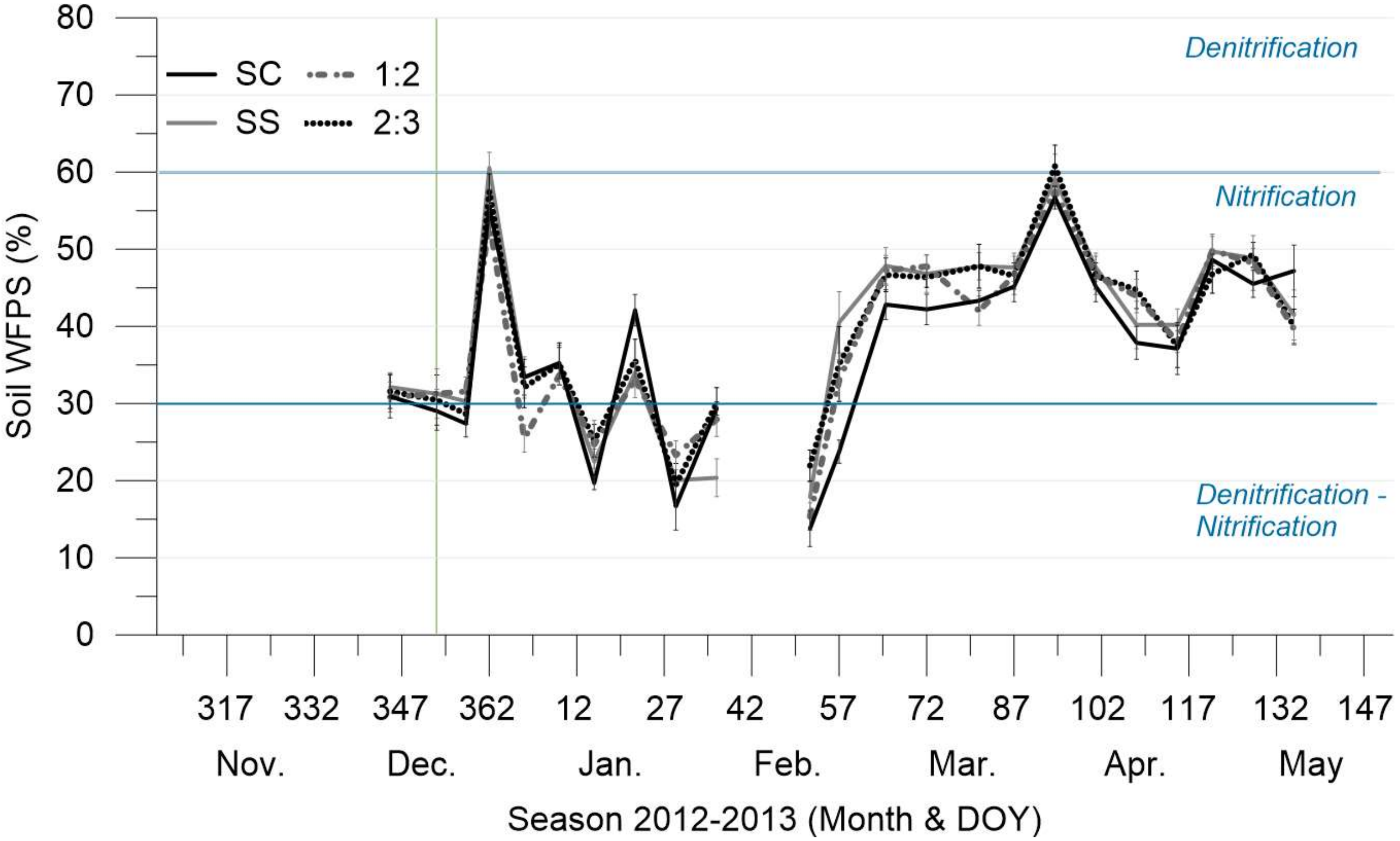

Figure 4.4. Mean water-filled porosity space (WFPS) and its standard error (bars) at 0-7cm depth in corn-soybean intercropping and rotated sole cropping treatments at UIB, Balcarce, Argentina, during 2012-2013 summer growing seasons. The green vertical line marks the date when urea was applied to SC, 1:2 and 2:3 cropping system treatments. The blue lines separate moisture conditions that best-suited denitrification and/or nitrification activity

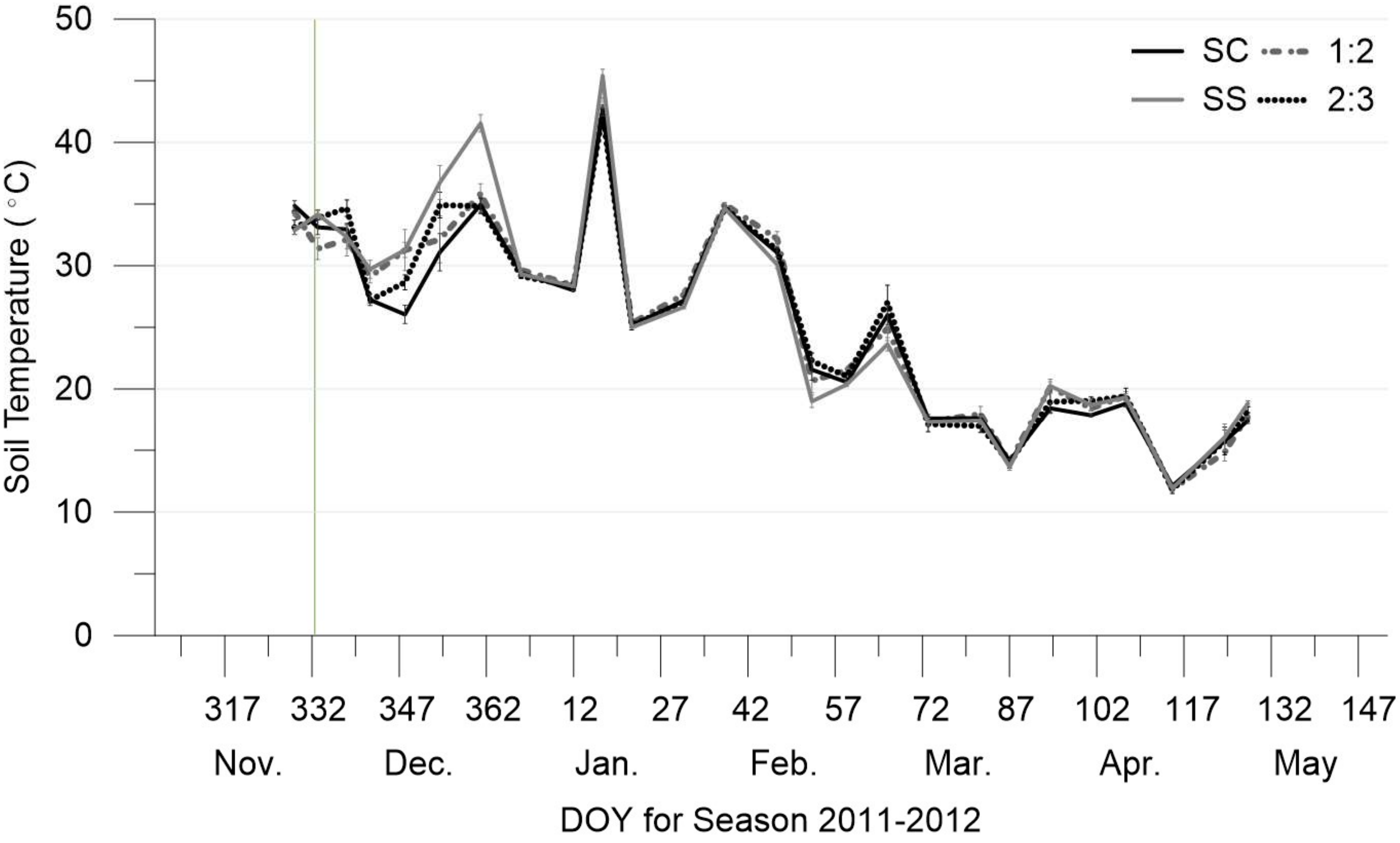

Figure 4.5. Mean soil temperatures and its standard error (bars) at 0-7cm depth in corn-soybean intercropping and rotated sole cropping treatments at UIB, Balcarce, Argentina, during 2011-2012 summer growing seasons. The green vertical line marks the date when urea was applied to SC, 1:2 and 2:3 cropping system treatments.

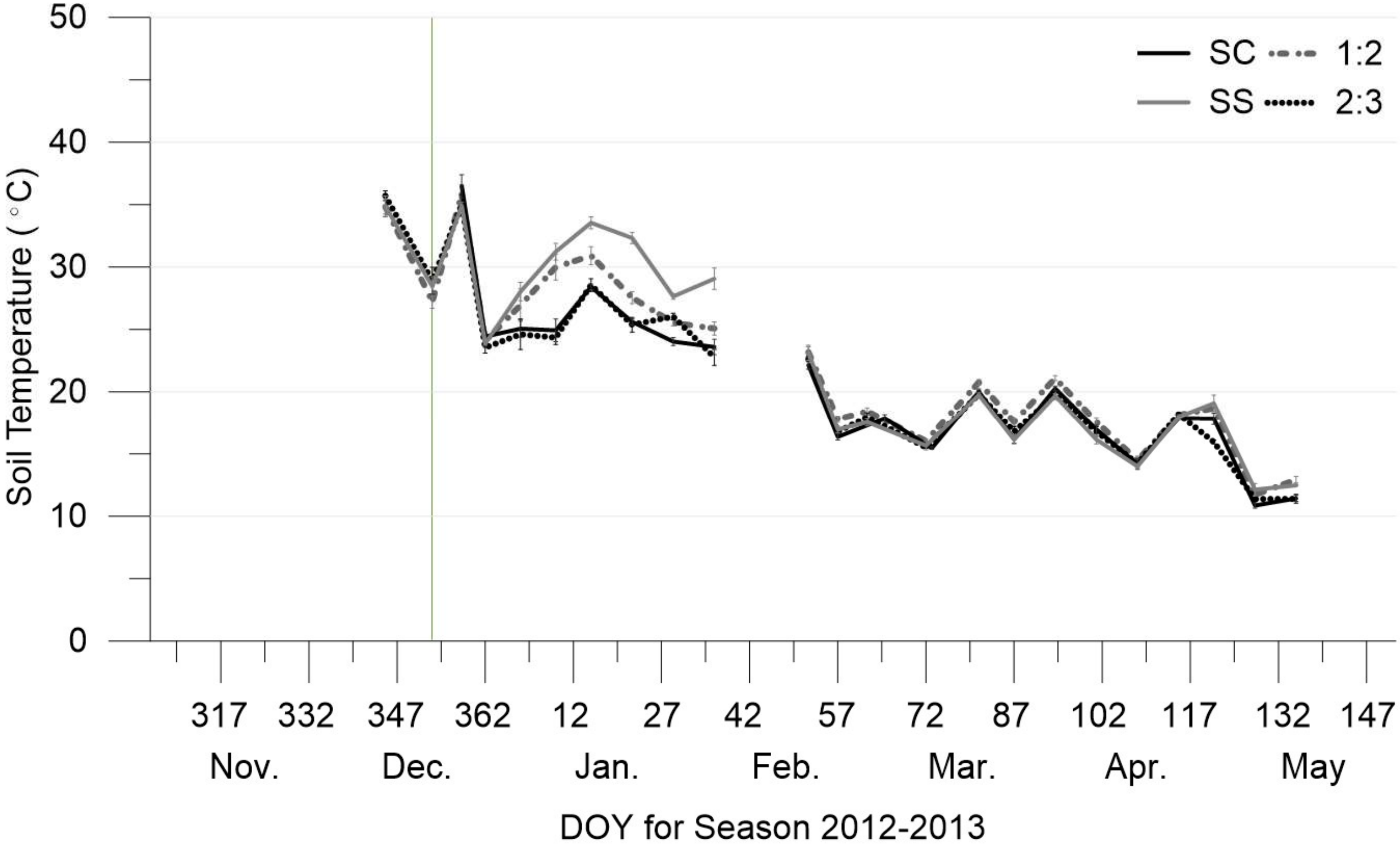

Figure 4.6. Mean soil temperatures and its standard error (bars) at 0-7cm depth in corn-soybean intercropping and rotated sole cropping systems at UIB, Balcarce, Argentina, during 2012-2013 summer growing seasons. The green vertical line marks the date when urea was applied to SC, 1:2 and 2:3 cropping system treatments.

4.3.2. CO_2 emissions and factors influencing soil respiration

4.3.2.1. Soil CO_2 emission rates during 2011-2012 and 2012-2013 growing seasons

Carbon dioxide emissions were greater in 2011-2012 than 2012-2013 for all treatments (t_{1164} = 5.55, p<0.001, Table 4.3). Corn-soybean cropping systems had CO_2 emission rates that varied from 5.3 - 86.5 kg CO_2-C ha^{-1} d^{-1} in 2011-2012 and 3.6 - 80.3 kg CO_2-C ha^{-2} d^{-1} in 2012-2013 (Figure 4.7, Figure 4.8, and Appendix 9.1). These soil CO_2 emission rates were among the 4.7-85.1 kg C ha^{-1} d^{-1} range found in other chamber based studies that were situated in temperate cropping systems (Rochette et al. 1999; Oertel et al. 2016; Shen et al. 2018). During the 2011-2012 season, the 1:2 intercropping treatment had the greatest CO_2 flux mean followed by sole soybean, 2:3 intercropping, then sole corn (32.7 - 27.7 kg CO_2-C ha^{-1} d^{-1}; Table 4.3) but the treatments were all significantly the same ($F_{1,3}$= 2.60, p=0.051). Likewise, 2012-2013 seasonal CO_2 flux means did not significantly differ between treatments ($F_{1,3}$ =1.63, p=0.181) ranging from 24.3 - 26.3 kg CO_2-C ha^{-1} d^{-1}. An explanation for the lack of differences between treatments for seasonal CO_2 flux means can relate to the types of crops cultivated. Raich and Tufekcioglu et al. (2000) reviewed soil respiration from various crops in Iowa and found that soybean (27 kg CO_2-C ha^{-1} d^{-1}) and corn (24 kg CO_2-C ha^{-1} d^{-1}) had similar CO_2 emissions.

4.3.2.2 Events that increased soil CO_2 emissions

The 2011-2012 season had CO_2 emissions that peaked after urea application and after large rain events that ended dry periods. Differences between treatments for CO_2 fluxes at individual dates occurred predominantly early in the season (Day 329 - 361); with soybeans having significantly lower fluxes than sole corn and intercropping systems. Crops were in their vegetative growth stages, and urea was recently applied during this early sampling period. Carbon dioxide emissions lowered mid-season as well as at the end of the season. In February

2012, the soil was at its driest (WFPS 4.0-10.8%), and corn ended its reproductive development. It was suspected that both crop development and low moisture content reduced microbial activity; thus, lowering root and soil CO_2 respiration mid-season (Rochette et al. 1999; Oertel et al. 2016). Rainfalls that ended dry periods resulted in a pulse of CO_2 from all treatments. The pulse of CO_2 was driven by the respiration of reactivated microorganisms (Fierer et al. 2003; Oertel et al. 2016).

4.3.2.3. Relationships between soil conditions and CO_2 emissions in corn-soybean cropping systems

Often variations in CO_2 soil emissions increase exponentially with variations in soil temperature (Raich and Potter 1995; Rochette et al. 1999; Oertel et al. 2016). Soil temperature variation during 2011-2012 explained 17%, 15%, 11% and 2% of the CO_2 variation in 1:2 intercropping, sole corn, 2:3 intercropping, and sole soybean, respectively. It was suspected that soil drying – rewetting events, crop moisture stress, and extreme soil temperatures (>37ºC) resulted in the cropping systems having a weak relationship between CO_2 emissions and soil temperature (Rochette et al. 1999; Oertel et al. 2016). In comparison, Rochette et al. (1999) had 19-45% of the CO_2 emission variation explained by soil temperature, when dry and rewetting periods occurred in their corn cropping systems. Soil temperature variations in 2012-2013 corresponded with 54%, 52%, 48% and 37% of the CO_2 variability in the 1:2 intercropping, sole corn, 2:3 intercropping and sole soybean treatments, respectively. The two seasons display that SC and 1:2 had greater response to soil temperature – CO_2 emissions relationships than the 2:3 and SS treatments. The relationship between WFPS and CO_2 emissions showed to be very weak within each cropping treatment for the both the 2011-2012 and 2012-2013 seasons, ranging from 0-4%. In the same season, the intercropping treatments and sole corn CO_2 emission variability was explained by approximately 30% in relation to the combination of

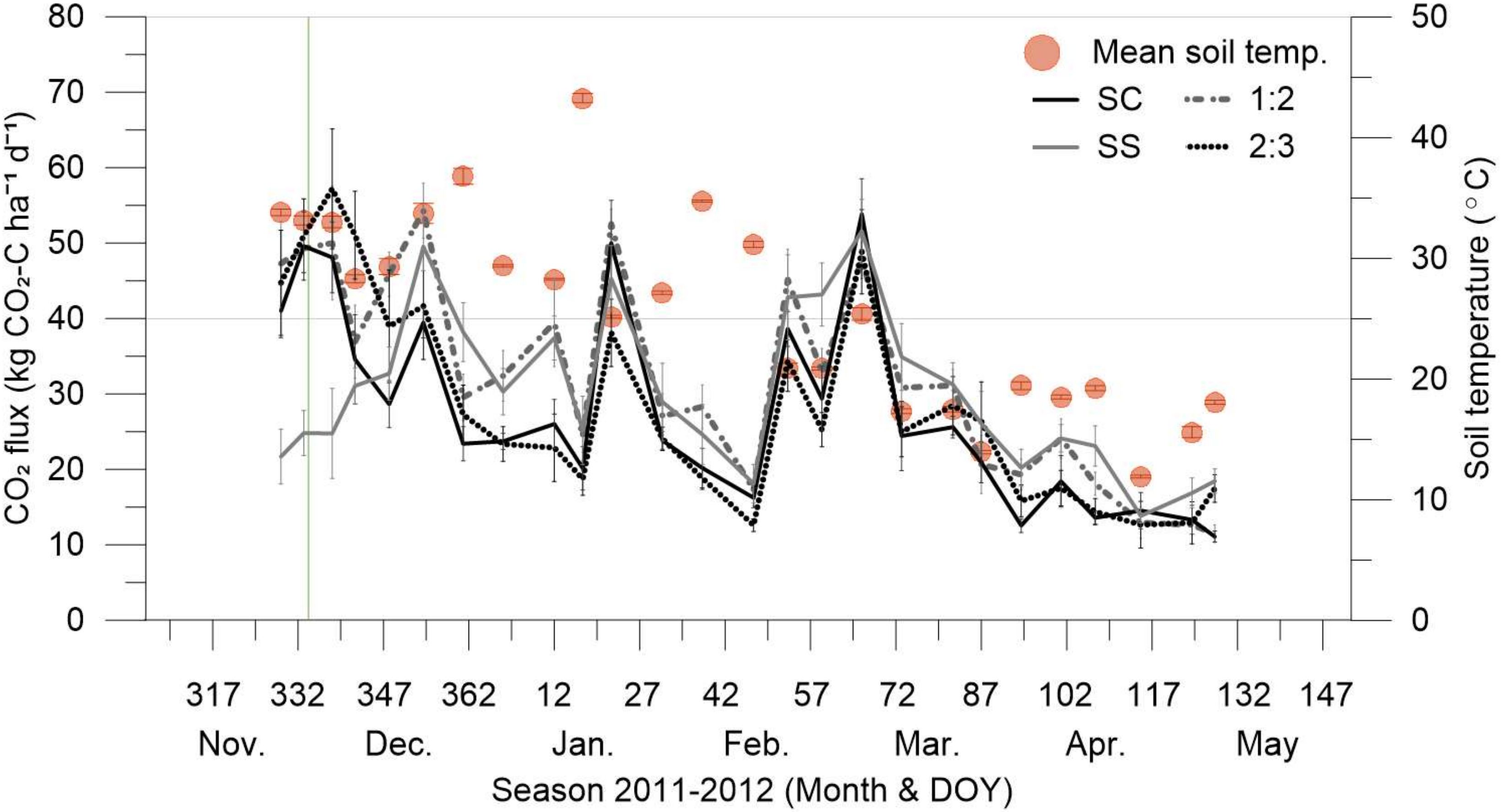

Figure 4.7. Treatment means for the soil CO_2-C flux (line graphs with standard error [SE] bars) and overall soil temperature mean (orange circles with SE bars) in a corn-soybean intercropping and rotated sole cropping treatments, at the UIB research site, located at Balcarce, Argentina, during the 2011-2012 growing seasons. Treatments were sole corn (SC), sole soybean (SS), one-row corn to two-rows soybean (1:2) and two-rows corn to three-rows soybean (2:3) intercropping. The green vertical line marks the date when urea was applied to treatments that consisted of corn (SC, 1:2 and 2:3).

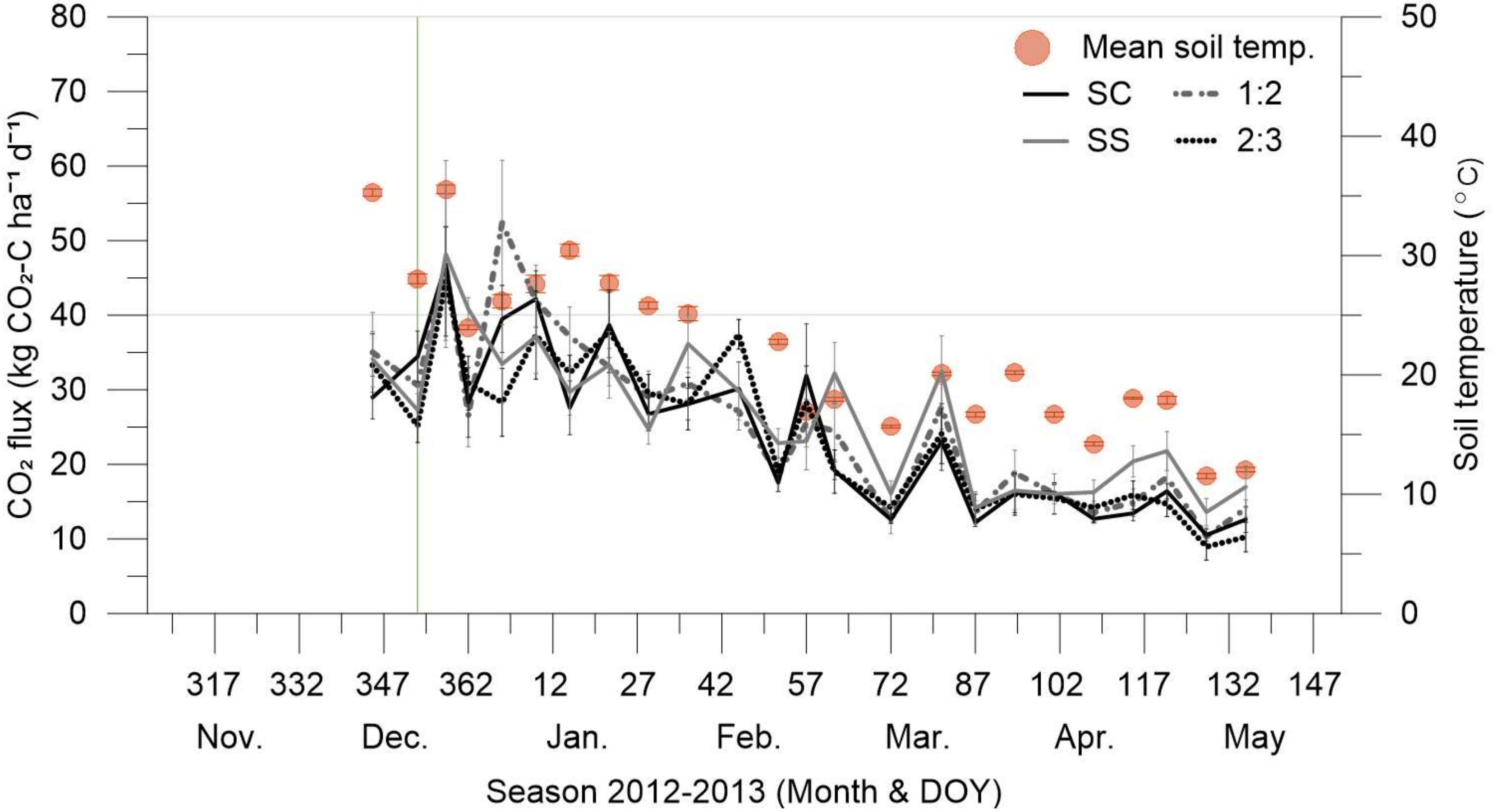

Figure 4.8. Treatment means for the soil CO_2-C flux (line graphs with standard error [SE] bars) and overall soil temperature mean (orange circles with SE bars) in a corn-soybean intercropping and rotated sole cropping treatments, at the UIB research site, located at Balcarce, Argentina, during the 2012-2013 growing seasons. Treatments were sole corn (SC), sole soybean (SS), one-row corn to two-rows soybean (1:2) and two-rows corn to three-rows soybean (2:3) intercropping. The green vertical line marks the date when urea was applied to treatments that consisted of corn (SC, 1:2 and 2:3)

WFPS x soil temperature – while 9% was explained in the sole soybean treatment. Carbon dioxide emissions variation in relation to WFPS x soil temperature variation in the 2012-2013 growing season had 51%, 46%, 43%, 36% explained within the 2:3 intercrop, sole corn, 1:2 intercrop, and sole soybean treatments, respectively.

4.3.3 N_2O fluxes in intercropping and sole cropping systems

4.3.3.1. Measured N_2O fluxes in the 2011-2012 summer growing season

Nitrous oxide flux measurements obtained in 2011-2012 were initiated on January 22, 2011 (DOY 22), when corn started anthesis until the end of the season on May 7th, 2012 (DOY 128). During this sampling period, N_2O fluxes varied from -6.1 to 44.1 g N_2O-N ha^{-1} d^{-1} (Figure 4.9). The 1:2 intercropping treatment had significantly higher N_2O flux mean (10.5 ± 1.08 [S.E] g N_2O-N $ha^{-1}d^{-1}$) than all the other cropping systems ($F_{1,3}$= 7.12 p<0.001; Table 4.3). Sole soybean had the lowest N_2O flux mean (4.4 ± 0.61 g N_2O-N ha^{-1} d^{-1}), which was not significantly different (p >0.844) than the 2:3 intercropping (5.2 ± 0.66 g N_2O-N $ha^{-1}d^{-1}$) and sole corn (6.7 ± 0.95 g N_2O-N ha^{-1} d^{-1}). A three-week period from February 28 to March 13, 2012 (DOY 59-73) had visibly higher N_2O emissions from treatments with corn (SC, 1:2 and 2:3), particularly the 1:2 intercropping treatment (Figure 4.9). Prior to this N_2O event, a second dry period occurred, and treatments with corn had significantly drier soils compared to sole soybean for weeks (DOY 17-38). Frequent rain events ended this dry period, totalling 153 mm of precipitation from February 17 to March 11, 2012 (DOY 48-71; Appendix 9.1). Rewetting after moisture-stress frequently results in increased soil N_2O emissions and is known as pulsing or the Birch effect (Birch 1958; Oertel et al. 2016). Rewetting enhances mineralization by releasing nitrogen from microbial biomass that died and accumulated during the dry period, providing a substrate for N_2O producing processes (Canarini and Dijkstra 2015; Oertel et al. 2016). Nitrification was most likely the main process producing N_2O after the rewetting event because soil WFPS

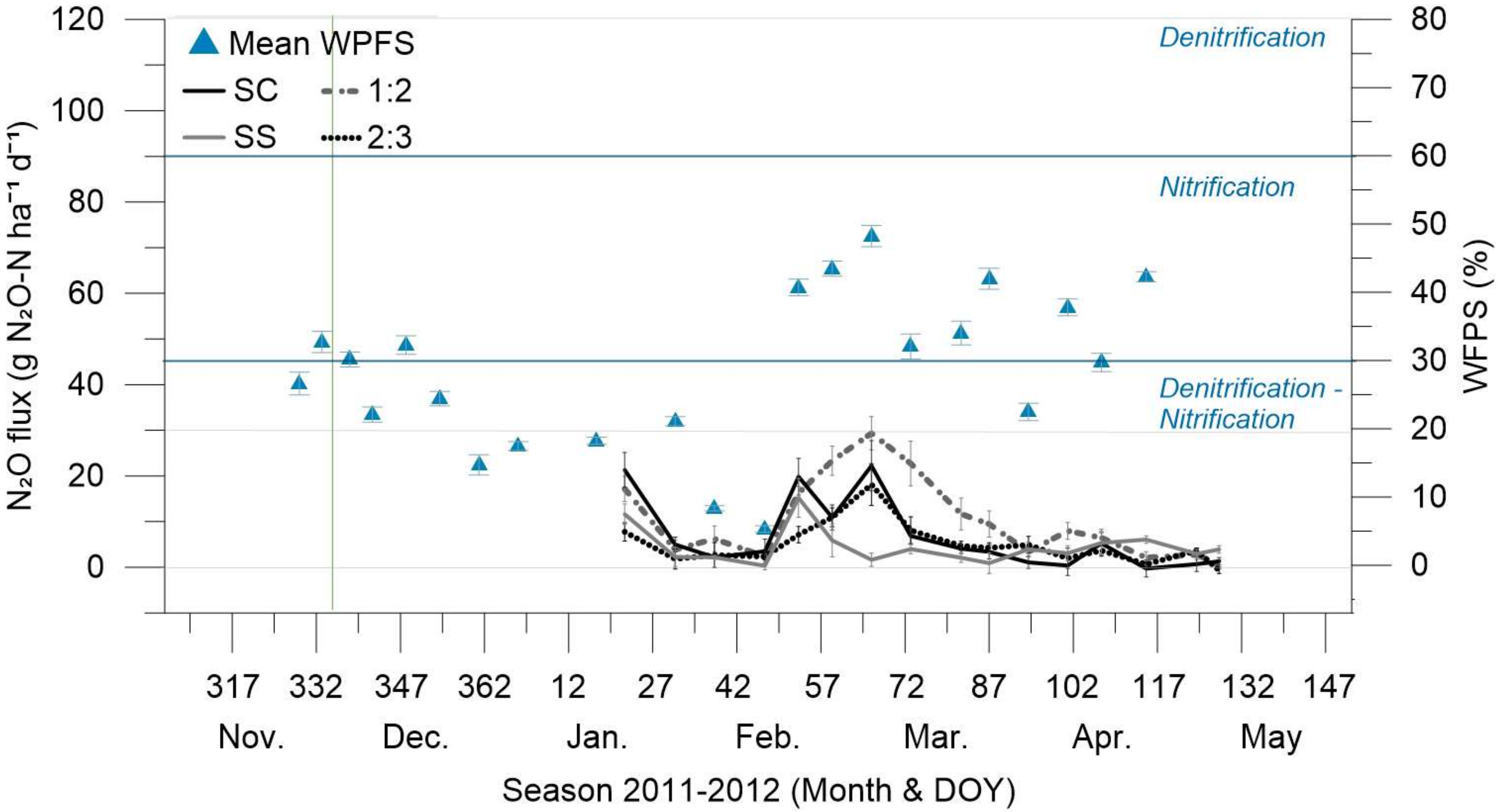

Figure 4.9. Mean soil N_2O-N flux (line graphs with standard error [SE] bars) in corn-soybean intercropping and rotated sole cropping treatments at UIB, Balcarce, Argentina, during the 2011-2012 growing seasons. The blue triangles with SE bars display the combined mean water-filled pore space (WFPS) for all treatments. The green vertical line marks the date when urea was applied to SC, 1:2 and 2:3 cropping systems.

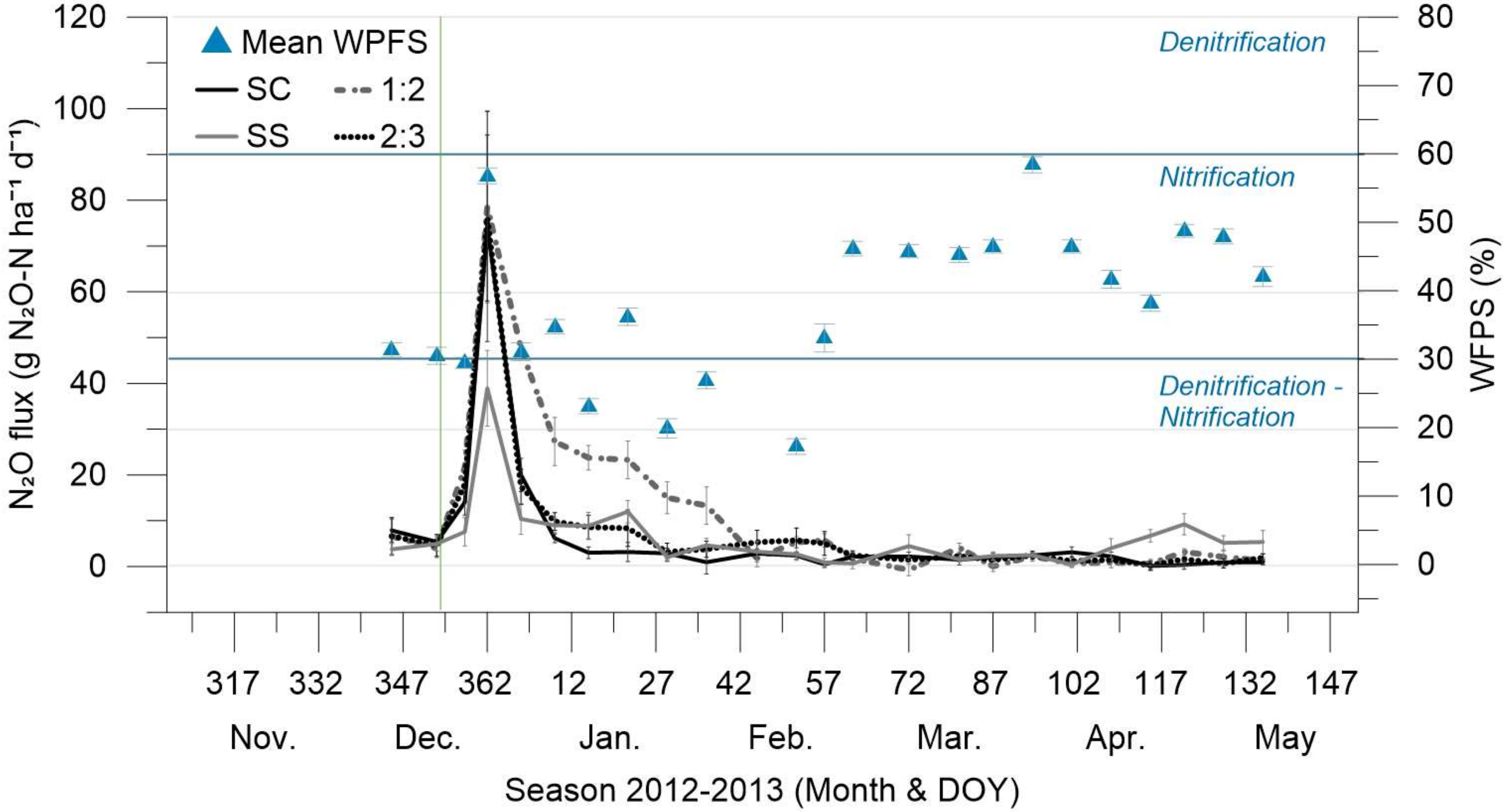

Figure 4.10. Mean soil N_2O-N flux (line graphs with standard error [SE] bars) in corn-soybean intercropping and rotated sole cropping treatments at UIB, Balcarce, Argentina, during the 2012-2013 growing seasons. The blue triangles with SE bars display the combined mean water-filled pore space (WFPS) of all treatments. The green vertical line marks the date when urea was applied to SC, 1:2 and 2:3 cropping system.

was in the optimal (45-50%) range for nitrifying microorganisms (Baggs 2008). There were likely peaks of N_2O produced before January 2012, after a rain event post-urea application in December 2011, and after the first rewetting (43 mm) in January (DOY 20-21). The anticipated N_2O peaks would probably not be as large as the second rewetting event that was measured or the post urea application in 2012-2013, because the soil WFPS was near or under 30% during these two periods (Baggs 2008; Oertel et al. 2016)

The lowest fluxes and nitrogen sequestration were recorded in 2011-2012 from sole corn and both intercropping systems, when soils were at their driest (February 16, DOY 47). Prolonged dry periods (WFPS < 20) have been found to reduce soil emissions significantly and influence soils to be net sinks (Goldberg and Gebauer 2009; Oertel et al. 2016). Additionally, N_2O emissions from all treatments lowered from April to May 2012 (DOY 92-128), when corn was harvested, soybeans were senescing, rainfall was frequent, and temperatures were cooler. These combined factors relate to slowing autotrophic and heterotrophic microorganism activity (Snyder et al. 2009; Oertel et al. 2016).

4.3.3.2. Measured N_2O fluxes in the 2012-2013 summer growing season

Compared to the previous growing season, the 2012-2013 season resulted in significantly lower N_2O flux means in sole corn (T_{192}=4.00, p = <0.001) and intercropping treatments (1:2, T_{188}=4.49, p = <0.001; 2:3, T_{194}=2.95, p=0.004) from January to May. The sole soybean treatment was not significantly different for N_2O flux means between the two seasons (T_{187}=0.32, p=0. 748). Season 2012-2013 had N_2O flux measurements for the entire season (December 2012 to May 2013) that varied from -8.3 to 170.1 g N ha^{-1} d^{-1} (Figure 4.10). These findings are among the range of other temperate corn-soybean rotation cropping systems (Mackenzie et al. 1997; Parkin and Kasper 2006; Venterea et al. 2010). The largest N_2O fluxes occurred in sole corn and intercropping systems from the end of December 2012 to mid-January 2013, with greatest N_2O fluxes occurring on December 28th. The combination of recently added nitrogen to the soil, and a WFPS around 60% provided a scenario for the greatest potential to emit N_2O from soils by both nitrification and denitrifying processes (Baggs 2008; Snyder et al. 2009). In the following weeks (January 3rd to February 5th) N_2O emissions lowered in all treatments except for 1:2 intercropping. The 1:2 intercropping treatment continuously had significantly larger N_2O fluxes than the other treatments on an individual sampling date basis from January 3rd to February 5th. These significant differences resulted in 1:2 intercropping to have the greatest seasonal mean flux (12.0 ± 1.80 [S.E.] g N_2O-N $ha^{-1}d^{-1}$), but was only significantly different ($p=0.004$) than sole corn treatment (6.3 ± 1.43 g N_2O-N $ha^{-1}d^{-1}$). From mid-February 2013 to May 2013, soils were a sink for nitrogen or had low mean N_2O fluxes (< 9.2 g N_2O-N ha^{-1} d^{-1}). During this time, three factors influenced lower N_2O emissions: i) soil temperatures were declining; ii) frequent precipitation maintained a soil WFPS between 30%-60% inhibiting pulse events; and iii) soil nitrogen was unavailable due to immobilization (NH_4^+ or NO_3^- assimilated by microorganisms; Figure 4.11) and crop uptake (Borken and Matzner 2009; Oertel et al. 2016). The low emissions occurring could have been from both nitrification and denitrification processes (Baggs 2011; Ussiri and Lal 2013); constant soil moisture would increase the potential for anaerobic microsites for denitrifying activity.

4.3.4. Factors influencing N_2O fluxes in corn-soybean cropping systems

4.3.4.1. Enhanced N_2O emissions in the 1:2 intercropping system

The 1:2 intercropping configuration resulted in N_2O flux means that were significantly greater than sole crops after rewetting in the 2011-2012 season, and after the urea application that occurred in the 2012-2013 season. In both instances, N_2O fluxes from the 1:2 intercropping treatment took longer to decline to levels similar to the other treatments (Figure 4.9; Figure 4.10). In contrast, the mean N_2O emission rate from 2:3 intercropping configuration did not significantly differ from that of the sole cropping treatments after these events. The configuration and land management of these intercropping treatments may have influenced microclimates, microbial populations, and carbon and nitrogen dynamics that affected N_2O processes and production (Oertel et al. 2016).

Regarding microclimates, the 1:2 intercropping treatment had the highest correlations with the limited climate resource (precipitation or soil temperature). In the warmer and dry season from January 2011 to May 2012, soil temperature had a poor association with N_2O in all treatments (0-7%). In this same period, the soil WFPS explained 24% of N_2O flux variability from 1:2 intercropping, and to a lesser extent explained 10% of 2:3 intercropping, 6% of sole corn, and 4% of sole soybean N_2O variability. The relationship between N_2O and WFPS x soil temperature explained 44% and 17% of the 1:2 and 2:3 intercrops, and 28% and 4% of the sole corn and soybean treatments, respectively. During the wet and cool season from January 2013 to May 2013, WFPS explained less than 1% of N_2O flux variability in sole crops, 10% in 2:3 intercropping, and 25% in 1:2 intercropping. Within this same season, soil temperature corresponded to 43% and 9% of N_2O emissions from 1:2 and 2:3 intercropping, and <4% from sole crops, respectively. The combined relationship of WFPS x soil temperature explained 12%, 20%, 31%, and 69% N_2O variability in the sole corn, sole soybean, 2:3 intercropping, and 1:2 intercropping treatments, respectively. The stronger relationships of N_2O production in 1:2 intercropping with soil moisture and temperature was suspected to be linked to biotic (microbial activity dynamics and crop demands) and abiotic (nitrogen availability) factors.

An incubation study by Bichel et al. (2016) and Bichel et al. (2017) – using soil from the same UIB corn-soybean research site as this present study – determined that the 1:2 intercropping treatment had greater soil microbial diversity, density, and activity. The prolonged and greater N_2O emissions in the 1:2 intercropping may be due to differing soil microbial community makeup. For instance, the 1:2 intercrop microbial diversity may include a wider range of microorganisms that produce N_2O, such as, a variety of autotrophic and heterotrophic nitrifiers, and anaerobic and aerobic denitrifiers causing a different response to soil conditions compared to the other treatments.

A study at the same site, by Regehr et al. (2015), further provides evidence to why 1:2 intercropping treatment would produce more N_2O compared to the other treatments. Regehr et al. (2015) expected gross mineralization to be highest in the sole soybean, the intercrops to be intermediates, and sole corn to be the lowest (and vice versa for gross immobilization). Alternatively, they found that gross mineralization was greatest in the intercropping treatments. The 2:3 intercropping treatment had significantly greater gross mineralization than the other treatments. Additionally, gross immobilization was the greatest in the 2:3 intercropping treatment; significantly more than sole soybean and 1:2 intercropping. This suggests that 2:3 intercropping had more effective C:N dynamics for controlling the supply of available nitrogen. While, the 1:2 intercropping system had a strong capability to mineralize nitrogen, but was weak at immobilizing nitrogen causing an increase in soil available nitrogen concentrations.

4.3.4.2. Nitrogen inputs added to sole corn and intercropping systems

Similar to Haung et al. (2017) and Shen et al. (2018) experimental designs, this study used the same rate of urea (150 kg N ha^{-1}) in sole corn and intercropping systems to prevent production biases for water-limited yields. The rate of urea applied was appropriate for sole corn cropping, but not an effective rate for the 1:2 and 2:3 intercropping systems. When there is excessive soil available nitrogen, there is more potential for nitrogen loss by volatilization, NO_3^- leaching, and N_2O emissions (Signor and Cerri, 2013; Oertel et al. 2016). After fertilizer additions were applied on December 19, 2012 (DOY 354), heavy rainfall events transpired (totalling 176 mm) by December 28th (DOY 363). Both NO_3^- and NH_4^+ soil concentrations declined in all treatments by December 28th, indicating N losses at the 0-15 cm soil depth (Figure 4.11).

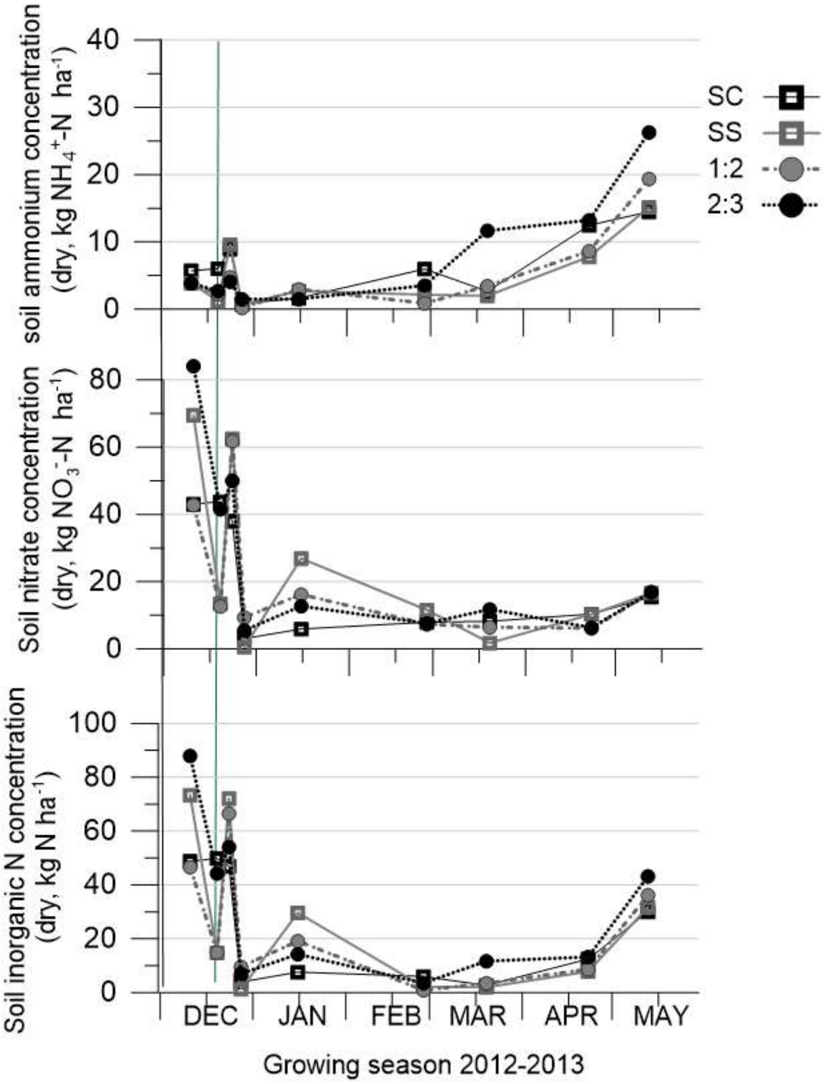

Figure 4.11. Soil NH_4^+, NO_3^- and total N concentrations collected from in corn-soybean intercropping and rotated sole cropping treatments at UIB, Balcarce, Argentina from December 2012-May 2013. The green vertical line marks the date when urea was applied to SC, 1:2 and 2:3 cropping system.

In January 2013 the total N concentrations increased for all treatments. However, the 1:2 intercropping treatments had greater concentrations of both NH_4+ (2.9 Kg NH_4^+-N ha^{-1}) and NO_3^- (16.2 Kg NO_3^--N ha^{-1}) in comparison to other fertilized treatments − sole corn (1.6 Kg NH_4^+-N ha^{-1}, 5.9 Kg NO_3^--N ha^{-1}) and 2:3 intercropping treatments (1.5 Kg NH_4^+-N ha^{-1}, 12.7 Kg NO_3^--N ha^{-1}). Concurrently, the 1:2 intercropping treatment had significantly higher N_2O emissions compared to all treatments during the month of January (Figure 4.10). The results from the

January soil N concentrations and N_2O emissions suggest that the 1:2 intercropping had greater N transforming microbial activity (from synthetic and organic N sources) that resulted in greater N_2O emissions. Though it should be noted that soil NO_3^- and NH_4^+ concentrations can fluctuate widely within short periods of time (Drinkwater et al. 2008), thus the monthly soil N concentrations provide limited knowledge on what was occurring inside the chamber exactly at the time when gases were collected.

Modernized corn-soybean intercropping systems are relatively new research in the Argentine Pampas. Therefore it is not surprising that nitrogen fertilizer rates had not yet been attuned to meet the demands of the two intercropping designs. Not only did the intercropping systems have more nitrogen fertilizer added per plant compared to sole corn treatment, the intercropping systems included soybeans that can self-supply nitrogen and facilitate the availability of nitrogen to corn through root excretions (Vandemeer, 1992, 88; Li et al. 2014; Brooker et al. 2015;). Excess nitrogen in soil inhibits N-fixation capabilities of legumes, and consequently, legumes can compete for available soil nitrogen with non-legumes (Salvagiotti et al. 2008). To further emphasize the need for adjusting fertilizer requirements for cereal-legume intercropping systems, data reviewed by Shcherbak et al. (2014) showed that fertilized legumes emitted significantly ($p<0.001$) larger percentage of nitrogen sourced from nitrogen inputs compared to fertilized cereals and grasses. This illustrates that there can be production (crop growth and GHGs) biases whether or not fertilizer rates stay consistent in an intercropping system due to competition and facilitation complexes. International studies found that reducing nitrogen inputs in corn-soybean intercropping by 20-50% compared to what is conventionally added to sole cropped corn improved intercropping crop production performance and reduce input costs (Nair et al. 1979; Ssali 1990; Rana et al. 2001; Yong 2018). Reducing the fertilizer rate from 150 to 100 kg N ha^{-1} could potentially provide 63-71 kg CO_2-C^{eq} ha^{-1} reduction of emitted as N_2O in the corn-soybean intercropping treatments (Shcherbak et al. 2014).

4.3.5. Evaluating cumulative greenhouse gas emitted from soil in corn-soybean cropping treatments

4.3.5.1. Cumulative CO_2-C equivalent soil emissions

In the order of lowest to highest, calculated cumulative CO_2 –C emissions per treatment for season 2011-2012 were SC < 2:3 < SS < 1:2, ranging from 4574.3 – 5367.5 CO_2-C kg ha^{-1}; the following 2012-2013 season was SC < 2:3 < 1:2 < SS ranging from 3707.9 – 4115.7 CO_2-C kg ha^{-1} (Table 4.4). Cropping systems that included soybeans had greater CO_2 emissions than sole corn, because the growing season was longer for soybeans production, hence, more autotrophic respiration occurred. Cumulative N_2O-N emissions from treatments by lowest to highest order for January 2012 to May 2012 was SS < 2:3 < SC < 1:2 ranging from 63.7 to 153.3 CO_2-C^{eq} kg ha^{-1}. For the following 2012-2013 season, the order was SS < SC < 2:3 <1:2 ranging from 120.6 to 229.7 CO_2-C^{eq} kg ha^{-1} (Table 4.4). These are contrasting findings to Haung et al. (2017) and Shen et al. (2018) – where intercropping had lower cumulative N_2O than sole corn. Experimental design and study site differences are factors that affect N_2O emission. For example, both Haung et al. (2017) and Shen et al. (2018) corn-soybean intercropping systems differed from the present study by having simultaneous planting and harvesting times and alkaline soils consisting of low carbon content. Moreover, Haung et al. (2017) used an additive intercropping design, while the present study used a substitutive design. These site conditions and designs alter both soil carbon – nitrogen and competition-facilitation dynamics – two factors that can impact N_2O and CO_2 emissions rates.

Table 4.4. Cumulative CO_2 (kg C ha^{-1}) and N_2O (g N ha^{-1}) emissions per month during 2011-2012 and 2012-2013 growing seasons, for corn-soybean cropping treatments at UIB, Balcarce, Argentina. SC, SS, 1:2, and 2:3 represent sole corn, sole soybean 1:2 intercropping and 2:3 intercropping, respectively. DOY refers to day of year.

		Cumulative CO_2 and N_2O emissions from corn-soybean cropping system							
Month	DOY	SC	SS	1:2	2:3	SC	SS	1:2	2:3
		Cumulative CO_2 emissions (CO_2-C kg ha^{-1})				*Cumulative N_2O emissions (CO_2-C^{eq} kg ha^{-1})*			
Season 2011-2012									
Nov.	329-334	263.3	136.4	287.8	280.9	-	-	-	-
Dec.	335-365	1113.6	1093.7	1372.6	1349.5	-	-	-	-
Jan.	1-31	964.8	1098.3	1170.3	893.6	25.1	13.6	20.2	9.2
Feb.	32-60	712.4	846.9	857.7	646.1	27.0	17.7	30.3	14.6
Mar.	61-01	955.3	1151.5	1014.1	940.6	39.0	11.6	79.5	37.6
Apr.	92-121	450.7	619.9	556.4	472.3	7.3	17.0	20.1	11.4
May	122-128	170.0	113.6	87.9	94.4	0.5	3.6	2.0	1.9
Season	**329-128**	**4574.3**	**5086.4**	**5367.5**	**4649.7**	**99.3**	**63.7**	**153.3**	**75.2**
Season 2012-2013									
Nov.	-	-	-	-	-	-	-	-	-
Dec.	346-366	704.5	765.3	725.5	694.2	56.5	30.7	60.4	57.7
Jan.	1-31	1091.0	1020.7	1197.2	1035.3	45.6	44.2	125.1	56.6
Feb.	32-59	754.4	816.5	753.1	813.5	6.8	11.3	30.2	16.3
Mar.	60-90	536.5	755.8	617.2	561.6	7.5	8.8	5.3	8.1
Apr.	91-120	436.8	514.2	474.2	458.0	7.6	13.1	4.2	5.4
May	121-134	184.8	243.0	196.1	161.2	1.2	12.4	4.5	2.0
Season	**346-134**	**3707.9**	**4115.7**	**3963.4**	**3723.8**	**125.1**	**120.6**	**229.7**	**146.2**

4.3.5.2. Introducing the Intercropping Greenhouse Gas Interpretation calculation

The land equivalent ratio (LER) calculation is a popular tool to evaluate the performance of intercropping systems (Fletcher et al. 2016; Bybee-Finley and Ryan 2018). The LER evaluates the relative land requirements and effective productivity of intercropping compared to sole cropping (Caviglia and Andrade 2010; Bybee-Finley and Ryan 2018). Yield, biomass, and total aboveground LER for 2011-2012 and 2012-2013 seasons are shown in Table 4.5. Under non-ideal weather conditions for corn in 2011-2012, intercrops had 11% (1:2) and 27% (2:3) more total yield than growing the crops in two sole cropping designs. Late sowing and cooler temperatures in the following season resulted in intercropping having a yield disadvantage by -11% (1:2) and -7% (2:3) compared to corn and soybean sole cropping.

Table 4.5. Land equivalent ratios for 1:2 and 2:3 corn-soybean intercropping, for two growing seasons at UIB, Balcarce, Argentina.

	Land Equivalent Ratio			
Season	2011-2012		2012-2013	
Treatment	1:2	2:3	1:2	2:3
Yield	1.11	1.27	0.82	0.93
Biomass	1.14	1.20	0.90	0.97
Total Aboveground	1.13	1.22	0.88	0.96

Data received from UIB, Argentina and Regehr 2015.

The use of LER aids in evaluating intensification improvements. Influenced by this calculation, I created a new tool to evaluate sustainability improvements – specifically, the GHG emission mitigation potential of intercropping. The new calculation developed in the present study is termed the Greenhouse Gas Interpretation (IGI) value. It is a simple calculation that compares intercropping to the two sole crops combined by using cumulative gas production (CO_2, N_2O and CO_2 + N_2O) in the form of CO_2-C equivalents. The calculation assumes that the combined land coverage of sole corn and sole soybean equals that of the corn-soybean intercropping land coverage (Figure 4.12). The calculation for IGI is shown in Equation 4.3:

$$IGI = \frac{(I_f \times 2)}{SS_f + SC_f}$$ ***Equation 4.3***

where I_f is the cumulative CO_2-C equivalent emissions for a given number of days (i.e. monthly or seasonally) in a selected intercropping system (i.e. 1:2 or 2:3 configuration). Cumulative CO_2-C equivalent emissions (of the same time period) from the two corresponding sole cropping systems were represented as SS_f for sole soybean and SC_f sole corn. If the IGI values are <1 then the intercropping system emitted less cumulative CO_2 or N_2O than combined sole corn and sole soybean fields. If the IGI values are 1 or >1 then intercropping system emitted at par or more cumulative CO_2 or N_2O emissions than combined sole corn and sole soybean cropping systems. To be considered an SI cropping practice that mitigates a GHGs, the IGI needs to be < 1.

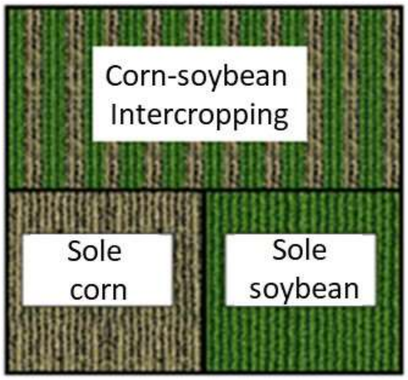

Figure 4.12. A depiction of the intercropping greenhouse gas interpretation (IGI) assumption that intercropping covers the same area as sole corn and sole soybean combined.

4.3.5.3. IGI values for corn-soybean intercropping systems

Within the two growing seasons, 1:2 intercropping produced 1 - 10% more CO_2 (IGI value = 1.10), and 88 - 89% more N_2O emissions derived from soil, compared to growing both corn and soybean by sole cropping (Table 4.6). The combined CO_2 equivalent of CO_2 + N_2O emissions in the 1:2 intercropping treatment produced 4% to 12% more than the sole crops. The 2:3 intercropping treatment produced 4-5% less CO_2, and 4% less to 18% more N_2O compared to growing corn and soybean as sole crops. The combination of the two gases resulted in 2:3 intercropping treatment having 4% lower gas emission than combined sole crops (Table 4.6).

The IGI calculation developed is a useful tool to determine sources of soil GHG emission throughout the season. Monthly CO_2 IGI values ranged from 0.62-1.44 for the 1:2 intercropping treatment and 0.67-1.41 for the 2:3 intercropping treatment (Table 4.6). The highest CO_2 IGI values occurred in November 2011 and December 2011 when crops were in the early vegetative growth stages, fertilizer was applied, and a dry period was commencing. Monthly N_2O IGI values ranged from 0.38-3.70 for the 1:2 intercropping treatment, and 0.29-1.80 for the 2:3 intercropping treatment (Table 4.6). Highest N_2O-IGI values for both intercropping systems occurred in February 2013 – the driest month of the 2013 season – perhaps this soil moisture influenced the soil microbial activity in the intercropping treatments (Figure 4.4).

Table 4.6. Cumulative CO_2 (kg C ha^{-1}) and N_2O (CO_2-C^{eq} ha^{-1}) emissions and Intercropping Greenhouse gas Interpretation (IGI) values (unitless) per month during 2011-2012 and 2012-2013 growing seasons for corn-soybean cropping treatments at UIB, Balcarce, Argentina. SC, SS, 1:2 and 2:3 represent sole corn, sole soybean 1:2 intercropping and 2:3 intercropping respectively. IGI values <1 the intercropping treatments emits less of a greenhouse gas than when two corresponding sole crops are cultivated.

		CO_2 (IGI CO_2-C·ha^{-1})		*N_2O (IGI CO_2-C^{eq} ha^{-1})*		*CO_2+N_2O (IGI CO_2-C^{eq} ha^{-1})*	
		Corn-soybean cropping treatments					
Month	DOY	1:2	2:3	1:2	2:3	1:2	2:3
Season 2011-2012							
Nov.	329-334	1.44	1.41	-	-	-	-
Dec.	335-365	1.24	1.22	-	-	-	-
Jan.	1-31	1.13	0.81	1.04	0.47	1.13	0.81
Feb.	32-60	1.10	0.83	1.36	0.65	1.11	0.82
Mar.	61-01	0.96	0.89	3.13	1.48	1.01	0.91
Apr.	92-121	1.04	0.89	1.65	0.94	1.05	0.88
May	122-128	0.62	0.67	1.01	0.96	0.63	0.67
Season	**329-128**	**1.11**	**0.96**	**1.88**	**0.96**	**1.12**	**0.96**
Season 2012-2013							
Nov.	-	-	-	-	-	-	-
Dec.	346-366	0.99	0.94	1.32	1.28	1.01	0.97
Jan.	1-31	1.13	0.98	2.85	1.28	1.20	0.99
Feb.	32-59	0.96	1.04	3.70	1.80	0.99	1.04
Mar.	60-90	0.96	0.87	0.59	0.98	0.95	0.87
Apr.	91-120	1.00	0.96	0.38	0.51	0.98	0.95
May	121-134	0.92	0.75	0.65	0.29	0.91	0.74
Season	**346-134**	**1.01**	**0.95**	**1.89**	**1.18**	**1.04**	**0.96**

4.4. CONCLUSION

Corn-soybean intercropping systems produced similar CO_2 emissions as corresponding sole crops when the growing seasons were 14.5% below and 14% above the fifteen-year precipitation average. The 2:3 intercropping configuration had similar N_2O emissions compared to the sole crops, with cumulative N_2O emitted throughout the season being intermediary with respect to the two sole crops. Findings from this study and previous studies on this research site have shown that 1:2 intercropping configuration was inferior to the 2:3 intercropping design regarding carbon and nitrogen dynamics (Regehr et al. 2015; Bichel et al. 2016). Nitrous oxide emissions were statistically greater in the 1:2 intercropping treatment compared to other treatments. Further research is required to determine why 1:2 intercropping had greater N_2O emissions. Some possible factors include microclimate variations, resource competition between crops, microorganisms present in the treatment soil (Bichel et al. 2016), less effective mineralization and immobilization regulation (Regehr et al. 2015), and non-ideal nitrogen application for the intercropping configuration. Finding solutions that reduce N_2O emissions in corn-soybean intercropping systems would increase incentives for the practice to be applied in modern cropping systems.

This study developed the intercropping GHG interpretation (IGI) tool to evaluate GHG mitigation of different intercropping configurations compared to the combination of two sole cropping systems. For the 1:2 intercropping treatment the summed (CO_2 + N_2O) IGI values equalled 1.04 - 1.12 for the two growing seasons. The summed IGI value for 2:3 intercropping was 0.96 for both years – expressing the practice mitigated soil GHG emissions under the conditions of the study. This study found that 2:3 intercropping had more potential to become an SI practice than the 1:2 intercropping configuration – however, the 2:3 intercropping system did not display a meaningful overall reduction in emissions (4% lower than combined sole crops). It is recommended that future research adjust urea rates to determine ideal nitrogen efficiency rates for the intercropping systems.

Intercropping systems that are managed with ideal nitrogen rate would mitigate soil CO_2 and N_2O emissions – improving the potential of the practice to be SI. However, the ability of a cropping practice to mitigate GHGs, on its own, does not fully characterize whether it is suitable for SI or would be adopted within a given region. As highlighted in Farming Systems Research (FSR) literature (Collinson 2000, 51; Klerkx et al. 2012, 460; Fischer et al. 2014, 307) and SI reviews (Mahon et al. 2017 and Weltin et al. 2018), the social-ecological context and producers perspectives on a practice plays a role in determining whether a new technology will be adopted within a given region. The next chapter of this dissertation incorporates social actors, to assess whether corn-soybean intercropping is a viable SI practice within the region of interest.

CHAPTER 5

SOCIAL SCIENCES STUDY

Barriers and opportunities regarding adopting summer intercropping practices in the southeast Buenos Aires Pampas

5.1. INTRODUCTION

Studies in the natural sciences on sustainable-intensification (SI) research promote the concept as a desirable solution, to address sustainability and food insecurity issues, but adoption of SI strategies among farmers has been less enthusiastic. Sustainable intensification was initially developed for smallholders in the 1990s, yet recent studies state that adoption rates of SI strategies by smallholders remain low (Snapp et al. 2010; Franke et al. 2014; Ortega et al. 2016; Waldman et al. 2016; Droppelman et al. 2017; Alomia-Hinojosa et al. 2018). Interactions with smallholders revealed that low adoption rates related to regional socio-economic, political, and cultural barriers (Franke et al. 2014; Ortega et al. 2016; Alomia-Hinojosa et al. 2018). These findings support those who strongly advocate for more integration of social actors and subjective observations, to construct effective all-encompassing SI research (Struik and Kuyper 2017; Mahon et al. 2017; Weltin et al. 2018). Recent reviews of SI articles from 2009 to 2016 revealed that social, economic, and political dimensions were under-represented, and most studies focused on objective measurements of the biophysical dimensions (Mahon et al. 2017; Weltin et al. 2018). Consequently, some studies on potential SI agricultural practices have made attempts to integrate socio-economic factors. For instance, the Monzon et al. (2014) study on modernized summer intercropping in the Argentine Pampas included economic variables but social variables were not extensively examined. The research described in the present chapter explores the adoptability of summer intercropping in the southeast Buenos Aires Pampas (SEBA) region through the perspectives of producers and practitioners.

Findings from natural sciences are important to develop the technology, and for assessing the feasibility of SI; however, it is only part of the agricultural change process. Sustainable-intensive practices are only useful if producers adopt them. Their decisions to adopt a practice are driven by their experiences, knowledge, circumstances, and opinions (Blackstock et al. 2006; Meijer et al. 2015; Alomia-Hinojosa et al. 2018). Producer perspectives help understand factors that affect practice adoptability, and can help direct future research and the implementation of SI programs.

5.1.1. Adoption of Intercropping for sustainable-intensification

Intercropping is the practice of growing two or more crops species together at the same coexisting time. Intercropping is considered SI because the practice has shown to use space, time and resources efficiently to grow crops, reduce climate and pest risks, and improve ecosystem services (Brooker et al. 2016; Droppelmann et al. 2017; Struik and Kuyper 2017). However, social changes can affect SI adoptability even in a region where it was once popular. In Sub-Sahara Africa (SSA), cereal-legume intercropping had an estimated adoption rate of 98% in the 1970s (Vandemeer 1992; Silberg et al. 2017). African producers used the practice to divert environmental and economic risks, but yield gaps remained large across SSA due to the lack of quality seeds and inaccessibility to fertilizers (Snapp et al. 2010; Silberg et al. 2017). Subsidy programs were implemented across the SSA as an attempt to improve the production of staple cereals (i.e. corn [*Zea mays*]) (Droppelmann et al. 2017). These subsidies influenced producers to change their cropping practices.

For instance, in Malawi, nitrogen fertilizers and improved corn seeds were subsidized by 90% of their costs. This led to producers abandoning legumes and intercropping to focus on corn monocropping (Franke et al. 2014; Snapp and Fisher 2015; Silberg et al. 2017). Frequent cultivation of corn diminished soil nitrogen, and in turn, progressed soil degradation (Snapp et al. 2010; Waldman et al. 2016; Silberg et al. 2017). Social scientific studies revealed that smallholders in Malawi shared that they were less interested in reverting to cereal-legume intercropping, because the practice was perceived to be more labour demanding and reduced the amount of staple crop grown within a field (Snapp et al. 2010; Franke et al. 2014; Silberg et al. 2017). Snapp et al. (2010) collaborated with smallholders to determine the most suitable cereal-legume intercropping strategy for SI. They found corn-soybean (*Glycine max)* intercropping was the most profitable, but provided the least direct food security. Intercropping corn with shrubby grain legumes was more suitable for the region, as it ensured food security, required the least labour, was affordable to financially restricted farmers, and mitigated climate risks. Snapp et al.'s (2010) study provides a good example of how social science research can help guide agricultural policies and practices.

In the Argentine Pampas corn-soybean and sunflower (*Helianthus annuus*) – soybean intercropping has been investigated since the 2000s, as an SI strategy to diversify fields, efficiently use resources, and increase production (Caviglia, and Andrade 2010; Monzon et al. 2014). The socio-economic and political context of the Argentine Pampas is different from the situation in Malawi. Policies, socio-economic circumstances, and technological advancements introduced since the 1990s were drivers that shifted the Pampa from diversified mixed agriculture to large-scale modernized sole cropping (Calviño and Monzon 2009, 55; Campi 2011, 190; Ferrazino et al. 2014). The lack of subsidies, high agriculture taxes, and market controls during the Kirchner-led government coerced producers to grow soybean more frequently or as a monocrop to avoid financial risks (Monzon et al. 2014; Urcola et al. 2015). Soybean encroachment in Argentina has contributed to biodiversity losses, an increase in the prevalence of herbicide-resistant weeds and diminishing carbon content of soils (Cavligia and Andrade 2010). Corn-soybean intercropping has the potential to increase soil carbon content, while allowing Pampean producers to grow soybean, making it an ideal SI practice for the environmental circumstances (Cavligia and Andrade 2010; Oelbermann et al. 2015); however, the adoptability of the practice under socio-economic and political circumstances is not well understood.

5.1.2. Study objectives and contributions

Crop producers and agricultural practitioners from the SEBA Pampas were interviewed to determine their perceptions of the Argentine Pampas agrarian structure, national agro-economic and political affairs, and field management. This information was used to clarify adoption limitations, and development opportunities for summer intercropping within the studied region. This study is unique compared to other perspective based cropping practices studies, as it focused on the very emergence of participation in intercropping – something that has never been done to my knowledge and something that allows for great insight into what motivates early adoption. Many studies learning from producer's perspectives select those who already apply the investigated cropping practice (i.e. Frey et al. 2007; Sileshi et al. 2008; Alomia-Hinojosa et al. 2018), or chose a practice that has been well established regionally for many years (i.e. Simmons et al. 1992; Singer et al. 2007; Mekoya et al. 2008; Silberg et al. 2017; Dicks et al. 2018).

5.1.3. Reasons for examining summer intercropping in the SEBA region

Interviews for my study were limited to the SEBA region of the Argentine Pampas, as this area's cooler climate is distinct from the rest of the Buenos Aires Pampas (Calviño and Monzon 2009). The Argentine Pampas cover a large area that is approximately 460 000 km^2 (Demaría et al. 2004). This large area includes regions that have distinctive climates and soil characteristics that affect the applicability of cropping practices. These regions also differ by socio-economic, political and cultural components that affect producers' decisions on what type of crop and practice to use (Franke et al. 2014; Alomia-Hinojosa et al. 2018). For example, the northeastern Pampas region is close to numerous ports and processors (<100 km), has productive well-drained loam soils, and a climate that allows for continuous cropping resulting in intense double cropping practices that are influenced by the crop price (Viglizzo et al. 1997; Morello et al. 2003; Satorre 2011; MAGyP 2014). The northwestern Pampas region is farther from ports (>200 km) and crops are grown on low fertility sandy loam soils that are exposed to heavy monsoonal rains storms (Caviglia and Andrade 2010; Pérez et al. 2015). Cropping practices in the northwestern Pampas tend to be related to climate and technological conditions and less likely to change with crop price (Viglizzo et al. 2005). These context specific related factors are important when identifying suitable SI cropping practices for a region. Intercropping is considered a potential SI cropping practice for both smallholders and modern agriculture types. However, a practiced deemed as SI ultimately depends on its regional suitability and its adoptability. Determining producers' perceived challenges and opportunities of summer intercropping within the SEBA region early on, aid developments to better suit regional and producers' needs.

5.2. METHODS

5.2.1. Site description

The SEBA region consists of eleven districts that are representative of the Southern Pampas ecoregion and borders north-easterly the Flooding Pampas ecoregion (Barral and Maceira 2012) (Figure 5.1). Southeast Buenos Aires consists of loess soils with a warm temperate climate (precipitation of 860 mm, mean temperature of 13.9°C). Cooler winters in SEBA makes the region best suited for winter cultivation of wheat (*Triticum aestivum*), oats (*Avena sativa*), barley (*Hordeum vulgare*), and canola (*Brassica napus*). Main summer crops of the region are soybean, sunflower, and corn.

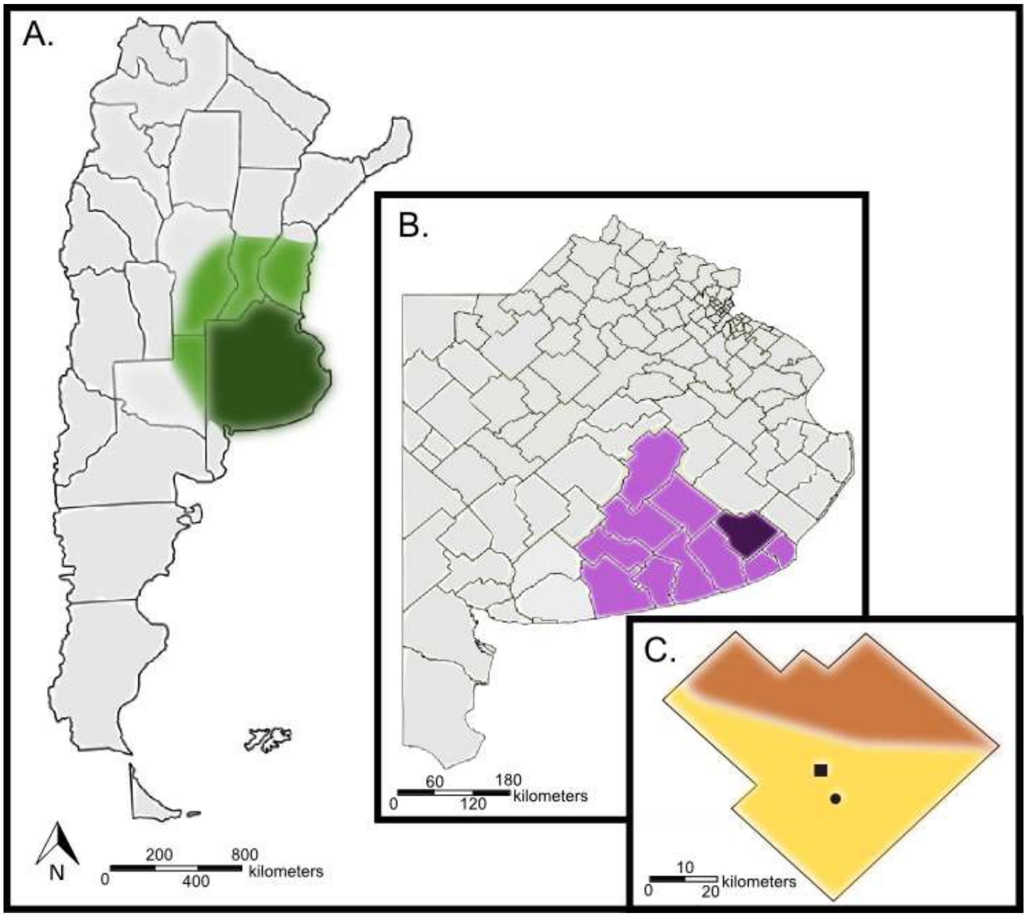

Figure 5.1. Map of case-study coverage. Map A highlights the Argentine Pampas coverage in green with the darker green area representing the Buenos Aires Province. Map B outlines the districts in the Buenos Aires provinces. Districts shaded in purple are within the southeast Buenos Aires region. The district shaded in dark purple shown in Map C is the Balcarce District. The black circle and rectangle represent the city of Balcarce and the Balcarce Integrated Unit, respectively. The yellow shaded area represents the Southern Pampas ecoregion, and the brown shaded area represents the Flooding Pampas ecoregion within the District of Balcarce*.* (Figure modified from Barral and Maceira 2012).

Located in the SEBA region was the Balcarce Integrated Unit (UIB), which was an agriculture experimental research facility that hosted academic institutions including the federally supported National Agriculture Technology Institute (INTA). Experimental fields at UIB included trials for summer intercropping – influencing the rationale to centralize my study in the Balcarce district. This study started with the hypothesis that producers who cultivated in close proximity to an agriculture research station would have greater exposure to intercropping and SI practices allowing for more discussion on the subject. The Balcarce district has an area of 417,200 ha with 39% of the area dedicated to grain and oilseed production (SAGPyA 2001). The total population of the Balcarce district is 43,823 with 88% of the population residing in the city of Balcarce, 3% living in surrounding villages and the remaining 9% lived on farms in the district (MAGPyA 2010; Urcola et al. 2015). The northeast section of the district includes ranches and livestock-crop mixed farms, as it is a part of the Flooding Pampas ecoregion; however, arable cropping systems dominate most of the district with approximately 250 farms (Barral and Maceira 2012; Urcola et al. 2015).

5.2.2. Study design

5.2.2.1 Study context

Research in practice does not always go as planned. Medawar (1963) explained why scientific papers are often a fraud, i.e. not because they are a product of deceit but a product of selective omission in writing, as if the entire research process went perfectly. He deemed that as misleading. In that spirit, my experience was consistent with the reality of research. Dyer (2010) indicated some producers in the region practiced corn-soybean intercropping. This provided the rationale for choosing this study area, and my study originally was designed as a comparative analysis of perspectives between intercropping and conventional producers. However, once I arrived, I became skeptical of the claims based on Dyer (2010). I initiated discussions with key informants and agricultural extension agents in SEBA. They confirmed my doubts; there was a strong consensus that intercropping was rarely practiced, because it was too new and unfamiliar to the region, and it was mostly restricted to experimental trials rather than production. Having committed resources to this region, I redesigned my study to be a qualitative assement for distinguishing barriers and drivers influencing the adoption of summer intercropping in the SEBA region, through the perspectives from regional producers and practitioners. This adaptive approach is aligned with the recent developments in environmental and transdisciplinary sustainability research that have started to move towards more iterative and heuristic research practices (e.g. Lang et al. 2012; Hurlbert and Pittman 2014; Filbee-Dexter et al. 2017; Levkoe and Blay-Palmer 2018).

5.2.2.2 Sampling

Interview participants were selected by purposive sampling (Patton 2015, 306). Both semi-structured and unstructured interviews were conducted. Snowball sampling was used to identify cash crop producers for semi-structured interviews. In turn, agricultural practitioners (people working in the agriculture sector but not necessarily cultivating crops) considered to be key informants, participated in unstructured interviews. The two types of interviews were used to gain general and in-depth information on the regional context and social factors that influence decision-making regarding cropping practice implementation (Patton 2015, 306; Palinkas et al. 2010).

Semi-structured interviews were conducted with eighteen modernized cash crop producers from the Balcarce district. Considering arable land was commonly rented in the Pampas (Gras 2009; Gras and Hernández 2014, 343), the producers interviewed were not necessarily cultivating all land within the Balcarce District, but were in the SEBA region. Questions used to guide the semi-structured interviews are shown in Table 5.1. The semi-structured interview guide was developed with the aid of four rural extension researchers from the Balcarce Integrated Unit, to ensure questions were applicable for producers in the SEBA region. Furthermore, the semi-structured questions and related forms (study description, consent and post-interview forms) were screened, reviewed and edited by two Spanish-English translators and by four informants, to ensure documents were coherent, and ethically and culturally appropriate for participants. The semi-structured questions were designed to obtain participants agricultural background characteristics as well as their opinions, values, and feelings regarding crop management and Argentina’s agricultural sector. Responses from these questions provided producers’ perspectives that directly and indirectly related to intercropping and crop management in the SEBA Pampas.

Unstructured interviews were conducted with six agricultural practitioners from the Balcarce District. Agriculture practitioners had specialized knowledge on intercropping systems, agronomy, agroecosystem management, agriculture sales, agro-economics, or agriculture extension within the Argentine Pampas. Two of the agricultural practitioners interviewed had experience with intercropping systems; this sample size reflects the reality of a small number of practitioners specializing in intercropping. Agricultural practitioners were interviewed using an unstructured format to permit the flexibility when pursuing detailed information on their knowledge, experience and expertise (Patton 2015, 437). During unstructured interviews, a few semi-structured questions were asked (Table 5.1), though most questions were emergent, and focused on practitioners’ specialization (Patton 2015, 441). Interviewing practitioners with different specializations allowed for obtaining detailed perspectives on the many dimensions of agriculture that can affect intercropping implementation, and was useful to illuminate common patterns and shared interests among the interviewed practitioners and producers (Patton 2015, 283).

5.2.2.3 Interviewing methods

Interviews were conducted in English or Spanish, depending on the participant’s preference. The location where interviews took place was mutually agreed upon by the participant, translator and me. The translator hired to conduct Spanish spoken interviews was fluent in English, had an agriculture background, with some intercropping research experience, and displayed qualities of empathetic neutrality. These translator characteristics were essential to obtain coherent in-depth information and to maintain rapport and openness during sensitive topics discussed during interviews (Patton 2015, 481). Interviews were voice recorded; the duration of semi-structured interviews averaged 17 minutes and ranged from 8 to 45 minutes; the duration of unstructured interviews averaged 65 minutes and ranged from 30 to 120 minutes. Interviews that were recorded in English were transcribed verbatim. Interviews recorded in Spanish were translated and transcribed to English. Recorded interviews were transcribed in one to five days after a participant interview. Throughout this chapter, participant quotes that include a superscript “T” indicate that the quotation was translated from Spanish to English.

A total of twenty-four people were interviewed (semi-structured and unstructured interviews), and a saturation point was met as recurring themes and patterns emerged regarding the Argentine Pampa agricultural sector and regional management practices that related to SI cropping practices. Commonly qualitative inquiries focus in-depth on relatively small sample sizes, sometimes only a single case (Patton 2015, 264). The age range of participants in this study ranged from 25 to 65 years old, and four of the participants were women. In Appendix 9.2, a cognitive map displays the different facilities where participants were sourced from to gain a variety of perspectives and minimize concentrated opinion biases. To maintain the anonymity of the participants, producers participating in the semi-structured interviews were identified in this chapter by numbers, while letters identified agricultural practitioners that participated in unstructured interviews. Interview research was accepted and conducted in accordance with the University of Waterloo Research Ethics Office and the Tri-Council Policy on Ethical Conduct for Research Involving Humans; insuring the confidentiality of participants interviewed.

Table 5.1. Semi-structured questions asked to crop producers to obtain perspectives on crop management in southeast Buenos Aires, Argentina.

Crop Management and agriculture sustainability in the Southeast Buenos Aires Pampas	
Question Rational	**Interview Questions**
Background questions to identify characteristics of the producer. Responses used to determine in field socio-economic perspectives that indirectly affect cropping practices.	***Crop production history:*** 1. Are you a renter, owner or employee of the property? 2. How many hectares do you cultivate? 3. How many years has the property been cultivated under cash crop? 4. What cash crops are cultivated on the property? 5. What are your yearly crop yield averages (yield per hectare) for the past five years? 6. Do your family members contribute to the farm work and do women participate in the farm work? **7.** Do you hire labour? Are they temporary or permanent workers?
Opinion and values questions. Responses used to determine in field biophysical and socio-economic perspectives that indirectly affect cropping practices.	***Knowledge and perceptions about soil and agricultural sustainability:*** 1. What is your definition of agricultural sustainability? 2. What is your definition of soil sustainability? 3. Are you concerned about environmental impacts due to cropping practices? ***Knowledge of better management practices:*** 1. Do you plan for the future year's crop production (e.g. rotations)? a. If yes, how many years do you plan in advance? 2. What influences your decision of what crops to cultivate each year? 3. What practices do you consider as being 'better management practices'? 4. What influences your choice of crop management practices? 5. Are there any features on your property that you would like to improve? a. If no, what is preventing you from improving it?

Continuation of Table 5.1.

Question Rational	**Interview Questions**
Background, opinion and values questions. Crop management questions to determine direct responses for intercropping.	***The type of cropping practices implemented and its outcome:*** 1. Do you practice no-till? 2. Do you practice monocropping? a. If yes why and what crops? b. If no, why? 3. Do you use a crop rotation? a. If so, what is the crop rotation? b. If no, why do you not use a crop rotation? 4. Have you ever intercropped? a. If yes: What was the intercropping design? What are the benefits of intercropping? What are the drawbacks of intercropping? b. If no, what are your main reasons for not applying intercropping practices?
Feeling, opinion, and values questions. For responses that could indirectly relate to socio-political perspectives that could affect intercropping or other sustainable intensive cropping practices.	***The potential for sustainable farm assistant programs:*** 1. Do you have any worries regarding the Argentine agriculture sector? a. If yes, what are they? 2. Do you feel you have support from: a. The federal government? b. Farm alliances? c. Agricultural companies? d. Balcarce government? e. NGOs? f. Neighbours? g. Which of the pre-mentioned sectors do you find supports you the most? 3. If there were workshops involving crop rotation and intercropping would you be willing to attend? Why or why not? 4. Would you be interested in attending workshops on soil erosion and soil degradation prevention? Why or why not?

Continuation of Table 5.1.

Question Rational	Interview Questions
Feeling, opinion, and values questions. For responses that could indirectly relate to socio-political perspectives that could affect intercropping or other sustainable intensive cropping practices.	5. Do you have any suggestions for soil and crop workshops that would be beneficial for you and other producers? 6. If there was an environmental farm management program available that provided information to assist you in evaluating the property and to aid in creating specific management plans for the property, would you be interested in participating? a. If yes or no, discuss your reasons why. 7. Would you more likely join a workshop or farm management program if it was organized by: The Federal government, Farm groups? (e.g. CREA, FAA) , Agricultural companies, Balcarce government, or independently?

5.2.3. Qualitative data analysis

The data were analyzed in three stages. A qualitative inductive analysis was constructed to identify categories of main factors that affected the adoptability of summer intercropping (Figure 5.2). Transcribed data from semi-structured and unstructured interviews were open coded using QSR NVivo® software (NVivo, version 10.0; Doncaster, Australia: Sage Publications Software, 2002). Semi-structured and unstructured interviews were separately analyzed inductively for emerging patterns and themes (Patton 2015, 541). Semi-structured interviews were analyzed for patterns and themes using group characteristics and by question answered per participant. In the unstructured interviews patterns and themes were revealed through questions (i.e. directly asking about intercropping) and by issues discussed by the participants. Preliminary themes and patterns were compared between the two types of interviews to identify similarities and to determine additional themes and patterns (Patton 2015, 553). Initial emergent themes and patterns were shared and discussed in May 2013 with participants and interested community members during a summary seminar organized at the

UIB and at the Balcarce community center to confirm accurate reflection of participant perspectives.

A deductive analysis was used to test themes and patterns that influenced summer intercropping and SI cropping practices, and to disregard themes that did not relate to the study’s foci (Patton 2015, 541). Field notes and literature were resources used to triangulate data and confirm validity within the deductive analysis (Patton 2015, 311). Field notes written by me, described interview settings, summarized seminar feedback, and contained observations from corn-soybean intercropping field trials at UIB. Literature consisted of peer-reviewed journals, and regional agriculture magazine and newspaper articles that focused on social, economic or political impacts to the agriculture sector, or concerned intercropping and / or SI cropping practices in the Pampas. Using literature and field notes, themes and patterns were revisited and cross-referenced between interviews to better define and describe major themes.

The final stage of analysis consisted of organizing major themes and patterns into categories and subcategories for discussion. Categories combined a number of major themes that had a common relation and pattern. Categories were redefined and strengthened by re-addressing findings from the deductive analysis, and by attaining feedback from informants who reviewed the emerging categories and allocated themes. Categories were further divided into sub-categories to organize key findings from the qualitative analysis.

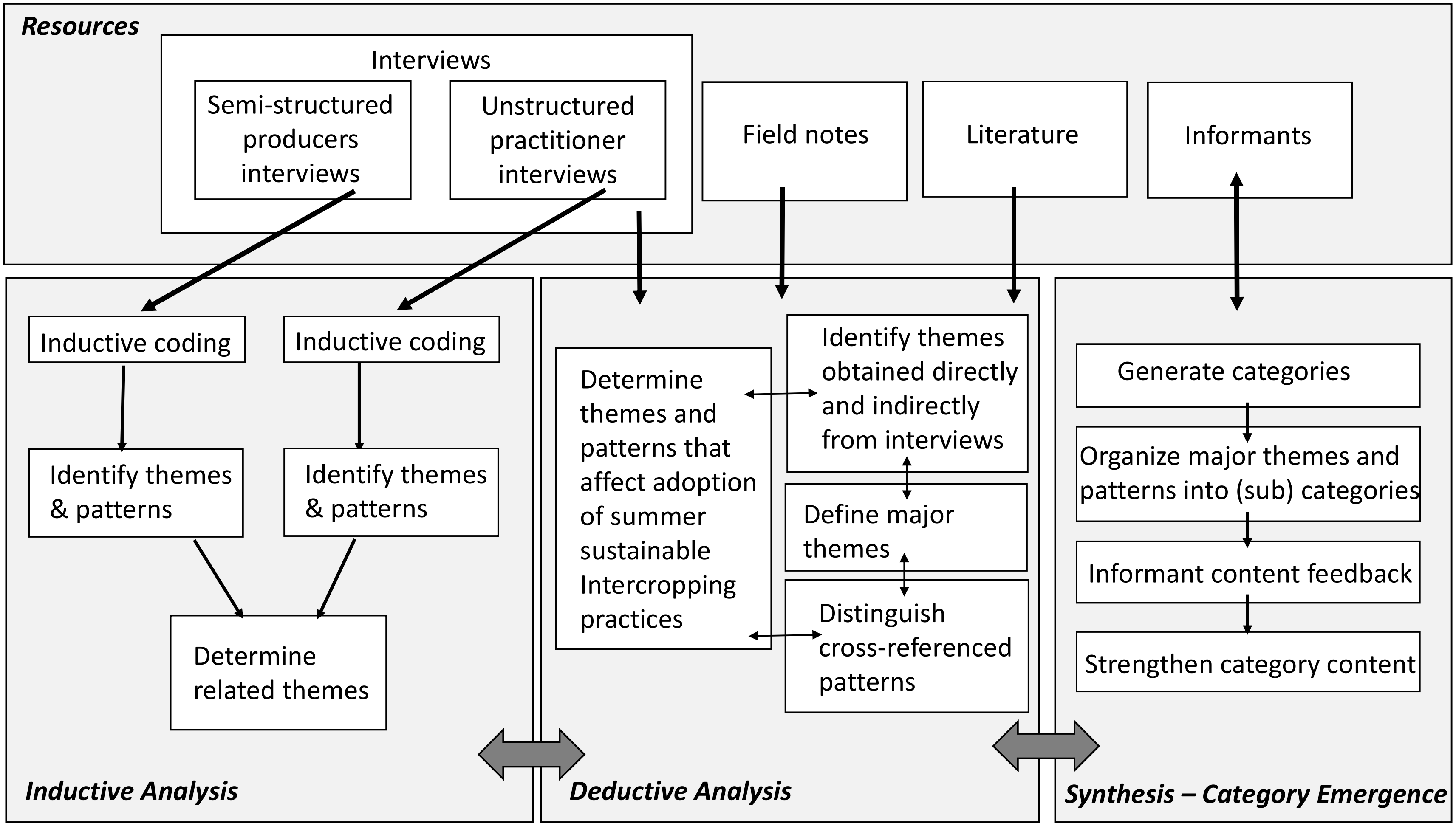

Figure 5.2. Qualitative data analysis conceptual map. Thick arrows represent the movement between types of analysis; medium arrows associate what resources were used in which type of analysis, and the small arrows represent the steps within each type of analysis

5.3. RESULTS AND DISCUSSION

5.3.1 Characteristics of interviewed southeast Buenos Aires producers

Participating producers cultivated land ranging from 46 to 4300 hectares. The majority of properties were 400-1000 hectares (Table 5.2), which was a similar distribution to findings in a Balcarce district farm survey by Urcola et al (2015). Land had been in cultivation for 2.5 to 50 years; participants who rented would cultivate a property for 1 to 10 years. All producers either utilized or provided contracting field services. Those who hired permanent labour had mixed crop-livestock operations or cultivated >1000 hectares. Regardless of farm size, tenure arrangements, or type of hired labour, all owner and renters interviewed utilized the Pampean technological package, incorporating soybean in their crop rotation as a main summer crop (average yield 2-3.5 t ha^{-1}) or as a double crop (0.6-1.5 t ha^{-1}). Soybeans covered 18% of the SEBA region and contributed 12% of the province's total soybean production between 2008 - 2011. During the same time span, 78% percent of producers interviewed cultivated sunflower (2-3.3 t ha^{-1}) as a summer crop. Sunflower production covered only 8% of SEBA, but it was a significant crop to the region, as it contributed 40% to the province and 25% to the nation's total sunflower (SIIA 2014). Thirty-five percent of interviewed producers cultivated corn (7-12 t ha^{-1}) as a summer crop. Corn production was not as common in the SEBA region covering only 2% of the area and contributed 5%, to the province's total corn production (SIIA 2014). During the winter season, 83% of producers cultivated wheat (4.6-6.5 t ha^{-1}), 66% cultivated barley (5-7 t ha^{-1}), and 11% cultivated rapeseed or oats. Wheat was the dominant winter crop covering 17% of the SEBA region contributing 43% of the province's total wheat production (SIIA 2014). Soybean and wheat had similarities in land coverage within the SEBA region, because it corresponded with wheat-soybean double cropping, being a common cropping practice in the region (Caviglia and Andrade 2010; Monzon et al. 2014).

Table 5.2. Characteristics of producers who participated in semi-structured interviews regarding crop management and the agriculture regime in the southeast Buenos Aires Pampas.

Cultivated Area (ha)	**< 50**	**100-200**	**400-1000**	**>1000**
# of Cases	**1**	**3**	**8**	**6**
Tenure				
Owner	1		1	3
Renter		3	2	1
Both			5	2
Location				
Balcarce	1	3	5	3
Balcarce + Southeast Pampas			3	3
Production System				
Annual crops	1	3	6	3
Mixed crop-livestock			2	3
Farm Labour				
Permanent				1
Contract		3	5	3
Both			2	2
Neither	1		1	

All producers interviewed expressed that they have never tried intercropping on their properties. All eight practitioners interviewed stated that summer intercropping was not a common practice, though they were aware of recent studies within the region that focused on summer intercropping. Practitioners confirmed that a few producers had tried wheat-soybean relay intercropping in order to seed second soybean earlier, to gain a yield advantage (INT D, F). The reasons why producers have not applied summer intercropping were related to: a lack of technical knowledge; difficult integration into the current Pampean agricultural model; inconveniences to field contractors; mechanization and technology restrictions; and in-field economic risks. Other interview questions indirectly revealed themes that affected the adoptability of summer intercropping that included government intervention, cost of production, the economic state of Argentina, and climate restrictions (Table 5.3). The combinations of emergent themes and patterns were categorized (as shown in Table 5.4) to create subsections for discussing adoption barriers and opportunities for summer intercropping in the region.

Table 5.3. Emergent themes from producer and practitioner interviews. Direct responses represent themes that emerged when asked about intercropping. Indirect responses represent themes that emerged throughout interviews that would affect adoption of summer intercropping and other sustainable intensive cropping practices.

Direct and indirect themes for the adoption of summer intercropping as a sustainable intensive practice	Producers Interviewed	Practitioner Interviewed
Direct: Emergent themes when asked about intercropping		
Technical knowledge and information sharing	6/18	2/6
Simplicity and inconveniences	4/18	3/6
Economic viability	4/18	3/6
Mechanization and technology limitations	6/18	2/6
No comment	5/18	
Indirect: Emergent themes throughout interviews that related to intercropping and sustainable intensive cropping practices.		
Government intervention on agriculture sector	18/18	6/6
Soybean encroachment and production	4 /18	6/6
Economic uncertainties	6/18	6/6
Direct costs	4/18	4/6
Climate limitations	5/18	5/6

Table 5.4. Categories and sub-categories developed during the qualitative analysis of interview data. Emergent themes were organized within sub-categories and keywords aid in the description of each sub-category.

Category	Sub-Category	Themes	Keywords
Producers & practitioners have limited experiences with modern summer intercropping research	Applying only reductive science prohibits holistic cropping strategies for intercropping	Technical knowledge & information sharing; Economic viability; Mechanization & technology limitations; Direct costs	Experimental trials; Reductive science; Research gaps; Producers' priorities; Agroecology; Inter/trans disciplines
	Intercropping knowledge needs to be distributed through shared experiences	Technical knowledge & information sharing; Mechanization and technology limitations	Knowledge transference; Shared experiences; Stakeholder collaboration
Field machinery is adapting to complex cropping systems, but field contractors prefer field uniformity	Challenges related to field mechanization that accommodates multi-cropping practices	Simplicity & inconvenience; Economic viability; Mechanization & technology limitations; Direct costs	Machine adaptability; Technology turnover; Machinery accessibility; Contracting services
	Field contractors' preferences to large & simplified systems is a barrier for producers to adopt more complex cropping practices	Simplicity & inconveniences; Mechanization & technology limitations; Climate limitations	Contractor competition; Contractor inconveniences; Farm size; Time sensitive sowing
Financial stability of soybean interferes with crop diversity	Government intervention encourages soybean sole cropping	Economic viability Government intervention; Economic uncertainties; Soybean encroachment	Agriculture policies; No government support; Market uncertainties; 'Risk-free' soybean; Unstable economy
	Producers had limited economic incentives to practice summer intercropping	Economic viability; Soybean encroachment; Direct costs; .	Minimal economic gains; Direct costs; Crop price
	The climate in the Balcarce district is unfavourable for summer intercropping	Economic viability; Direct costs; Climate limitations	'High risk' corn; Water stress; Growing degree days; Second soybean

5.3.2. Producers and practitioners have limited experiences with modern summer intercropping research

Many producers stated that there was limited information available regarding intercropping for the SEBA region (INT 1, 2, 12, 14, 16, 18):

> *No, because it's a new practice, so we lack the* knowledge. – INT 1^{T};
>
> *No. I do not know how to do it, I know it exists, but I never do it.* – INT 16^{T}*;*
>
> *There is a lack of information and knowledge about the practice.* – INT 18^{T}

These responses are consistent with the notion that intercropping in SEBA was still in the experimental stage. Prior to interviews, only five intercropping field seasons had been completed in SEBA for results to be used for modifying experimental trials. Field trials were designed for summer intercropping to be compatible with conventional cropping management (Caviglia 2009; Calviño and Monzon 2009) – possibly to ease producers into adopting the new practice. Furthermore, these intercropping field trials were compared to commonly practiced sole cropping, using reductive and positivist approaches. Outcomes of these summer intercropping trials were shared publicly in Argentina through workshops, conferences presentations (Cerrudo et al. 2007; INT D), technical reports, newspapers, and magazines (Caviglia 2009). However, my findings indicate that some practitioners interviewed believed that information gained from field trials at research facilities were shared ineffectively to producers, partly due to narrow research approaches and inefficient distribution of research findings. The following two subsections detail intercropping research limitations and communication gaps when extending these research findings to producers.

5.3.2.1. Applying only reductive science prohibits holistic cropping strategies for intercropping

The discrepancy between reductive methods in agricultural research and producers crop management needs were reflected in the field trials and interviews. Seventy-five percent of producers interviewed placed profits as a priority in their cropping systems. This is similar to findings in Ferrazino et al. (2014) survey of SEBA producers. One way to enhance producer's profits is to increase yield per area. Intercropping field trials were adjusted for sowing time, spacing, density and configurations in order to increase overall yield (Caviligia 2009; Echarte et al. 2011; Monzon et al. 2014). However, profitability from agricultural production is not only based on yield output; the cost and amount of inputs required for a practice, and long-term impacts of applied management practices affect the profitability of agricultural systems.

The majority of producers (16/18) indicated that they were concerned about the environmental impacts of agrochemicals and intensive cropping practices. Intercropping corn or sunflower with soybean, has been used by Argentine researchers, to address the intensive cultivation of soybean (Echarte et al. 2011; Coll et al. 2012). However, these intercropping initiatives did not have a main focus to reduce agrochemical input requirements. Some international studies have shown that intercropping requires less pesticide, herbicide, and fertilizer inputs compared to sole cropping due to facilitative relationships between two crop species (Snapp et al. 2010; Gao et al. 2014; Altieri et al. 2017; Bybee-Finley and Ryan 2018). However, opportunities to reduce input requirements for agrochemicals in intercropping systems is an understudied subject, within both agriculture management and bioengineering disciplines (Vanloqueren and Baret 2009).

Indeed, the producers' concerns for the excessive use of agrochemicals is a relevant aspect for sustainable and SI agricultural practices. Reducing the amount of agrochemical inputs used in modern intercropping systems is complex, but an important action to mitigate global warming, land degradation, and public health risks related to crop production (Mahon et al. 2017; Bernard and Lux 2017; Bybee-Finley and Ryan 2018). Furthermore, input efficiency is another form of improving profitability, by lowering short-term and long-term economic costs to producers (Bybee-Finley and Ryan 2018). For the case of producers in Argentina, synthetic inputs were considered expensive because they needed to be imported and were not subsidized (Taylor 2018). Interviewed producers expressed that they would likely be more willing to try a new practice if they could significantly improve profits by lowering input costs (INT A, D, 3). The following quotation is from a producer sharing the type of workshop they would like to participate in:

> *Regarding crops on how to increase the fertilizer efficiency, because that is the only way farmers can be sustainable. We need to increase at a faster rate because the money used to farm increases every year, the harvester, pay for the seeder, it all increases, inputs on the land and inflation in general* – INT 3

This quotation emphasized the importance of agrochemical input efficiency for Argentinian producers. Interestingly, reducing inputs and promoting facilitative relationships in intercropping systems have not been tested in the Argentine Pampas; during the time of study, there were no intercropping field trials focusing on enhancing agroecological processes. These findings strengthen the argument by other scholars, such as O’Leary and Smith (1999), Alrøe and Kristensen (2002), and Vanloqueren and Baret (2009), that the reductive methods commonly used in field trials are not an effective approach to study multi-crop cropping systems; more time and sample sizes are required, and the approach makes it difficult to stimulate symbiotic relationships between species. The results also support the conclusion that in cases where many variables interact, inter / transdisciplinary approaches and a high-level of producer participation may be more effective, in determining a broader range of applicable information

(Vanloqueren and Baret 2009; Darnhofer et al. 2015, 5; Struik and Kuyper 2017; Weltin et al. 2018).

5.3.2.2. Intercropping knowledge needs to be distributed through shared experiences

Another barrier that the findings revealed was that intercropping field trials were designed, managed, studied, and shared by researchers, with minimal involvement with crop producers. This style of research is internationally common for modern cropping practices, where field trials are located at the research station and controlled by academic researchers (Franzel et al. 2001; Doré et al. 2011). Trials are valuable to secure specific biophysical data and information (Fischer et al. 2014, 31). The disadvantage is that information from these field trials can be difficult to amalgamate and translated into mediums useful for producers' and their production systems as demonstrated by the following quotation:

> *I think that at this research station, it is a big one with a lot of investigations looking for solutions to very small problems and they are missing the macro vision. And each research team is focused on their own investigation, and they are not communicating between each other. Very good in each area, but the person in charge of transferring the information cannot know everything, so it is difficult to transfer this information.* – INT E[T]

The quotation highlights how researchers focus on a few components of a production system and seldom look at the production system as a whole. Furthermore, as a research participant pointed out (INT E), components within field trials are often studied under particular conditions and do not necessarily translate to local cropping systems due to land heterogeneity issues and socio-economic circumstances. Other studies have revealed similar observations (Natcher et al. 2016; Struik and Kuyper 2017; Almoia-Hinajosa et al. 2018). These types of knowledge transfer gaps are known to affect the adoptability of new cropping practices and contribute to existent yield gaps (Fischer et al. 2014, 45).

Ineffective communication and knowledge exchange between academic researchers and producers, also help explain why only eight of the eighteen producers felt supported by the federal agency INTA; the following quotations reinforced this observation:

> *I do not think INTA gives me much support, because it is a part of the government. I recognize INTA makes information, but it is difficult to apply it.* – INT 2^{T}

> *Even research and results are not feedback easily to producers. My impression is if I was in a helicopter looking down at this community, there is a college here that is making a lot of research, and all these farmers are here. What would you say? And then I would say, that the farmers must be attending the college often to hear what these guys are doing. But in practice that does not seem to be the case.* – INT B

These quotations demonstrate that even when intercropping information from agriculture research facilitates was publicly shared, transferring the information to producers was ineffective. Deficiencies in transferring knowledge is not an isolated incident, and is discussed as a limitation in other recent international intercropping studies (Silberg et al. 2017; Almoia-Hinajosa et al. 2018). Nevertheless, this finding contradicts my hypothesis that producers near summer-intercropping field trials would have exposure to the practice. Alternatively, producers felt more support from farmers' organizations (12/18 producers) than from the INTA research facility. The response may be partially explained by Hoffmann et al. (2007), who identified that producers preferred receiving and contributing information through an open dialogue with shared and relatable experiences. This implies that the adoptability of summer intercropping might improve with greater inclusion of producer participation. Producer participation was not a new revelation. Indeed, it is a principal in Farming Systems Research (Darnhofer et al. 2012,

12) and has been emphasized by other multi-cropping studies (Natcher et al. 2016; Franzel et al. 2001; Struik and Kuyper 2017; Alomia-Hinojosa et al. 2018).

The Region Consortiums for Agriculture Experimentation (CREA) is an example of farmers' organizations that was mentioned in a positive light during interviews for supporting producers and effectively transferring knowledge; as expressed in the following quotation:

> *I am not in a CREA group, but the group of producers has supported me the most.* – INT 10^{T}

The farmers' association in question is a bottom-up producer directed organization comprised of regional CREA groups made up of 10-12 members, and the amalgamation of these groups are known as AACREA (Argentina Association of CREA). The association is credited for effectively transferring knowledge through cooperative group dynamics. The impact of CREA has also been discussed in other academic literature. For instance, CREA groups have been described as settings where producers and practitioners share their experiences openly, and in return, they create collective knowledge and effectively solve mutual production system issues (Hoffmann et al. 2007; Peirano Vejo 2010). When a certain topic becomes of great interest among regional CREA groups, it is taken over by ACCREA who assembles a team or funds for researchers (including those from universities and INTA) to investigate the subject further (Peirano Vejo 2010). For summer intercropping in SEBA, studies by Caliviňo and Monzon (2009), Coll et al. (2012), and Monzon et al. (2014) have acknowledged support and advice from AACREA showing that some CREA members had invested interests to develop the practice into a high-tech alternative.

5.3.3. Field machinery is adapting to complex cropping systems, but field contractors prefer field uniformity

One-third of interviewed producers commented that technology was not suitable for intercropping (INT 1, 2, 3, 6, 9, 12). For example, a couple of producers stated that:

> *Intercropping doesn't have the machinery. It is a logistic problem.*
> – INT 12^{T}*;*
>
> *It is more demanding to do two crops than one crop. It involves more machines, more labour. [Intercropping is] More demanding.* – INT 3

These producers' comments echo with responses from practitioners who indicate that using conventional field equipment and crop varieties specialized for sole cropping systems, was inefficient in the use of labour and energy when applied to intercropping systems (INT A, F). Indeed, the availability of suitable mechanization is discussed as a barrier for intercropping in modernized cropping systems (Vandermeer 1992, 200; Caviglia 2009; Lithourgidis et al. 2011; Brooker et al. 2016).

Modern intercropping was expected to increase production by using natural resources more efficiently. Unfortunately, as Vanloqueren and Baret (2009) and Brooker et al. (2015) point out, the full potential of modernizing intercropping is unknown because the incorporation of biotechnology and machinery specifically for multi-cropping is not a priority. This appears to be in part a systemic challenge for agriculture production initiatives. For instance, a practitioner commented that the Kirchner-led government implemented an Agriculture Strategy Plan in 2010, which entailed a 58% increase in grain production by 2020. Yet, the Agriculture Strategy Plan – similarly to modern intercropping initiatives – did not give priority toward technology innovations to accomplish this goal:

> *Corn produced on the Agriculture Strategy Plan, I believe is 160 000 000 tonnes, but my question is how was it produced, with what, what was it produced for, and why was it produced? The plan only says how much. The Government's plan focuses on increasing yield. The point should be enhancing biotechnology and machinery; this is the real plan not the number of tonnes.* – INT E[T]

According to the available literature, there is little research globally on intercropping bioengineering (Vanloqueren and Baret 2009; Brooker et al. 2015; Bybee-Finley and Ryan 2018). In contrast, mechanical advancements entering modern agriculture systems have become more applicable to multi-cropping practices – whether developed for that intended use or not (Brooker et al. 2015; Bybee-Finley and Ryan 2018). The following subsections discuss how machinery and labour distribution in Argentina has both opportunities and barriers to promoting intercropping.

5.3.3.1. Challenges related to field mechanization that accommodates multi-cropping practices

Participants indicated that investing in the latest farm equipment was expensive for producers. However, there appear to be opportunities to overcome these technical challenges. One practitioner described how contracting services was necessary, to allow producers to have access to the newest field technology at an affordable cost:

> *In Argentina, the machines are very expensive relative to everything. So, you can't buy or see a new tractor just standing there it has to be moving. So, if you have land, let's say 200 hectares, you buy a new harvesting machine that can do your farming in one day. You can't buy that and leave it 364 days parked. So, the guys would be a contractor, or just contract the machine… Here the contractor can buy this machinery because they use it*

> *all the time and drain the life out of the machinery. I think that is really good, very efficient.* – INT A

Producers interviewed for this study either used or provided contracting services, displaying the importance of outsourced labour in the region. Other participants highlighted that contractors often use the most recent technologies (INT A, F). These participants' comments relate to a recent study by Muzlera (2014) that identifies Argentinian field contractors stay competitive by investing in efficient equipment that was no older than 3 to 5 years. Furthermore, Calzada (2017) calculated that contracting services have contributed to 60% of the purchases of machinery and were responsible for 70% of plants sown, 70% of agrochemicals applied, and 90% of crops harvested across the Argentine Pampas. New machinery entering in the Pampas that have automated precision, can adjust for site-specific conditions, and nearly carry out tasks autonomously, creates an opportunity for the adoption of novel or complex management strategies, including intercropping practices. The drawback to contracting services was that it was a business that profits through labour efficiency. The willingness and the expertise of contractors to operate in highly technical cropping systems showed to be a social barrier for intercropping adoption.

5.3.3.2. Field contractors' preferences to large and simplified systems is a barrier for producers to adopt more complex cropping practices

The high demand for field contractors and their equipment encouraged producers to simplify their fields. Field customizations, such as, intercropping was considered to cause inconveniences to contractors, which was illustrated in the following statements:

> *No because it is difficult for contractors, there is more manual labour, and need for the machinery. It is complicated the intercropping system. It is not practical now, perhaps in the future, but not soon.* – INT 1^T

> *… always there is a lot of demand for contractors. It is not like there is limited amount of demand. So, contractors have a lot of work, and I do not think they will get involved in intercropping… the market would be too small for that...when you are bigger [production scale] the contractors will go with you and have the best technology. If you are a guy with 10 hectares then probably you will not get the guy with the best technology, so you will have to go with the guy with the old machinery that makes one row and two days to do it. But, he would do it.* – INT A

Participants also felt that contractors would be uninterested in participating in an intercropping niche market, as contractors prefer to work on large, simplified plots and are busy throughout the season (INT A, F). Considering that most producers in SEBA do not invest in field machinery, it is less likely producers would adopt intercropping practices. These findings are supported by Urcola et al. (2015), who concluded that the high demand for contractors, left smaller-scale producers waiting for their availability. Drawn-out waiting often resulted in late sowing, reducing the productive and economic performances of small producers. This shows that the implementation of any novel cropping practice in SEBA highly depends on its practicality and profitability (i.e. time versus labour) to those providing contracting services.

5.3.4. Financial stability of soybean interferes with crop diversity

The majority of participants (12 out of 18) stated that for agriculture to be sustainable, it needed to be profitable for producers. This finding is in contrast to Snapp et al. (2010) where producers in Malawi favoured direct food security rather than profits. Theoretical and empirical literature has illustrated that uncertainty and risks contribute to producers' decision-making and their adoption to new technologies (Snapp et al. 2010; Franke et al. 2014; Meijer et al. 2015). In the case of Argentinian producers, financial uncertainty is a consistent issue (INT A, D, C, E). One practitioner went into more detail of why they thought producers focused on profitability:

> *It’s true, they [producers] have money, but they know that they actually don’t have it. The next year can be very dry, two years and plants do not grow. You never know, so you never relax. In here [Argentina] it’s because it is very unstable, and the government takes the farmers money during the high peaks but does not give back when they are down.* – INT A

Literature indicates that in Argentina, economic risks surpassed environmental risks, even though both subjects were of great concerns in the Argentine agricultural sector (Viglizzo et al. 2003; Ferrazino et al. 2014; Monzon et al. 2014; Urcola et al. 2015). Producers of SEBA in this study diverted economic risks by frequently incorporating soybean in their production system (INT B, C, D, F). Other studies have supported this finding in the SEBA region as well as other regions within the Pampas (Ferrazino et al. 2014; Urcola et al. 2015; Phélinas and Choumert 2017). Economic factors that influenced producers’ crop management decisions included the direct cost of production (11/18), crop price (5/18), and local market fluctuations (4/18). My findings indicate that soybean production fulfills all three criteria – it had the lowest cost of production, a relatively high crop price, and the crop was unaffected by local market fluctuations (INT A, C, D).

This last category explores how Argentinian producers chose practices that protected them from revenue loss that related to governmental intervention, unstable currency, and market and climate variabilities. Some participants expressed that these influencing financial factors increased production risks, which in turn, prevented crop diversity in the region. Intercropping is more difficult to promote when soybean as a sole crop has the lowest risk and is more profitable than any other crop. This highlights how producers from SEBA – and other regions within the Argentine Pampas – were dependent on soybean production due to multiple economic uncertainties.

5.3.4.1 Government intervention encourages soybean sole cropping

All producers and practitioners interviewed felt that the Kirchner-led government did not support crop producers. Agricultural policies were main barriers preventing producers from adopting alternative cropping practices, or for them to diversify their cropping system. For example, one producer summarized their discontentment with the comment:

> *Misinformation, and the lack of support, and enforcement from the state prevents farmers to follow more sustainable practices.* – INT 11[T]

The Kirchner-led government made producers feel unsupported, because of the placement of inconsistent levies causing market fluctuations, and relatively high taxes on selected crops (INT A, B, C, D, E, 2, 10, 14, 15, 16, 18). Existing literature supports their concerns (Richardson 2009; Nogués 2011; Gallo 2012; Gras and Hernández 2014, 346). For instance, corn, sunflower, and wheat were subjected to monthly export levies in attempts to maintain domestic food availability and affordability (Richardson 2009; Nogués 2011). The inconsistency of the levies is known to affect the price and sale of these commodities, which has created financial uncertainties for Argentinian crop producers. Conversely, soybeans were not considered a significant food source in the nation’s diet, allowing the crop to be sold in an open competitive market (Nogués 2011; Sharma 2011; Calvo 2014). The following excerpt is from a practitioner expressing how these policies have encouraged them, and other producers to concentrate on soybean production:

> *No. We don’t have a big domestic market it is very small. It is the mills [that] are the only buyers. So, it’s like hunting in the zoo…There is no competition between exporters and domestic buyers. There is only interest and competition in soybeans between oil producers and seed exporters. So, that is why Argentina is soybean dependant….because it is free to export. It’s low risk to grow it, and it’s roundup ready, it’s no-till here and it works.*

> *The problem is the organic matter lessens, and the soil structure degrades.*
> – INT C

Other interviewed practitioners (INT A, B, D, F) explained that export levies on alternative summer crops, and lax seed patent enforcements made soybeans more stable, and profitable for producers; even though soybean was highly taxed (35%) in comparison to corn (20%), sunflower and wheat (23%). Literature on the Argentine agriculture regime confirms this finding (Campi 2011, 188; Nogués 2011; Gallo 2012). In addition to government policies, participants pointed out the economic state of the country affected their cropping decisions, as illustrated by the direct quotations:

> *I would like to diversify the crops, but it is not feasible because of the economic problems...Less risk to not diversify.* – INT 2[T]

The economic problems that the participant referred to likely related to the double-digit inflation and the unstable peso currency devaluation that has occurred in Argentina, within the past decade (and in previous decades), preventing Argentinians to save and secure finances (Markley 2014). The combination of the national economic situation, federal government policies, and international demand for soybean, has encouraged Argentinian producers to focus on soybean – a low investment crop, and limit production on crops considered a high-investment and risk. As a result, many producers chose to limit crop diversification. All the interviewed producers expressed that they rotated their crops with the inclusion of soybean. One producer commented on the simplicity of their cropping system:

> *…every year we have soybean in all the years. We have soybean as single crop then as a double crop, in a sense that is monocropping.* – INT 3

This above comment aligns with Calviño et al.'s (2003) discussion, which concludes that the crop rotation in the region, was often as simple as soybeans in the summer season and a winter grain. Other studies have calculated that on average soybean is sown three out of every five years in a given field (Barral and Maceira's 2012; Cambreri 2013). The high frequency of soybean cultivation reveals that economic and political restrictions have compelled producers to prioritize short-term economic gains, and put aside environmental concerns, in order for them to continue their livelihood. Ferrazino et al. (2014) came to a similar observation when analyzing soil quality surveys by SEBA producers. This observation suggests that soybeans as a sole crop will continue to dominate the Pampean landscape unless socio-political and economic changes occur. The below quotation summarizes this outcome:

> *I think the way to reduce soybean is that there should be other activities with the same profitability as soybean, and this is a political decision.*
> – INT E^{T}

Summer intercropping would likely not be adopted until corn or sunflower becomes a less risky investment, and soybean stops being the "golden seed". For corn and sunflowers to have a higher cultivation frequency throughout the Pampas, export levies would need to be lowered, the Argentine peso requires stability, and more enforcement needs to be placed on soybean patents.

5.3.4.2. Producers had limited economic incentives to practice summer intercropping

Findings indicated that the management requirements for SI intercropping do not produce significant economic incentives. The direct economic benefits were identified as a key criterion, for interviewed producers to adopt given cropping practices rather than its environmental benefits, as indicated in the direct quotation below:

> *Intercropping would be interesting, but you have to show the farmers the benefits of it, if it is only biological benefits – keeping the structure of the land or keeping the biodiversity, or keeping better conditions and things like that – I think you will get a lot less candidates than if you showed the economic benefits.* – INT D

Over a third of the interviewees believed that yield gains from intercropping were not worth the extra time required to manage the practice (INT A, B, D, F, 3, 7, 12,17). As explicitly stated by one producer familiar with summer intercropping:

> *Increase in yield and returns are not as worth it, for the time demand and the economic returns you gain.* – INT 3

Calculations by Cambreri (2013) and Monzon et al. (2014) on corn-soybean intercropping direct costs and profitability support this claim. These researchers determined that the 2012 direct costs for corn-soybean intercropping in the SEBA region, was at least twice the cost compared to sole cropping soybean, and cost 25% more than sole cropping corn in the same given area. Though intercropping had higher direct costs, the average gross margins for corn-soybean intercropping (\$474 USD t ha^{-1}) was similar to sole cropped soybean (\$473 USD t ha^{-1}). Irrigated sole cropped corn had larger gross margins than both sole cropped soybean and corn-soybean intercropping (Monzon et al. 2014). These calculations display that the financial outcome of corn-soybean intercropping would not be motivating for producers to adopt the practice. The adoptability of the practice would improve when its gross margins are significantly larger than sole soybean production. In order for this to occur, the price ratio of soybean to corn needs to be less than 2.2 (Monzon et al. 2014; Cambreri 2013) and the direct costs to intercrop need to be reduced.

5.3.4.3. The climate in the Balcarce district is unfavourable for summer intercropping

In connection with economic circumstances, participants discussed that climate limitations regulated the profitability of a cropping practice by affecting input requirements and the overall yield. Interviewed practitioners commented on how the region was susceptible to dry periods in January when corn is at its most critical growth stage (INT A, C, D), and the summer season is short, which lowers the yield potential for second soybean (INT A, D, F). These climate observations by practitioners are confirmed by field studies within the SEBA region (Sadras and Calviño 2001; Andrade et al. 2002; Coll et al. 2012; Monzon et al. 2014, Chapter 4). The risk of corn yield loss from water stress partially explains why the percentage of corn sown in the SEBA area is low (2%; SIIA 2014) and that 65% of interviewed producers expressed that they did not include corn in their rotations. Ensuring good corn yields require producers to invest in quality seeds and irrigation systems. The direct quotations below are from one producer who avoided growing corn and two other producers who had the financial capacity to include corn in their rotations:

> *Corn is not in our rotation because it costs too much.* – INT 2^{T}
>
> *I am going to grow maize [corn] because I am a new irrigation farmer. I bought a drip irrigation system for 43 hectares.* – INT C
>
> *It depends; in general, you grow corn, you expect to earn more. This year the costs are really high and the drought from last year, they [the producers] lost a lot of money. They say they are not planting corn this year. In general, if it yields a lot, you expect more income. For us, we do it;*

> *we can afford the investment. It is a higher investment, it is risky but if you have a good year, you have good money, for us.* – INT 9

Similarly to many SEBA producers who cultivate corn, SEBA researchers that conducted corn-soybean intercropping field trials predominantly applied irrigation management. Thus SEBA producers without irrigation systems would have less interest in adopting an intercropping practice requiring water supplementation. In a Pampa-wide corn-soybean intercropping study by Monzon (2014), they found that applying the practice under rain-fed conditions was more applicable in the northern regions of the Pampas (Cordoba and Entre Ríos provinces) than in SEBA.

Rain-fed corn-soybean intercropping trials occurred at UIB in SEBA during 2011-2012. During that growing season, rainfall declined by 14.5% from the fifteen-year average. As a result, corn yields declined by 54% when it was sole cropped, and declined by 31-35% when intercropped with soybean (Chapter 4 and 6). This field trial showed that corn when intercropped mitigated yield losses from water-stress better than in a sole cropping scenario. Conversely, the economic and yield losses of corn as a sole crop and as an intercrop were greater than growing soybean as a sole crop. Thus, soybean as a sole crop fared better when mitigating water-stress related risks. Two practitioners explained how soybean production works well for minimizing climate-related risks. The first practitioner explained that lower investment equals less economic loss when yields fail:

> *In those cases with sunflower and corn, both are hybrids, very expensive seeds, so it's an expensive risk. If you fail on the seed, it's too expensive…soybean, it would be different because you don't lose…The soybean seed is very cheap, usually the farmers do not buy [soybean] they just use it. So they seed, if it doesn't grow, it is not that bad.* – INT A.

The other practitioner explained how growing second soybean in a region with a short summer season increased the risk of reduced yields when planting was delayed*;* however, this was not considered a dire crop management decision:

> *The further you go in terms of your agenda, it is risker…we know farmers that took the risk of sowing soybeans even til January the 20th. But of course, we know that the shorter [maturity] varieties, the less yield potential. The second [soybean] crop, I think it is around somewhere between 600-800 kg/ha when they harvest, and they sell it, and it is a plus. At the same time, this year due to the big drought in some areas, the second crop was so important, they were begging to have a good second crop because 30-40% of land is in hands of renters who pays a lot per hectare, so maybe that makes a difference to breaking even, losing, or earning some money.* – INT D

This last quotation highlights how sole cropped second soybeans was used as a "bonus" round during a growing season. Under corn-soybean intercropping, soybeans were planted in late November and December, which was similar to when it was ideal to plant second soybean. However, in a substitutive intercropping design, soybean cannot be treated as a 'plus' within the SEBA region.

The shorter summer growing season in SEBA affected soybean yields. Thus, the overall productivity of summer intercropping was lower when compared to relative sole crops, and when compared to summer intercropping within northern regions of the Pampas (Monzon et al. 2014). Monzon et al. (2014) found that half of the sixteen corn-soybean intercropping trials in SEBA did not achieve yields greater than relative crops grown separately as sole crops. Furthermore, Monzon et al. (2014) determined that a minimum of 1850 growing degree days be needed for corn-soybean intercropping to achieve competitive yields; the SEBA region approaches this limit with an average of 1983 ± 150.5 growing degree days (INTA 2015).

If the yield for corn-soybean intercropping cannot be consistently equal to or greater than sole cropping two crops, the practice was not economically beneficial for producers. Simultaneous planting of sunflower-soybean intercropping may be more economically feasible in SEBA. Producers mentioned the region was a central area for sunflower production (INT C), which coincides with the literature (Sadras and Calviño 2001; Coll et al. 2012). Overall potential yields of sunflower-soybean showed to be more promising than corn-soybean within the SEBA region (Echarte 2011; Coll et al. 2012; Appendix 9.2). Conversely, sunflower-soybean intercropping does not contribute to soil organic carbon (Calviglia and Andrade 2010), nor has it shown to efficiently use water and solar radiation in the SEBA region (Coll et al. 2012) – two main environmental benefits of corn-soybean intercropping. To my knowledge, there were no sunflower-soybean intercropping studies in the SEBA region without irrigation, nor was there a published economic analysis for this intercropping combination.

5.4. CONCLUSION

Participants in this study revealed that the lack of information available on intercropping, technology limitations, labour inconveniences, climate constraints, economic risks, and restrictive production policies, were barriers to adopting summer intercropping in SEBA. Economic uncertainties and Kirchner-led government intervention strongly influenced producers cropping practice decisions. Without support from the government, producers were hesitant to try new cropping practices, let alone diversify their fields. Frequently cultivating soybean diverted economic risks, but this strategy heightened environment, social, and long-term economic implications.

Experimental field trials of summer intercropping were capable of increasing yields per area within the Pampas, except the limited growing degree days for soybean stagnated the overall yield progression of intercrops in SEBA. Yield and gross margins achieved in corn-soybean intercropping were similar to sole cropping soybeans, but higher direct costs of summer intercropping and investing in irrigation were factors that disinterested producers from adopting the practice.

The complexity of intercropping was a deterrent to producers, because they did not want to inconvenience field contractors. Field contractors were essential to crop production in the Argentine Pampas; their services allowed producers to have access to expensive and state-of-the-art field equipment. New technology entering the Pampas in the near future will have increased capabilities for multi-cropping, minimizing inconveniences. Nevertheless, agroecological innovations and biotechnology specifically for multi-cropping are needed to boost summer intercropping interests.

Main gaps in regional research for modernized intercropping were agrochemical mitigation and fostering facilitative relationships in multi-cropping environments. Closing these two research gaps would contribute to making intercropping more economically feasible and enhance its environmental benefits. Filling in these research gaps require concerted efforts from multiple stakeholders including researchers and producers. The contribution of interdisciplinary and transdisciplinary approaches and increased practitioner involvement is recommended, to complement research by specialists who use reductive methods. Site suitability is an essential component to SI cropping practices; in the case of corn-soybean intercropping, it had poor adoptability in the SEBA region according to producers' and practitioners' perspectives obtained during this study. The practice may have greater potential in the northern regions of the Pampas. Internationally, the practice may have greater reception in regions with a warm and humid temperate climate, where there is economic stability, and with a government that is supportive of producers and endorses SI innovations.

CHAPTER 6

INTERDISCIPLINARY STUDY

Characterizing corn-soybean intercropping as a sustainable-intensive cropping practice

6.1. INTRODUCTION

Sustainable-intensification (SI) was introduced in the 1990s to support smallholder livelihoods in Africa, Asia, and Latin America by improving the production of underutilized land (Pretty 1997; Weltin et al. 2018). Subsequently, research and development for SI expanded to larger and modernized agricultural systems as a tactic to manage food insecurity, adapt to climate changes, and minimize agriculture-related environmental degradation and biodiversity losses (Pretty and Bharucha 2014; Wezel et al. 2015; Weltin et al. 2018). Sustainable-intensification evolved as a promising strategy for producers to grow more food on less land, by being resource efficient, promoting innovation, and applying best available technologies, including ecological management and genetic improvements, while being economically viable, socially appropriate, and environmentally cautious (Pretty and Bharucha 2014; Weltin et al. 2018). This strategy has the potential to redesign agricultural systems, however, the research itself has its drawbacks.

The multiple dimensions embedded in the concept of SI creates challenges when researching the subject (Pretty and Barucha 2014). Researchers have called for more disciplinary collaborations, and interdisciplinary and transdisciplinary approaches when undertaking studies of the subject area (Jordan and Davis 2015; Weltin et al. 2018). For example, recent systematic reviews by Mahon et al. (2017) and Weltin et al. (2018) discuss how social and political dimensions were under-represented in SI literature – yet these two dimensions are highly influential actors in producers' adoption of technologies and practices (Darnhofer et al. 2012, 5; Weltin et al. 2018). Limited instructions on how to assess SI along with the undefined scope, scale and specified indicators have created research, development and adoption barriers (Pretty and Bharucha 2014; Petersen and Snapp 2015; Mahon et al. 2017; Weltin et al. 2018). The broadness of the SI concept has been defended as a means to avoid one particular vision of agriculture production or ideal technologies, because agriculture systems are diverse and context-sensitive (Pretty 2011; Pretty and Bharucha 2014; Petersen and Snapp 2015; Hunter et al. 2017). Within this chapter, the drawbacks to SI research were addressed by developing and applying an interdisciplinary framework to investigate corn [*Zea mays*]-soybean [*Glycine max*] intercropping in the southeast Buenos Aires (SEBA) region of the Argentine Pampas.

6.1.1. Corn-soybean intercropping as a sustainable-intensification in the Argentina Pampas

Since 2005, Argentinian researchers in the SEBA region investigated corn-soybean intercropping as an SI strategy to: i) increase production without land expansion; ii) use natural resources more efficiently in modernized agroecosystems; and iii) lower the occurrence of soybean monocropping across the landscape (Coll et al. 2012; Monzon et al. 2014; Andrade et al. 2017). In the SEBA region, corn-soybean intercropping trials were designed to suit the regional temperate climate, utilize existing mechanical and input technologies, and to use reductionist approaches to compare the practice with corn and soybean sole cropping (Calviño and Monzon 2009; Caviglia 2009). Researchers mainly focused on field-scale biophysical aspects of corn-soybean intercropping (i.e. Echarte et al. 2011; Coll et al. 2012); while, few researchers analyzed economic dimensions of the practice (Monzon et al. 2014; Cambreri 2013). Moreover, the social and political dimensions of corn-soybean intercropping were not studied in detail in the SEBA region. Perhaps the biggest research gap for corn-soybean intercropping was created by disproportionate emphasis put upon a few components to justify the practice as SI, opposed to investigating how the practice fits into the entire SEBA agricultural system to achieve SI in a unified manner.

6.1.2. Integrating previous chapters to assess SEBA corn-soybean intercropping

To examine how corn-soybean intercropping fits into the SEBA agricultural system, this sixth chapter used qualitative interdisciplinary methods, with the Farming Systems Research (FSR) approach. This chapter integrated information from the previous chapters of this dissertation. The previous chapters used different methodologies, dimensions, and temporal and spatial scales; each chapter covered separate parts of investigating corn-soybean intercropping and the SEBA agricultural system. The FSR approach will be applied in this chapter to illuminate interactions between the parts, to assess SEBA corn-soybean intercropping holistically (i.e. understanding the big picture by the sum of its parts) (Darnhofer et al. 2012; Patton 2015, 144).

Like SI, the FSR approach has no standardized methodology (Darnhofer et al. 2012, 4). The core principle of FSR is that it relies on interdisciplinary and observations from researchers to investigate interconnections between a system's elements (i.e. soil, plants, animals, infrastructure), and to integrate societal actors (i.e. perceptions, values, and preferences) to understand the 'real world' situation (Stroud and Kirkby 2000, 95; Darnhofer et al. 2012). Moreover, FSR emphasizes that farming practices cannot be bounded and isolated at the farm-scale; instead, the farm is embedded in a territory, a locale, and a region with specific agro-ecological context, economic opportunities and social (cultural and political) values (Hart 2000, 50; Darnhofer et al. 2012). It is acknowledged that incorporating all the features of FSR into a single study is a daunting challenge, particularly on an emerging cropping practice where research resources are limited. However, the thesis already has built three key steps to meet this challenge: i) an understanding of the social-ecological context (Chapter 2); ii) an evaluation of corn-soybean intercropping production and logistics at the field-scale (Chapter 3); and iii) a gain in perspectives on the constraints and opportunities for corn-soybean intercropping in the SEBA region (Chapter 4).

6.1.3 Study objectives and contributions

With this foundation, my objective was to holistically characterize and evaluate corn-soybean intercropping as an SI cropping practice, by interconnecting research findings from my dissertation and other researchers' studies. I wanted to characterize the practice to determine its suitability within the SEBA region of the Argentina Pampas. By suitability, I mean: i) determining if corn-soybean intercropping should be considered an SI cropping practice; and ii) determining whether corn-soybean intercropping is a practical cropping practice for producers to adopt in the SEBA region. In order to achieve my objectives, an SI evaluative framework was developed that included customized sets of indicators (for the farm type) and incorporated cross-scale examinations (i.e. field to landscape boundaries) (Petersen and Snapp 2015; Mahon et al. 2017). The evaluative framework is described in more detail on the following page; it is meant to be a step towards interpreting agriculture activities as SI (or not) in a more transparent manner.

The present study is unique in that it comprehensively assessed a cropping practice intended to be SI from its early development to experimental stages. Recent SI studies have discussed theoretically what practices (e.g. intercropping) could become SI (Reddy 2016, 69; Pretty and Bharucha 2014; Wezel et al. 2015). While, others have looked at one or two dimensions (often biophysical or economic) of a cropping practice considered SI (Caviglia et al. 2010; DwivedI et al. 2016; Kumar et al. 2018). Lastly, some researchers assessed agricultural activities that were already established and adopted by producers (Franke et al. 2018; Weltin et al. 2018) through an SI lens. Characterizing modernized cropping practices for SI – during its development phases is beneficial to determine where more research focus is required – to determine how to ease implementation for producers and stakeholders, and to recognize the limitations of a cropping practice within regional circumstances. Knowing these issues at the early stages of development allows researchers and producers to find solutions to improve the practice, or to quickly move on to researching other practices that better suit the region.

6.1.4. Evaluative framework for identifying sustainable-intensive cropping practices

With acknowledgement of alternatives from other authors (e.g. Petersen and Snapp 2015; Wezel et al. 2015), the framework I developed and used was most influenced by Jordan and Davis (2015). They discussed SI as an ideal vision of agriculture, and to create new agricultural research and developmental systems, they suggested there are "middle-ways" between conventional and agroecological paths. Conventional cropping practices are considered intensive and productivist by focusing on agronomy and economics to achieve increased yields per unit of area, time and resource (Caviglia and Andrade 2010; Pretty and Bharucha 2014). In contrast – and less common in modernized systems, agroecological cropping practices combine agronomy and ecology to maintain yields, while attempting to preserve social and environmental well-being, by mimicking natural processes (Altieri et al. 2017). More often agroecology is considered a path for sustainable cropping practices, as it focuses on enhancing functional biodiversity, and conserving on-site resources (Karami and Keshavarz 2009, 20; Kershen 2013; Altieri et al. 2017).

Integrating these two contrasting approaches when developing novel cropping practices can result in many middle-way outcomes. Some outcomes will be balanced, while other outcomes may have biases towards conventional (intensification), or agro-ecological (sustainable) principles. Agriculture experts have been concerned that the current application of SI has resulted in a productivist bias encouraging business-as-usual practices and greenwashing the concept of SI (Petersen and Snap 2016; Altieri et al. 2017; Mahon et al. 2017; Weltin et al. 2018). The resolution I sought was a framework that allows evaluation and determines if a given SI cropping practice leans more towards the ‘intensification’ or ‘sustainable’ end, and whether the cropping practice overall is a strong or weak application of the SI concept.

6.2. METHODS

6.2.1. Description of sub-studies used in the case study

As mentioned above, this chapter synthesizes findings presented in the previous chapters – not for the purpose of summarizing, rather to integrated findings in order to study SEBA corn-soybean intercropping, within an interdisciplinary context (Darnhofer et al. 2012, 25; Patton 2015, 144). For the remainder of this chapter, the studies from the previous chapters are described as sub-studies; I summarize these below for clarity.

- *Sub-study 1: Social-ecological context and historical overview of the Argentine Pampas (Chapter 3)*

  This sub-study provided the context of the larger system that the Argentine Pampas production systems are nested within. Chapter 3 examined geography, socioeconomic history, and the agriculture regime of Argentina. Information on the social, political, and economic patterns from the sub-study was integrated into this current chapter, to acknowledge events that affect the regional-level and field-level decision making, and influencers that impacted novel cropping practices development and implementation (Leguizamón 2014).

- *Sub-study 2: Evaluating CO_2 and N_2O soil emissions from corn-soybean intercropping systems in south-east Buenos Aires, Argentina (Chapter 4)*

  The second sub-study was a reductive natural sciences study that compared corn and soybean sole cropping to two configurations of relay row corn-soybean intercropping – one row corn to two rows soybean (1:2) and two rows corn to three rows soybean (2:3) at the field scale, for the summer growing seasons (2010-2011 and 2011-2013). The experimental site was in the SEBA region at the Balcarce Integrated Unit (UIB) research facility (37º 47’S, 58º 18’W) that is associated with the National Agriculture Institute of Technology (INTA) and the National Scientific and Technological Research Council (CONICET). Quantitative data collected focused on soil derived greenhouse gases (GHG) from each cropping system, specifically observing fluxes of carbon dioxide (CO_2) and nitrous oxide (N_2O). Field notes were collected during this sub-study on soil and crop management operations, plant growth stages and harvest outcomes. Both GHG data and field notes were integrated into this current chapter. Greenhouse gas emissions were used to characterize corn-soybean intercropping, because it is a prevalent topic discussed in SI literature (Mahon et al. 2017), yet there is limited information on the mitigation potential of intercropping (Qin et al. 2013; Chapagain and Riseman 2014; Sánchez et al. 2016). Field notes contributed to characterizing information on the in-field physical, biological, and technical factors that were directly related to the cultivation of corn and soybean in an intercropping system.

- *Sub-study 3: Barrier and Opportunities for Adopting Summer Intercropping Practices in the Southeast Buenos Aires Pampas (Chapter 5)*

  This third sub-study was an inductive social sciences’ study that collected qualitative interview data, at a landscape scale, within three months. A total of twenty-four interviews were conducted within the SEBA region of the Argentine Pampas using purposive sampling. Eighteen semi-structured interviews were conducted with crop producers, and six unstructured interviews were conducted with agricultural practitioners. Interviews provided insight into cultural, technical, economic, and political factors that affect real-world logistics of corn-soybean intercropping. Situational knowledge gained from these interviews were integrated into this current chapter, to provide context to whether the cropping practice was a practical option to be adopted in the SEBA region (Patton 2015, 367; Weltin et al. 2018). Interview data that were not used in this sub-study were re-examined to determine framework (sub)categories (section 6.2.2) and act as resources for characterizing corn-soybean intercropping (section 6.2.3).

Multiple studies can be combined in a number of ways depending on the approach, motivation, integration extent, and organizational structure (Klein 2017, 15). This case-study integrated resources in an interdisciplinary manner from the sub-studies, academic literature, and databases. There are different typologies of interdisciplinary research. This interdisciplinary investigation was broad-scope and was methodologically motivated using cross-cutting organizational principals. The investigation was broad-scope based, because sub-studies were applied at different scales with differing methods (Klein 2017, 16). The motivation behind this research was to increase the transparency with respect to the SI designation, by using a more holistic evaluative framework (Klein 2017,19). Cross-cutting principles were used to develop the SI evaluative framework; ideas and findings across disciplines were centered around SI. Ideas and findings from different disciplinary studies were detached and brought together into the created framework to build a new coherent whole (Klein 2017, 21).

6.2.2. Creating a sustainable-intensive evaluative framework for the case study

A conceptual map of the grounded theory methods used to create the framework is in Figure 6.1. Grounded theory is a systematic thematic analysis where a theory emerges from the researcher's observations and interviews within a real-world setting by connecting inductive and deductive procedures via constant comparison methods (Patton 2015, 110). Observations used in the inductive portion of the grounded theory process included my three sub-studies; and studying literature on agriculture sustainability, intensification, and SI. Patterns were inductively identified and were interpreted to generate preliminary categories and supportive subcategories that were organized under the two main themes – "Sustainability" and "Intensification" (Patton 2015, 382; Jordan and Davis 2015). The second stage of this grounded theory process involved selectively coding interviews. Interviews with producers and practitioners were coded for themes related to the preliminary (sub)categories.

Separate from coding, SI indicators from Mahon et al. (2017) systematic literature review were used to organize, modify, and bound subcategories. Mahon et al. (2017) used the PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-analysis) framework to screen articles that measured, quantified or discussed SI agriculture. From the 75 articles identified, a total of 218 indicators were suggested in their study. Mahon et al. (2017) listed the indicators and the number of articles referencing each indicator. Originally Mahon et al. (2017) grouped indicators by resource, system, resource units, governance, system resource users, interactors and outcomes, to define what types of indicators for SI existed. Indicators were regrouped in the present study and used as a referencing tool to examine features of modernized corn-soybean intercropping. All indicators were included when regrouped and placed into formulated subcategories to avoid biases in the framework (Levkoe and Blay Palmer 2018). Each indicator was placed within a subcategory where it had the most relevance. Subcategories and categories were verified, using an iterative triangulation process (Patton 2015, 316). This process eliminated (sub)category redundancy and determined what

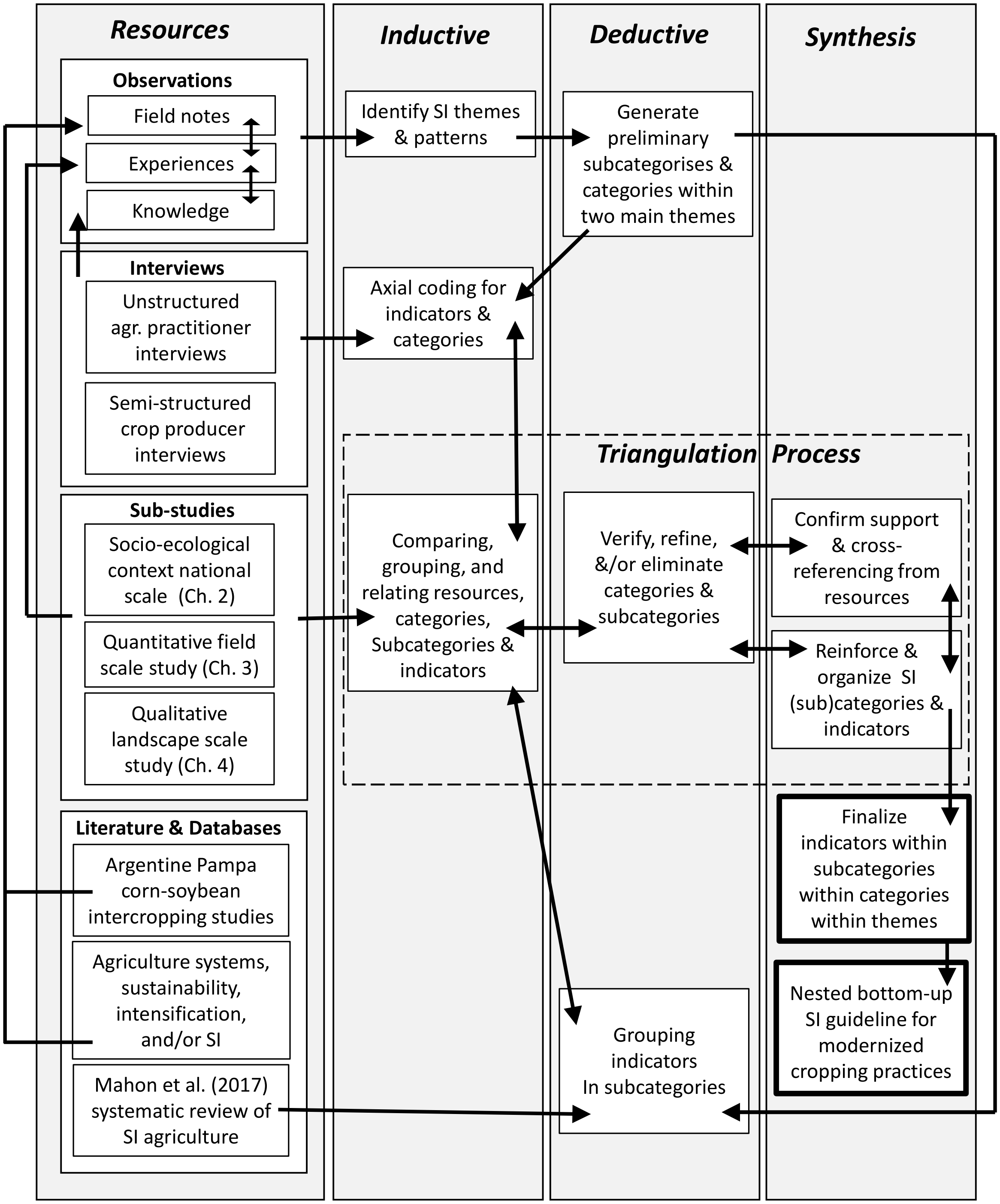

Figure 6.1. Conceptualization of the methods and resources used to establish the sustainable-intensification evaluative framework to assess corn-soybean intercropping in the southeast Buenos Aires Pampas.

(sub)categories were most applicable for assessing this case study. This process was repeated until a point was reached where new data did not change the emerging (sub)categories (Patton 2015, 556). For organizational purposes, indicators within each subcategory were placed in order of most referenced to least, according to Mahon et al. (2017). The average (and standard deviation) of the number of references for indicators within each subcategory was calculated. These numbers do not necessarily show the subcategory importance for SI; rather, it illustrated which sub-categories were more refined for SI than others.

6.2.3. Using the framework to evaluate whether SEBA corn-soybean intercropping can be considered a sustainable-intensive cropping practice

A bottom-up (data-driven) process was used within the framework to evaluate whether corn-soybean intercropping was identified as a SI cropping practice; where subcategories were the local parts, categories were intermediaries, and the themes “Sustainability” and “Intensification” were the global constructs (Yin 2009, 137). Subcategories were bounded by indicators for framework structure, but not all indicators were used when characterizing the practice. Indicators were used if relevant to the case study and if data on the indicator were available. Data used in this characterizing process were obtained from peer-reviewed research articles, databases, sub-studies, interviews, field notes and memos (Yin 2009, 120; Patton 2015, 536). A combination of data that I collected and from other studies, were applied to the framework, to cover the wide range of indicators within each subcategory adequately. Data were organized within the subcategories, and the relationships between subcategories provided a rationale for each designated category. Information within categories characterized the practice, as well as highlighted related knowledge connections and research gaps. Under the themes of “Sustainability” and “Intensification”, an overall characterization was conceptualized by revealing categorical strengths, weakness, trade-offs and synergies (Patton 2015, 556).

Categorical features were used to determine the balance of sustainability and intensification of the cropping practice in the region. For example, if the practice corresponded to one category in the sustainability theme but related to multiple categories in the intensification theme, then the practice would be considered SI with a skew towards intensification. The bottom-up process of characterizing corn-soybean intercropping also led to providing an overview of categorical features that can change with time and circumstance (i.e. situational context) (Pretty and Bharucha 2014, Weltin et al. 2018).

6.3. RESULTS AND DISCUSSION

This results and discussion section was separated into five subsections. The first subsection reveals the components of the constructed framework and examines patterns of data integration (section 6.3.1). The next two subsections are categorical reviews of SEBA corn-soybean intercropping separated by themes of “Sustainable” (subsection 6.3.2) and “Intensification” (subsection 6.3.3). Within these two subsection sub-studies, interviews, and peer-reviewed articles are sources used to inform the findings. To maintain anonymity, interview sources were referred to as numbers to identify producers participating in semi-structured interviews and letters to identify agricultural practitioners with unstructured interviews. The superscript “T” indicates quotations that have been translated from Spanish to English. The fourth subsection (subsection 6.3.4) includes the suitability and characterization synthesis of corn-soybean intercropping as a SI practice in the SEBA region. Lastly, subsection 6.3.5 provides suggestions on how to continually evolve the SI framework for emerging cropping practices.

6.3.1. Developed framework and data integration

The “Sustainability” and “Intensification” themes contained four categories, each theme nests three subcategories (Figure 6.2) that are comprised of 3 to 22 indicators from Mahon et al. (2017). The ‘Sustainability’ themed categories are: i) knowledge intensity; ii) socio-political suitability; iii) diversity and complexity; and iv) long-term environmental outcomes. The Intensification themed categories are: i) chemical input mitigation; ii) labour and technology efficiency; iii) increased production; and iv) short-term profitability. Indicators organized by subcategory and category within themes of “Sustainability” and “Intensification” are shown in Tables 6.1 (Sustainability theme) and 6.2 (Intensification theme). Most suggested indicators were within sub-categories belonging to the long-term environmental outcomes category. In contrast, sub-categories belonging to the socio-political suitability category embodied the greatest amount of indicators, but these indicators were the least suggested within the Mahon et al. (2017) literature review. The observation of a weighted bias of ecological measures is in accordance to other studies that have noted this bias for some agricultural sustainability assessments and SI assessments (Alrøe and Noe 2016; Hunter et al. 2017; Mahon et al. 2017; Talukder et al. 2017). With regards to evaluating SEBA corn-soybean intercropping as a SI practice, previous studies (Caviglia 2009; Calviño and Monzon 2009; Caviglia and Andrade 2010; Coll et al. 2012; Cambareri 2013; Monzon et al. 2014; Regehr et al.2015; Bichel et al. 2016; Novelli et al. 2017; Oelbermann et al. 2017) supported biophysical and economic indicators shown in the framework (categories: Increased production, Short-term profitability, and Long-term outcome). Some of these studies briefly mentioned issues related to knowledge, social and political relevant indicators, such as, “direction of government policy”, “informal seed systems”, “farmer membership in agriculture organizations”, “farmer to farmer exchange”, “land ownership”, and “capital intensity” (Caviglia et al. 2004; Calviño and Monzon 2009; Cavligia and Andrade 2010; Cambareri 2013; Monzon et al. 2014).

Figure 6.2. The sustainable-intensification framework with a bottom-up approach to characterize corn-soybean intercropping in modern cropping systems

Table 6.1. Sustainability theme of the sustainable-intensification framework for modernized cropping practices using indicators from Mahon et al. (2017).

Sustainability Theme	
Subcategories	Indicators
Category: Knowledge Intensity	
Sufficient research available on practice 5.0 ± 3.74 (n=4)*	education and knowledge^{11‡} (+†); funding for agriculture research^{5} (+); educational level of farmer^{3} (+); knowledge per ha^{1} (+)
Resources publicly available for practice 5.3 ± 3.05 (n=3)	farmer advice and information infrastructure^{8} (+); farmer participation in research^{6} (+); number and amount of time training was received^{2} (+)
Farmer networks 3.2 ± 2.68 (n=5)	farmer membership in agriculture organizations^{7} (+); farmer to farmer exchange^{2} (+); informal seed systems^{2} (+); access to information^{1} (+); farmer isolation^{1} (-)
Category: Socio-Political Suitability	
Government support 2.0 ± 1.20 (n=16)	subsidies to encourage SI practices ^{4}(±); payment for environmental services^{4} (+); cost of food to consumers^{3} (-); regulation on water quality^{2} (+); regulation on crop protection chemicals^{2} (+); taxation encouraging SI practices^{2} (±); investment in agriculture ^{2} (±); investment in market development^{2} (+); direction of government policy^{2} (±); limiting imports of agricultural products^{1} (+); liberalising trade^{1} (+); regulation on seed quality^{1} (+); removal of subsidies to encourage SI practices^{1} (+); regulation of air quality^{1} (+); regulation on farming practices^{1} (+); GDP in agriculture^{1} (+)
Community & infrastructure support 1.9 ± 1.35 (n=20)	gender equality^{7} (+); cultural autonomy^{3} (+); farmer age^{3} (-); population density/ha^{2} (+); capital intensity^{2} (+); community equality^{2} (+); waste production^{2} (-); regional mean income from agriculture^{2} (+); national mean income from agriculture^{2} (+); farmer health^{2} (+); infrastructure age^{1} (-); total value of farm infrastructure^{1} (+); public perceptions^{1} (+); number of leisure/tourism opportunities^{1} (+); conflict amongst users^{1} (-); recycling of waste products^{1} (+); renewable energy focus^{1} (+); household dependency ratio^{1} (-); attitude towards quality of life^{1} (+); attitude towards empowerment^{1} (±)
Amend to land tenure conditions 4.0 ± 1.55 (n=5)	security of land tenure^{5} (+); strength of land rights^{4} (±); land ownership^{4} (±); land holdings^{5} (+); percentage of land owned by farmers^{1} (+)
Category: Diversity and Complexity	
production & landscape diversity 3.8 ± 4.71 (n=10)	diversity of crops^{14} (+); diversity of livestock^{11} (+); crop rotations^{3} (+); crop-livestock integration^{3} (+); floristic diversity^{2} (+); structural diversity^{1} (+); percentage area of land under different production systems^{1} (±); management of uncropped areas within the landscape^{1} (+); size of patches of uncropped land^{1} (+); area of high nature value farmland^{1} (+)
Market diversification 2.7 ± 3.73 (n=6)	market access^{11} (+); recreation value of social-ecological system^{3} (+); participation in direct sales markets^{1} (+); value of tourism to community^{1} (+); household purchases (% change in consumption/time)^{1} (±); access to market information^{1} (+)
Species diversity & welfare 4.5 ± 2.32 (n=19)	number of keystone species^{8} (+); diversity of soil biota^{8} (+); habitat fragmentation^{7} (-); livestock welfare^{7} (+); wild biodiversity^{6} (+); farm-land bird number^{6} (+); crop pollinator numbers^{6} (+); species extirpation^{5} (-); livestock stocking density^{5} (-); diversity of wild birds species^{4} (+); complexity of ecological networks^{3} (+); butterfly diversity^{3} (+); un-natural behaviours of livestock incidence^{3} (-); mammal diversity^{2} (+); earthworm populations/m^{2} of topsoil^{2} (+); livestock disorders incidences^{2} (-); incidence of lameness in livestock^{2} (-); number of beneficial insects^{1}(+); livestock mortality rate^{1} (-)

Continuation Table 6.1

Category: Long-Term Environmental Outcomes	
Improve water use efficiency & water quality 4.3 ± 3.55 (n=12)	water holding capacity^{9} (+); area under irrigation^{9} (+); water footprint (total water use/given area)^{9} (-); water quality^{8} (+); depth of water table^{6} (+); management of water way conservation^{3} (+); water exploitation index^{2} (-); diffuse water pollution^{2} (-); water logging of soils^{1} (-); soil infiltration rate^{1} (+); bacteria count of water^{1} (+); water- use efficiency^{1} (+)
Enhance soil organic matter & soil fertility 6.1 ± 5.71 (n=15)	soil organic matter content^{20} (+); soil erosion^{18} (-); soil texture^{8} (-); continuous soil coverage^{7} (+); nutrient balance^{6} (-); soil pH^{6} (±); management for soil conservation^{6} (±); salinization^{5} (-); soil compaction^{4} (-); low soil pH^{3} (-); soil depth^{2} (+); rate of soil loss (ha/yr)^{2} (-); desertification^{2} (-); soil porosity^{1} (+); farmers' perception of on farm soil loss^{1} (±)
Mitigate GHG emissions & improve energy efficiency 3.4 ± 4.03 (n=17)	GHG emissions (t/ha)^{18} (-); carbon dioxide emissions (CO_2 t/ha)^{5} (-); energy efficiency (kWh & fuel use)^{5} (+); carbon sequestration^{4} (+); number of tillage operations^{4} (-); below ground carbon (mg C/g soil)^{4} (+); GHG/unit of product^{3} (-); above ground carbon (+); GHG/unit of input^{2} (-); GHG/farm^{2} (-); eco-efficiency score^{2} (+); physical proximity to markets^{1} (+); carbon footprint^{1} (-); energy intensity^{1} (+); GHG/crop grown^{1} (-); GHG/unit area^{1} (-); total carbon (above and below ground)^{1}(+)

* Calculated mean for number of sources per indicator per subcategory.

[‡] Indicators from Mahon et al. 2017 are in order of most suggested to least suggested with number subscripts indicated number of articles referring to the indicator.

[†] Symbols (+), (-), and (±) represent indicators with positive, negative or neutral measurements respectively.

Table 6.2. Intensification theme of the sustainable-intensification framework for modernized cropping practices using indicators from Mahon et al. (2017).

Intensification Theme	
Subcategories	Indicators
Category: Chemical Input Mitigation	
Improve pesticide use efficiency 4.7 ± 4.02 (n=8)*	integrated pest and disease management^{13}[‡] (+)[†]; number of crop protection chemical treatments^{10} (-); farmer exposure to agrochemicals^{4} (-); crop protection run-off^{3} (-); quantity of crop protection chemicals used^{2} (-); incidence of crop pest and diseases^{2} (-); timing of crop protection application^{2} (±); incidences of insect pests^{2} (-)
Improve fertilizer-use efficiency 4.6 ± 3.41 (n=12)	fertilizer use (kg/ha)^{12} (±); nitrate runoff^{10} (-); mineralisable nitrogen in soil^{4} (+); use of organically derived fertilizer^{4} (+); use of chemical fertilizers^{4} (-); plant available phosphorus^{4} (+); phosphate runoff^{3} (-); biological nitrogen fixation^{3} (+); soil capacity for denitrification^{1} (+); soil capacity for remediating excess phosphorus^{1} (+);
Improve herbicide-use efficiency 2.0 ± 1.00 (n=2)	incidence of weed species^{3} (-); incidence of invasive species^{1} (-)

Continuation Table 6.2

Category: Labour and Technology Efficiency	
Technology accessible & affordable to producers 6.3 ± 8.39 (n=3)	access to appropriate technology^{16} (+); number of technologies adopted on farm over time^{2} (+); percentage of farmers adopting a technology^{1} (+)
Permits labour flexibility & efficiency 2.0 ± 1.29 (n=7)	labour reduction (time to perform a task)^{4} (+); hired labour^{3} (±); family labour^{3} (±); availability of labour^{1} (+); locally sourced labour^{1} (+); labour intensity^{1} (+); farmer work/life balance^{1} (+)
Ideal technology existent for practice 3.6 ± 3.85 (n=8)	use of improved crop varieties^{11} (+), resource use efficiency^{8} (+); use of improved livestock varieties^{4} (+); input intensity^{2} (+); attitude towards technology^{1} (+); percent of land on which technology has been adopted^{1} (+); total factor productivity^{1} (+); capital productivity^{1} (+)
Category: Increased Production	
Increase crop & landscape intensity 6.3 ± 3.77 (n=7)	yield(t/ha)^{13} (+); increase in yields^{8} (+); yield (kg)/input used^{7} (+); cropping intensity^{6} (+); land use intensity^{6} (+); percentage of land under production^{2} (-); percent of land in productive use throughout the year^{2} (+)
Closing yield gaps 7.7 ± 4.61 (n=3)	Yield of each agricultural product^{13} (+); yield gap^{5} (-); variability in yield^{5} (-)
Improving yield quality 2.2 ± 1.39 (n=9)	nutritional status^{5} (+); calories producer/ha^{4} (+); protein per unit/ha^{2} (+); food safety^{2} (+); incidence in pesticides in food^{2} (-); Incidence of mycotoxins in food^{2} (-); nutrient quality of fodder^{1} (+); incidents of food borne diseases^{1} (-); calorific value/ha^{1} (+)
Category: Short-Term Profitability	
Reduce natural and manmade risks 1.5 ± 0.67 (n=12)	farm level food stores^{3} (+); planting cover strips and field buffers^{2} (+); price shocks^{2} (-); environmental climate shocks and anomalies^{2} (-); imports of fodder^{2} (-); rainfall variability^{1} (-); altered fire regime^{1} (-); attitude towards risk^{1} (±); attitude towards climate change^{1} (±); use of terraces^{1} (+); access to insurance^{1} (+); slope of the land above 25%^{1} (-);
Affordable initial fixed costs 3.6 ± 2.9 (n=5)	Access to credit^{8} (+); dependency on subsidies^{5} (-); financial savings^{2} (+); cost of production^{2} (-); farmer debt^{1} (-)
Practice provides competitive income for producers 4.8 ± 3.99 (n=10)	farmer income^{13} (+); non-agricultural employment^{8} (+); off-farm employment^{8} (+); value of yield of agricultural product^{7} (+); income per ha^{3} (+); profit/person day of labour^{3} (+); value per unit/ha^{2} (+); number of farmers in poverty^{2} (-); profit/unit area/unit of labour^{1} (+); attitude towards wealth^{1} (±)

* Calculated mean for number of sources per indicator per subcategory.

‡ Indicators from Mahon et al. 2017 are in order of most suggested to least suggested with number subscripts indicated number of articles referring to the indicator.

† Symbols (+), (-), and (±) represent indicators with positive, negative or neutral measurements respectively.

The framework revealed previous research lacked information on input mitigation trials and technologies, and research extension efforts for Argentine intercropping systems. Intercropping literature that relates to the framework subcategories are summarized as tables in Appendix 9.3.1(Sustainability theme) and Appendix 9.3.2 (Intensification theme) along with the integration of my findings from the sub-studies and interviews. Information from the sub-studies and interviews contributed to the social, political, and technology dimensions of the cropping practice allowing for greater coverage of subcategories within the framework. Interview resources strongly reflected politically relevant indicators related to the "Government support" subcategory. Input from interviewers revealed that political dimensions affected corn-soybean intercropping being adopted by producers in the SEBA region. The following two subsections detail the categorical findings within "Sustainability" and "Intensification" themes that were used to characterize regional corn-soybean intercropping.

6.3.2. Sustainable themed categories

6.3.2.1. Knowledge intensity

Generally, intercropping is known as a cropping practice that has been under-researched because of time, financial, and resource constraints (O'Leary and Smith 1999; Shennan 2008; Alrøe and Kristensen 2002; Vanloqueren and Baret 2009). Most intercropping studies are short-term (less than two years), and there is a lack of knowledge of the long-term outcomes of intercropping (Connolly et al. 2001; Shennan 2008). Regarding temperate intercropping research in Argentina, there is a considerable amount of information presented as peer-reviewed articles for the scientific audience – including many (> 20 articles since 2005) on SEBA corn-soybean intercropping. This information was federally funded through the INTA and CONICET that are partnered with universities, research centres, non-government organization (NGO) farm groups, and agriculture companies. Articles on corn-soybean intercropping mostly focused on production, determining natural resource use efficiencies, and observing carbon and nitrogen dynamics. Intercropping research findings were shared with producers through workshops, conferences presentations (INT D), newspapers, magazines, technical reports (Caviglia 2009), and peer-reviewed articles (Chapter 5; INT A). However, summer intercropping was studied for only a few years limiting the amount of detailed technical information that could be shared with producers.

Summer intercropping was not used by interviewed producers and practitioners for their cash cropping operations, nor did they know anyone who had (Chapter 5). Often in agricultural research (including SEBA intercropping studies), agronomic data of alternative cropping practices are acquired through on-station trials and modelling (Doré et al. 2011). Fewer research groups incentivize producers to jointly participate in developments of novel cropping practices (Doré et al. 2011). This is unfortunate because producers' involvement in agriculture developments have shown to extend knowledge, and improve the regional suitability of practices and techniques (Franzel et al. 2001; Snapp et al. 2010; Pretty et al. 2011; Darnhofer 2012; 8).

Within this case study, one of the barriers preventing producers' participation with intercropping revolved around academic research structure and government intervention (Chapter 5; INT B, E). Argentina is a leader in agricultural research and development (World Bank et al. 2015). Academics in agriculture were funded by the Argentine federal government, NGOs, and international organizations. Additionally, higher education was available to everyone through subsides allowing for a stream of people to study agriculture (Rozada and Menendez 2002). Most SEBA producers participating in a survey by Ferranzino et al. (2014) had a university degree. Producers had access to higher education facilities, agriculture services and dealerships, farmers groups, and network agencies for conventional agriculture information, advice, and support (Calviño and Monzon 2009, 59; Monzon et al. 2014; INT A, B, D,1, 2, 3, 9, 10, 18). However, producers were not supported directly by the federal government and were discouraged from trying new practices (INT E, 2). The following is a quote from a practitioner providing a reason why producers were not interested in research participation:

> *There are not many farmers with experimental plots… They [INTA] do not go with farmers, INTA they have their own fields… But the issue is that you have to be careful. That sometimes the experiments are designed by students and the guy that is producing is doing it for a living. So, if it fails or the project does not make sense, the owner is the one that is going to pay the bill.* – INT B

Producers were not subsidized. Instead, producers were heavily taxed and were regulated by policies that caused market instabilities (Caviglia et al. 2004; Nogués 2011; Calvo 2014). Without compensation, producers would be less willing to participate in trial and errors of new cropping practices while already managing economic and climate risks within their production system.

6.3.2.2. Socio-political suitability

The federal Kirchner-led government existed from 2003 to 2015 in Argentina, and they imposed a number of policies that impacted the agricultural sector. These policies included: i) importation taxes on agriculture capital and consumable inputs; ii) exportation taxes on producers (soybean 35%, corn 20%, wheat [*Triticum aestivum*] *23%, and* sunflower [*Helianthus annuus*] 32%); and iii) commodity price controls and inconsistent export levies on corn and wheat (Richardson 2009; Nogués 2011; INT B, C, E, 14, 15). Policies and regulations were put in place to fund the nation's debt burden, welfare services, and to regulate domestic market food supplies (Nogués 2011; Gallo 2012; INT A, D, E). Government policies put stronger restrictions on wheat sales than corn and sunflower, because of the greater domestic demand for wheat flour (Leguizamon et al. 2014; INT D, E, F). Stricter wheat restrictions placed SEBA producers at a disadvantage – because the region had fewer growing degree days for summer crops than northern regions resulting in lower relative yields for corn and soybean – but the SEBA region had the best conditions for wheat production in the country (Caviglia 2009; Leguizamon et al. 2014; Urcola et al. 2015; INT A, C, F). The profit margin was very narrow for wheat due to high production costs and selling at low prices (i.e. an uncompetitive domestic market) (Richardson 2009; Cavligia and Andrade 2010; Nogués 2011; INT B, C, E). It was common for producers to double-crop using wheat with second soybean in order to at least "break even" (Caviglia et al. 2004; INT D, E). Some producers avoided growing winter crops and chose to focus exclusively on soybean production (Urcola et al. 2015; INT B, D, F). Producers were compelled to grow soybean more frequently, because of the low production costs, larger profit margins, and the ability to sell on an open and stable international market for a relatively high crop price (Chapter 3 and 5; INT B, C, E). Nationally, soybean and its sub-products accounted for 26% of exported sales, 5.5% of the GDP, and 10% of tax revenue in 2013 (Frayssinet 2015).

The Kirchner-led government policies and the lack of subsidies for crop production made all producers interviewed feel they were not supported by the government (Chapter 5; INT A, C, D, E). One practitioner summarized the relationship between producers and the government with the following quote:

> *Our main problem is that the government needs money because they don't have any and they are extracting what they can and that is us … No, the government does not support us. It is anti-agriculture. We are enemies. We're their prisoners.* – INT C

Some producers and practitioners expressed that they understood the need for food supply regulation, but felt policy implementation should be proportional to farm size:

> *…the government they say that all producers have to pay taxes at the same proportion, at the same rate, and it is not good. The enterprises should pay in a bigger way than the small producers.* – INT F

> *The policies benefit big corporate producers. The small producers have a problem with this model. Taxes on the exportation makes small producers grow soybean.* – INT 2^{T}

Since the 1990s, small to medium scale farms were sold or rented due to the inability to compete with large agribusiness (Gras 2009; Gras and Hernández 2014, 343; Regúnaga and Rodriguez 2015), Farm families moved to the urban settlements and investments in rural infrastructure diminished (INT A, C, D, E). Below is a direct quote from a practitioner that expressed his frustration with the insufficient upkeep of rural infrastructure and the rural population decline:

> *But how would we get people to live in the rural areas? There are no schools, nor hospitals in the rural area, no electricity, no health care, no tv, no education.* – INT E^{T}

As of 2009, approximately 75% of grains were produced by land leaseholders in the Argentine Pampas (Leguizamon et al. 2014). In 2010, the SEBA region had 42% of land under some form lease (Urcola et al. 2015). Leases provided flexibility for renters, and the landowners received greater profits than if they were to farm it themselves (Urcola et al. 2015; Leguizmón 2016; INT A, B, D, F). The social and environmental consequence of large areas of land being leased was that renters were less likely to invest in land improvements or maintenance (Cavligia and Andrade 2010; Arora et al. 2015; Phélinas and Choumert 2017). A study by Arora et al. (2015) found that 82% of Pampean Argentinian producers who rented land were more focused on maximizing profits than maintaining the land.

Under these socio-political circumstances, corn-soybean intercropping would not be applied for land conserving purposes; rather producers would be more willing to use the practice for economic benefits (INT D, 3). Maintaining stable profits for producers during the time of the study was difficult because of the nation’s economic uncertainty (Markley 2014; INT D, F, 3, 8). Saving money was hindered because of an inflation rate of 25-30% that was unrecognized by the government – peso devaluation – and restrictions for foreign currency exchange (Markley 2014, INT D). These economic factors increased the cost of production and compelled both owners and renters to focus on short-term gains (Regúnaga and Rodriguez 2015). Until the government incentivizes producers to grow and sell crops other than soybean, summer intercropping will continue to be an uncommon practice.

6.3.2.3. Diversity and complexity

Researchers, practitioners, and producers expressed environmental and social concerns related to soybean encroachment throughout the Pampas (Calviño and Monzon 2009; 61; Barral and Maceira 2011; INT C, D, E, 2, 3, 12). Soybean cultivated areas in Argentina expanded from 1.9 Mha in 1980 to 19.7 Mha by 2013 (Monzon et al. 2014); occupying over 65% of the total 30 Mha cropped area (yieldgap 2014). The expansion of soybean cultivation altered landscapes and ecosystems by changing pastures and forests to fields (Campi 2011, 189; Barral and Maceira 2012; Leguizmón 2014; Bouza et al. 2016, 295; INT C, E). As well, soybeans have displaced other field crops including corn (yieldgap 2014; Calviño and Monzon 2009, 55). Growing soybean continuously has degraded soil structure, reduced organic matter, and increased herbicide-resistant weeds, increasing usage and expenses for fertilizers and agrochemicals (Cavligia and Andrade 2010; INT C, D, E). The combination of land use change and land degrading management practices in Argentina were estimated to cost about $ 70 US billion in ecosystem services that were equivalent to 26% of the national GDP (Bouza et al.

2016). Increased coverage of soybeans was concerning, as it connected homogenous landscapes leaving no constraints to contagious disturbances that spread through a system, such as, fire, floods, and infestations (Margosian et al. 2009).

Corn-soybean intercropping was studied in part to be an alternative practice to soybean production, to minimize economic dependency on the legume and to fragment the landscape (Coll et al. 2012; Monzon et al. 2014). Fragmenting landscapes with various crops or applying multi-cropping practices to fields are strategies used to immobilize contagious disturbances. Corn-soybean intercropping reduces disease and pest infestation frequencies within a field, by diluting vulnerable crops, creating dispersal barriers using short and tall structured crops, and modifying microclimates (Bourdreau 2013; Pamela 2014). Intercropping practices can protect crops above ground and below ground. A review by Bourdreau (2013) found that foliar fungal diseases were reduced in 73% of 200 intercropping studies, and that corn-soybean intercropping reduced vector spread of the corn viruses. Below-ground, Gao et al. (2014) discovered that in intercropping systems, corn excretions of cinnamic acid significantly suppressed red crown rot in soybean – a root bourne parasitic disease. Additionally, soils within the corn-soybean intercropping fields at the SEBA regional UIB research site were found to have microbial communities that were richer, more diverse, and more active than corresponding sole cropping systems (Bichel et al. 2016; Bichel et al. 2017). It is possible that the more complex microbial communities in intercropping systems hinder soil-bourne pathogens, although this particular subject is understudied (Shennan 2008; Wu and Zhau 2009; Bordreau 2013).

Bichel et al. (2016) suggested that greater microbial communities in corn-soybean intercrops increased organic carbon content in soils; thus improving soil health. Healthy soils improve overall biodiversity richness in an agroecosystem (Medan 2011). A biodiversity study conducted by Medan et al. (2011), in the Argentine Pampas, revealed that soybean fields had a greater proportion of herbivore insect assemblages than predatory insects. This inverse relationship was more apparent in soybean fields surrounded by other soybean fields (de la Fuente et al. 2010; Medan et al. 2011). Structural variation of intercropping enhances predatory insect habitat preventing herbivore insect infestations (Martin et al. 1989; Vandemeer 1992, 94; Shennan 2008; Sharaby et al. 2015; Lopes et al. 2015). de la Fuente et al. (2014) investigated insect assemblages in the SEBA region for sunflower-soybean intercropping and corresponding sole cropping systems. They determined insect mean abundance and richness were similar or lower in intercrops, compared to sole cropping, when similar doses of agrochemicals were applied. Chemical usage, habitat loss, cultivation expansion, and landscape homogenization are outcomes of agriculture intensification that have diminished and altered flora and fauna biodiversity in the Pampas since the 20th century (Medan 2011; Hallett et al. 2013; Hobbs et al. 2014). The use of intercropping across landscapes would inherently increase fauna and flora diversity, promote biocontrol and lower pesticide dosages used on fields.

6.3.2.4. Long-term environmental outcomes

The SEBA region had prime agriculture land suitable for both winter and summer crop cultivation. Flat plains of loess loam textured soil that was slightly acidic (~ pH 5.7) covered the region with interruptions of the Tandillas hills (Calviño and Monzon 2009, 57). These soils contained relatively high levels of SOC (28.8-38.0 g kg^{-1}) compared to rest of the Buenos Aires province (~25.4 g kg^{-1}) (Calviño and Monzon 2009, 57; Saínz-Rozas et al. 2011; INT D). Summers in the region were susceptible to water deficits; encouraging irrigation supplementation for corn production (INT C; Chapter 5). Corn-soybean intercropping and sole cropping experimental sites at UIB used irrigation prior to the year 2011. Water-use efficiency was shown to be better in the intercropping systems than sole cropping systems, in regards to higher water infiltration rates (Dyer 2010), less evaporation loss (Valenzuela et al. 2009), and improved water capture and usage by crops (Coll et al. 2012). Intercropping allowed for available water to infiltrate to deeper soil depths (Dyer 2010). Water was more efficiently used in the intercropping systems, because the crops captured water at different root depths, and the crops had different peak water demands throughout the season (Coll et al. 2012).

Water retention was also improved when organic matter increased in soils. Soil organic matter was the top suggested indicator in Mahon et al. (2017), because it plays a critical role in biological, chemical, and physical functions of agricultural soils. Other features of soil organic matter include improved cation exchange capacity, nutrient turnover, soil structure, and carbon sequestration (Reddy 2016, 85). Soil organic matter is commonly measured using soil organic carbon concentrations (Skjemstad and Baldock 2008, 225). Soil organic carbon is lowered by practices of monocropping, simple rotations and intensive tilling, as these activities increase organic matter decomposition rates (Novelli et al. 2017). Activities that diversify crops and increase crop intensity (grow more per area and time) are known to improve soil organic matter, by adding assorted crop residues to the soil. In turn, improving the organic matter quality of the soils promote carbon sequestration and lower erosion risks (Regehr et al. 2016; Bichel et al 2016; Novelli et al, 2017). Seven years of data collected from a minimal tillage corn-soybean intercropping and sole cropping site at UIB was modelled by Oelbermann et al. (2017), using the model Century. They estimated that within 100 years, soil organic carbon could increase up to 47% in corn-soybean intercropping, 21% in sole cropped corn, and 2% in sole cropped soybean systems.

The second most suggested indicator from Mahon et al. (2017) was GHG emissions. Mitigating agriculture derived GHG emissions was a top priority within SI research to reduce the agriculture sector’s carbon footprint and to minimize global warming impacts (Tilman et al. 2011). Intercropping has the potential to reduce GHGs (Sánchez et al. 2016; Tang et al.2017; Huang et al. 2017; Shen et al. 2018). However, the corn-soybean intercropping experimental trial at UIB resulted in cumulative GHGs with CO_2 equivalence to be near par (-4%; 2:3 intercropping) or greater (4 - 12%; 1:2 intercropping) than growing corn and soybean as sole crops (Chapter 4). More research is required to understand the microbial dynamics that influence the varied results between the two intercropping configurations (Regehr et al. 2015; Bichel et al. 2016; Chapter 4). As well more research on improving nitrogen-use efficiency in intercropping systems would aid in mitigation efforts to lower GHG emissions (Chapter 4).

6.3.3. Intensification themed categories

6.3.3.1. Chemical input mitigation

Pampean cropping systems predominantly used the "technological package" that relied heavily on synthetic inputs and frequent soybean production (Campi 2011, 181; INT A, D). This type of crop management has shown to induce a treadmill effect, where input rates become less effective over time, due to soil degradation and weed resistance; thus, input dosages increase and so do production costs (Binimelis et al. 2009; Leguizamón et al. 2014; INT F, 6). In the long term, this treadmill effect declines yields and increases off-site and onsite environmental and social costs (Binimelis et al. 2009; Fischer et al. 2014, 229; INT 1, 3, 9). Below is a quotation from a practitioner discussing the need to refocus Pampean crop management strategies:

> *I think that regions like this, in Balcarce, we are getting to a plateau of production and it is time for us to think, okay we will not get better production, so we can start reducing the use of inputs. I think we have to change the goal now. We can't keep thinking about increased production over increased production. Instead, we need to think how can we increase production with less inputs?* – INT A

Taking advantage of ecological relationships would lower dependence on synthetic inputs (Altieri et al. 2017). Intercropping is a practice known to enhance ecological relationships; the practice has the ability to naturally suppress weeds (Liebman and Dyck 1993; Poggio 2005; Ghosh et al. 2007), regulate nitrogen and phosphorus availability (Martin et al. 1991; Altieri et al. 2017), improve root nutrient access (Hauggard-Nielson et al. 2005; Ghaley et al 2005; Bybee-

Finley and Ryan 2018), and lower pest and disease occurrences (Carsky et al. 1994; Singh et al. 1997; Hauggard-Nielson et al. 2009; Bordreau 2013; Pamela 2014; Gao et al. 2014). The overwhelming challenge is to integrate and enhance these ecological relationships in already established large-scale cropping systems (Vanloqueren and Baret 2009; Altieri et al. 2017).

In regards to pest and nutrient management, corn-soybean intercropping research trials in the SEBA region were not designed for input-use efficiency, nor for enhancing facilitative ecological relationships (Chapter 4). Studies at UIB compared summer intercropping to sole cropping systems using the same rates of fertilizers, pesticides, and herbicides to avoid production bias. This comparative intercropping research design with the same input usage was standard in other local and international studies (Calviglia 2009; Echarte et al. 2011; Haung et al. 2017; Shen et al. 2018). Although it is a paradox, since synthetic inputs are added at rates to optimize sole cropping systems and position intercropping systems at a disadvantage.

For example, cereal-legume intercropping has been found to perform better with lower fertilizer rates than recommended rates for sole cropping (Nair et al. 1979; Martin et al. 1989; Lithourgidis 2011; Snapp et al. 2010; Yong 2018). Too much soil nitrogen inhibits legumes from fixing atmospheric nitrogen, and alternatively, soybeans will obtain soil nitrogen that was intended for corn (Ofori and Stern 1987, 58; Salvagiotti et al. 2008). International studies found that reducing nitrogen inputs in corn-soybean intercropping by 20-66% – compared to what is conventionally added to sole cropped corn – improved intercropping crop production performance and reduced input costs (Nair et al. 1979; Martin et al. 1989; Ssali 1990; Rana et al. 2001; Yong 2018). From an environmental viewpoint, lowering nitrogen additions to intercrops in SEBA would minimize excess nitrogen being used by weeds, or lost as nitrate and nitrous oxide (Lithourgidis 2011; Yong et al. 2018; Chapter 4).

All research trials for corn-soybean intercropping in the Pampas applied glyphosate, a common herbicide used in conventional cropping systems. There is much debate on the environmental and health effects of the broad spectrum weed control. However, weed resistance to the herbicide was evident in the Argentine Pampas (Bouza et al. 2016; Yanniccari et al. 2017; INT F, 6). Integrating ecological relationships with controlling weeds is ideal to avoid weed resistance, conserve field biodiversity richness, and to reduce production costs and labour demands (Shennan 2008; Chauhan et al. 2012); these intercropping components have not yet been studied in Argentina. International studies have shown that corn-legume intercropping suppresses weeds by increased canopy coverage and reducing light availability for weeds (Ofori and Stern 1987, 55; Vandermeer 1992, 127; Chauhan et al. 2012)

Structural and crop residue diversification in intercropping systems have shown to provide habitat for predatory-and-prey relationships that regulates both pests and weeds (Vandemeer 1992, 180; Shennan 2008; Chauhan et al.2012). For instance, seed predation by ground-dwelling invertebrates and small animals is a natural broad-spectrum weed control that is enhanced with cropping system complexity (Cromar et al. 1999). Corn residues have been shown to have greater seed predation than soybean residues (Cromar et al. 1999). It is suspected that corn residue enhances habitat and mobility for invertebrates; thus, corn provides physical and biological weed control benefits when intercropped with soybean. The complexity and ecological relationships within intercropping systems make the practice a good candidate, to grow more with less fertilizer, pesticides, and herbicides (Shennan 2008; Chauhan et al. 2012). Production results for modernized intercropping research are more likely conservative estimates, considering research designs and available technologies applied to modernized intercropping systems are not ideal and impede ecological relationships (Vandemeer 1992, 27).

6.3.3.2. Labour and technology

Argentinian producers have shown to be very responsive to new technologies for cash cropping (INT A, F, 3); most notably in the 1990s, during the short-lived Convertibility Plan that welcomed technology projects and programs supportive to commercializing agriculture (Campi

2011,185; Nogués 2011; Chapter 3). The successful promotion of no-tillage merited Argentina with the second highest international adoption rates (Barksy and Gelman 2009, 489; Campi 2011, 194; Calviño and Monzon 2009). Moreover, Argentina was among the first countries to use genetically modified crops. In 1996, soybeans tolerant to glyphosate were introduced and quickly adopted by the Pampean producers (Campi 2011, 188; Gras and Hernández 2014, 343; Chapter 3). Within four years, 90% of soybeans sown in Argentina were glyphosate-tolerant (Calviño and Monzon 2009). Open trade policies and the peso at par with the USD dollar supported large-scale producers to have a brief period of economic vitality, to test new technologies (Regúnaga and Rodriguez 2015). These two technologies altered the agricultural structure and landscape of the Pampas, throughout the following decade. Though adoption was rapid in the 1990s, extensive research to improve the practicality of soybean cultivation and no-tillage existed since the 1960s and 1970s (McKell and Peiretti 2004).

Corn-soybean intercropping was investigated during a time of restrictive policies towards producers. Since the early 2000s, Argentinian researchers observed production and conservational benefits of summer intercropping, but field operations were hindered by technological limitations (Caviglia 2009). Corn-soybean intercropping in the north of Buenos Aires was shown to be more productive, and operations were more flexible allowing simultaneous planting due to its warmer climate (Calviño and Monzon 2009). By comparison, the cooler climate and shorter summers in the SEBA region, limited planting times for summer intercropping operations (Calviño and Monzon 2009, 61; INT A, F). Summer intercropping planting dates needed to be staggered to avoid inter competition effects at peak growth periods. In December – a month after corn planting – soybeans were planted, within a limited time frame, to avoid yield losses. It was estimated that soybean sown after December 25th had a yield loss of 38- 60 kg ha^{-1} per day sowing delay, because of fewer growing degree days in the region (Calviño et al. 2003; Calviño and Monzon 2009, 62; La Menza et al. 2017; INT A D, B,). At the corn-soybean UIB research site, during 2012-2013 summer season, delayed planting of soybeans (December 21st) contributed to soybean yield losses of 22% as a sole crop, and 54% - 66% as an intercrop (2:3 and 1:2 configurations respectively) compared to yields from previous years (2008-2011). Within that same season, the overall yield disadvantage was -7% and -18% for the two intercropping systems, compared to sole cropping the two crops due to reduced yields of soybean (Chapter 4).

Producers preferred to use more flexible cropping practice options, to avoid economic and production losses from delayed planting by contractors, who were hired to complete field work (Urcola et al. 2015; INT A, 9, 10). The field machinery required adjustments and modifications to accommodate uneven height and staggered spacing of intercrops, accumulating additional time and labour demands from field contractors (INT A, E, F, 1, 2, 3). Additionally, harvesting intercropped systems with conventional combines were not efficient. Corn harvesting risked damage to soybean crops and the stubble of corn affected threshing quality (Caviglia 2009).

Rare was the field contractor who provided customized services for multi-cropping (INT A, F). Pampean field contractors were in high demand and they were economically incentivized to go with producers who had larger and simplified fields (Urcola et al. 2015; Chapter 5; INT A, 18); smaller producers or ones with complicated requests were more likely to have longer waits (Urcola et al. 2015; INT A). Pressure to have simplified and uniform fields was a drawback when participating in the contractor business model. However, the benefit to using contractors was having the most recent technologies available to producers (Calviño and Monzon 2009, 65; .Fischer et al. 2014, 233; INT A, B, F, 2). Recent advancements in engineering have made field equipment more flexible, autonomous, and precise, making intercropping less cumbersome (Blackmore 2008; Tey and Brindal 2012; Chapter 4). If there is more evidence showing intercropping to be more economical and practical, it is very likely technology will emerge to solve initial setbacks as shown historically with no tillage, soybean production, and double cropping in the Pampas (Calviglia 2009).

A greater barrier than mechanization for intercropping was the lack of seed varieties specialized for multi-crop environments (O'Leary and Smith 1999; Vanloqueren and Baret 2009). Corn and soybean seeds used in intercropping systems within the Argentine Pampas were varieties developed for sole crop environments. Varieties selected for intercropping were based on traits to minimize competition between the two crops (Andrade et al. 2012; INT A). Corn seeds were selected for high radiation efficiency with less leafiness that matured early (Capristo et al. 2007; Andrade et al. 2012). Soybean characteristics were inoculated, branching, radiation efficient and late to mature, to minimize nutrient competition and shade intolerance (INT A). At UIB there was an intercropping seed breeding initiative to reduce suppressive effects on soybean, but the study was unsuccessful, as described in the below quotation:

> *He was looking at breeding soybeans. He worked on the intercrop with soybean…so he was looking at the soybean plants that do not react too much to the light signals… Yea since it didn't work with the intercrop that well, they cut the line [cultivar]* – INT A

Seed varieties bred to maximize facilitative relationships in multi-crop environments would benefit intercropping productivity and operations. However, achieving varieties with these traits involves long-term investments and dedication (Vandemeer 1992, 202; Carsky et al. 1994; Singh et al. 1997; Vanloqueren and Baret 2009; Fischer et al. 2014, 315). The time to develop and characterize intercropping seed varieties was estimated to take thirty years (Vandemeer1992, 202; Singh et al. 1997); decades longer than the three to six years needed to develop sole cropped inbred varieties (Fischer et al. 2014, 187; INT D).

6.3.3.3. Increased production

In order to meet projected 2050 global demands for corn and soybean, the recommended increased production rate is 30 kg ha^{-1} yr^{-1} or 0.64% per year for corn and 19 kg ha^{-1} yr^{-1} or 0.82% per year for soybean (Fischer et al. 2014, 20). Argentine production increases were close to the recommended rate for corn and surpassed the rate for soybean (Fischer et al. 2014). Corn production in Argentina increased at a rate of 0.60% per year (1990-2010), predominantly due to yield improvements. The yield gap for corn within the SEBA region was 44.8% and shrinking due to farm (actual) yields advancing at a quicker pace than water-limited yields (rain-fed controlled site with optimal nutrient and pest control) (Fischer et al. 2014; 253, yieldgap 2014; Table 6.3). Water shortage was the main factor affecting yield gaps for corn in SEBA, and other factors included phosphorus and sulphur soil deficiencies, herbicide-resistant weeds, crop price, and transport infrastructure (Fischer et al. 2014, 232; INT 3, F). Land expansion was the predominant factor to soybean production advancing by 1.5% per year in Argentina (Fischer et al. 2014, 253; yieldgap 2014).

The yield gap for soybean in the SEBA region was 29.7%, which was within the 20-30% range for producer attainable yields (yieldgap 2014; Fischer et al. 2014, 299). Sowing pools and contractors in the Pampas attributed to the lower yield gap for soybeans (and corn) by offering high tech machinery, precision farming techniques, and the most recent crop varieties (Fischer et al. 2014, 98). The yield gap for corn-soybean intercropping could not be calculated, because data on producer's (actual) yield did not exist (Table 6.4). Nevertheless, the potential yield (irrigated with optimal water, nutrient and pest control) and water-limited yield data for intercropping were useful for comparison, with other cropping practices and for obtaining intercropping production baselines.

Intercropping was a strategy to enhance production, by using space and time more efficiently rather than through field expansion (Coll et al. 2012; Fischer et al. 2014, 48; INT A, F). SEBA corn-soybean intercropping shortened the fallow period by an average of 20 days for corn, and 46 days for soybean as sole crops (Coll et al. 2012). Intercropping extended the summer growing season; however, intercropping schemes (configuration, orientation, spacing and density) and crop types (species, variety, and maturity group) impacted overall production (Vandemeer 1992; 15; Caviligia 2009; Monzon et al. 2014). The land equivalent ratio (LER) is often used to determine whether an intercropping design had a yield advantage in comparison to growing the two crops as sole crops. When the LER is >1 then intercropping has a yield (or biomass) advantage; when the LER of < 1, intercropping is similar or is at a disadvantage (Vandermeer 1992, 19). Using corn-soybean intercropping to increase yields was successful, in the northern region of Buenos Aires, with potential yield LERs ranging from 1.05 to 1.50 (Caviglia 2009; Monzon et al. 2014).

The SEBA region had a cooler climate with an average of growing degree days equalling 983 ± 150.5 (S.D) that approached the limit of 1850 growing degree days for corn-soybean intercropping (Monzon et al. 2014). Due to the cooler climate and shorter summer, the SEBA region had lower potential yield LERs (0.95 - 1.07) with a mean of 1.03 ± 0.02 (Echarte et al. 2011; Monzon et al. 2014; Table 6.4). Within the UIB study site, the 2:3 configuration for corn-soybean intercropping was the superior design for increased production – as it produced 1.1 t/ha more corn yield than the 1:2 intercropping configuration – but soybean yields were similar between the two configurations. At the same site, the potential yield of corn when intercropped with soybean had less variance, between years compared to being sole cropped. The opposite effect occurred for soybean potential yield variance because the legume was the suppressed crop in the intercropping system.

Another important component for increasing production is crop quality, because it influences retail price, product grading, and nutritional value. Corn and soybean are global staples predominantly used for commercial livestock feed, biofuel and human food products (Bouza et al. 2016; INT C, E). Soybean as an animal feed is a high protein source (constituting 30-40% protein per bean), while, corn grain and fodder (nitrogen content of 6-9%) is utilized as a main energy source, and used for its digestibility (Prithiviraj et al. 2000; Paporotti et al. 2008). Multiple studies found that intercropping corn and soybean for livestock silage increased quality, by improving protein content (Martin et al. 1990; Paporotti et al. 2008; Sánchez et al. 2016; Baghdadi et al. 2016), fibre, and fermentation acids (Erdal et al. 2016). At the UIB study site in SEBA, Cambreri (2013) studied protein and oil content of soybean, when intercropped with corn and sole cropped. Results indicated that protein content was similar between the two cropping systems, but the oil content was significantly higher when soybeans were intercropped.

Table 6.3. Corn and soybean yield information for the southeast Argentine Pampa region from 1985-2012 and corn-soybean intercropping yield from UIB, Balcarce, Argentina, from 2008-2013.

Crop type	Potential yield (Y_p) (t/ha)	Water limited yield (Y_w) (t/ha)	Actual yield (Y_a) (t/ha)	Relative yield § (%)	Relative yield gap (%)	Water limitation index (%)
Southeast Pampa Region* (1985-2012)						
Sole cropping						
Corn	16.1	10.9 (44%)†	6.0 (29%)	55.2	44.8	32.6
1st Soybean	6.0	3.1 (48%)	2.0 (22%)	70.3	29.7	48.1
2nd Soybean		2.4 (59%)				
Intercropping at UIB, Argentina (2008-2013)‡						
Sole cropping						
Corn	12.3 (8%)	9.2 (54%)	-	-	-	25.3
Soybean	3.2 (35%)	3.0 (20%)	-	-	-	19.8
1:2 Intercrop						
Corn	7.8 (3%)	6.2 (27%)	-	-	-	27.5
Soybean	1.3 (43%)	0.7 (19%)	-	-	-	18.6
2:3 Intercrop						
Corn	8.2 (4%)	7.3 (31%)	-	-	-	31.5
Soybean	1.3 (49%)	0.7 (33%)	-	-	-	32.8

* Source from Yieldgap 2014

† temporal variability (StDev/Mean x 100)

‡ Sourced from field data collected by Echarte, L, at UIB, Argentina; Potential yields 2008-2011; water limited yields 2012-2013.

Relative yield = (Ya/Yw)×100;
Relative yield gap = (1-Ya/Yw)×100)

Absolute Yield gap = (Yw-Ya);
Water limitation index = (1-Yw/Yp)×100

Table 6.4. Corn-soybean intercropping land equivalent ratio (LER) for yield and biomass, for potential yield (irrigated) from 2007-2011, and water-limited yields (Y_p) from 2011-2012 at UIB, Balcarce, Argentina.

Cropping Practice	Mean Irrigated (Potential Y_p)	Rainfed (Water-limited Y_w)	
Season	2007-2008 to 2010-2011	2011-2012	2012-2013
	Yield Land Equivalent Ratio		
1:2 intercrop	1.05 (14.5) †‡	1.11	0.82
2:3 intercrop	1.07 (12.5)	1.27	0.93
	Shoot Biomass Land Equivalent Ratio		
1:2 intercrop	0.99 (15.0)	1.14	0.90
2:3 intercrop	1.02 (13.3)	1.20	0.97

† temporal variability (%)

‡ Sourced from field data collected by Echarte, L, at UIB, Argentina.

6.3.3.4. Short-term economics

Growing soybeans was the most economical option for Pampean producers and those participating in sowing pools. Soybean production required minimal inputs and the costs of seeds were relatively inexpensive due to relaxed patent controls (Calviño and Monzon 2009, 61; INT C, D, F, 2). Production costs of sole cropping soybean were at least 61% lower than growing corn as a sole crop (Monzon et al. 2014). Corn was associated with higher direct costs, because of the cost of seeds, and the crop was a heavy consumer of nitrogen and water requiring more fertilizer and irrigation for profitable yields (INT 9). A study by Monzon et al. (2014) calculated the direct costs and gross margins for corn-soybean intercropping compared to growing the crops in two sole cropping systems. Soybeans intercropped cost were 65% less the total cost when sole cropped, and intercropped corn was 85% less than the total cost when sole cropped. These lower costs were associated with use reductions in seeds, pesticides, fertilizers, and labour when compared to the sum of two sole cropping systems (Monzon et al. 2014). Nevertheless, the direct costs for corn-soybean intercropping were twice the amount when compared to soybeans grown as a sole crop on the same given area.

Sole corn production was a higher investment, but the yield response from irrigation and fertilizer made the cereal more profitable than sole soybean and corn-soybean intercropping (Monzon et al. 2014; INT 9; Chapter 5). Corn-soybean intercropping involved more direct costs than sole cropped soybean, but had similar profitability (Cambreri 2013; Monzon et al. 2014, INT A, B, 3). For corn-soybean intercropping to be more economically competitive: i) yield response of intercropped soybeans needed to be improved with technology advancements; and/or ii) government policies and market demands need to change. (Coll et al. 2012; Monzon et al. 2014; Chapter 5).

Intercropping is known as a smallholder strategy, to lower environmental and economic risks (Shennan 2008; Altieri et al. 2012; Boudreau 2013). The practice used has been applied to lower pest and disease incidences and to compensate for variable weather conditions, which in turn reduces long-term direct costs and improves yield stability (Hart 2000, 45; Altieri et al. 2017). Field trials in SEBA and the northern regions of the Pampas identified corn-soybean intercropping as an option to cultivate corn, when irrigation systems were not available (Coll et al. 2012; Monzon et al. 2014).

The SEBA region was prone to prolonged dry periods in the summer months causing water-stress and lowing yields in corn that was rain-fed and sole cropped (INT A, D). Producers who did not have irrigation systems avoided growing corn, to prevent economic losses, and were more likely to grow soybean more frequently (Chapter 5). Corn-soybean intercropping presented a strategy to minimize corn yield losses from water stress. For instance, the 2011-2012 growing season at UIB had 14.5% less rainfall than the ten-year average; yet rain-fed corn-soybean intercropping had an LER of 1.11 (1:2 intercropping) and 1.27 (2:3 intercropping) (Table 6.4). Both intercropping and corresponding sole crop treatments had yield losses, though intercropping had less dramatic losses for corn. Sole corn yields declined by 54%, while intercropped corn yields declined by 31-35% in comparison to previously obtained irrigated (potential) yields. Rain-fed and irrigated yields were similar for sole soybean, but soybeans declined by 30 to 42% when intercropped under rain-fed conditions. Soybean was the suppressed crop in the intercropping system; thus, it was prone to greater production losses (INT A). Nevertheless, it is ideal for the suppressed crop to be a cheaper investment.

6.3.4. Sustainable-intensive cropping practice characterization

6.3.4.1. Characterization of corn-soybean intercropping

Sustainable-intensification is a middle-way between two contrasting approaches; being in the middle, there is a spectrum of different outcomes. This spectrum results in a lack of clarity – making it difficult for researchers, policy makers and farmers – to be guided on a way forward and to prevent the use of greenwashed activities. The SI framework developed in this chapter used sustainability and intensification as two separate themes to display balance or biases between the two terms – in order to detect where a cropping practice was on the middle-way spectrum. An ideal SI cropping practice would embody elements of all four categories, for each theme, creating equal balance and synergies. Considering SI is a concept in its early phases of development, it is more likely current cropping practices developed for SI would not fulfill all categories. Instead, the cropping practices would have trade-offs and possibly have a bias towards sustainability or intensification. The categories in the framework provide descriptive features of a practice being considered as SI – to help assess the practices weaknesses and strengths – including its ability to be adopted in a given region.

Based on the framework created in this study, SEBA corn-soybean intercropping was a weak interpretation of SI. The practice had one category fulfilled in the Sustainability theme and one in the Intensification theme. There were unknowns and impracticalities restricting other categories from being fulfilled. Corn-soybean intercropping had low suitability for the SEBA region, during the time of the study. Corn-soybean intercropping was sustainable in the SEBA region in regards to diversity and complexity. Corn-soybean intercropping provided a crop management alternative, in a situation where soybeans production dependency became an environmental concern. Under the Intensification theme, the practice increased production by extending the growing season and provided a minor increase in overall yields and yield quality. Other categories had minor to major constraints preventing the practice having a stronger and more centric interpretation of SI.

6.3.4.2. Major constraints

Limited technological advancements was a large barrier preventing corn-soybean intercropping from being an ideal SI cropping practice. Investments into biotechnology and selective breeding programs for intercropping environments, specifically interspecies facilitation and shorter maturation dates would substantially progress corn-soybean intercropping production, as a SI practice. These investments into intercropping involve additional time, labour, and resources making intercropping advancements a costly endeavour. Within the past five years, soybean varieties were being developed to suit cooler climates, and this may aid with corn-soybean intercropping in the SEBA region. However, these soybean varieties that required less growing degree days were bred to expand soybean southward into the Patagonia region (Leguizamón 2014); research that is conflicting to the concept of SI. Emerging biotechnology of CRISPR/cas9 genome editing is a promising advancement to provide numerous opportunities to agriculture including intercropping (Khatodia et al. 2016; Liu et al. 2017). Heritable modification using CRISPR/Cas9 has shown to have success in both corn and soybean (Liu et al. 2017). If this technology is used for developing suitable intercropping seed varieties, it is expected to reduce time and costs in comparison to selective breeding.

Conventional mechanization caters to large-scale simplified cropping systems, but it is becoming more precise and autonomous minimizing mechanical restrictions on modern corn-soybean intercropping (Lithourgidis et al. 2011). In 2015, the federal government changed to a centre-right Macri-led presidency, they removed import substitution policies, to promote new investments and improve infrastructure (e.g. machinery, ports and silos) to the Argentine agricultural sector (Sanchez and Lopardo 2015; Williamson 2016; Gilbert and Devereux 2017). This border opening may bring in new machinery and technology – as what occurred in the 1950s and 1990s – changing Argentina's agriculture regime (Barksy and Gelman 2009, 393; Campi 2011, 185; Chapter 3). With new technology entering Argentina and enhancements to agriculture infrastructure, it is hoped that the resources will be used towards SI research and development, rather than continually intensifying cropping systems at the cost of ecological services.

6.3.4.3. Intermediate constraints

The Argentine federal government and national economic status at the time of study weakened corn-soybean intercropping potential, within the "socio-political suitability" and "short-term profitability" categories. Both government and economic positions are variables that historically changed frequently, and drastically within Argentina (Chapter 3). Intercropping research trials at UIB occurred alongside the leftist Kirchner-led presidency (2006-2013) that heavily taxed producers. By 2015, the Macri-led presidency immediately changed agriculture policies to better support producers that included lowering or removing importation taxes, crop export taxes, and crop export levies (Bronstien 2015). These changes increased corn profitability by removing levees and export tax on corn, and lowing direct costs for corn by 15% (Bronstien 2015; Williamson 2016). Corn production was competitive with soybean production under the Macri-led government. Soybean production was less incentivized to producers – the export tax of 28% remains (7% tax reduction) – with firmer regulations on genetically modified soybean patents, and soybean input costs increased due to pest and weed resistance (Williamson 2016; Rizzi 2016). Under these circumstances, corn-soybean intercropping provides more economic benefits to producers, and more government incentives compared to the previous decade. In regards to food security, new policies by the Macri government could result in less availability of corn to the local community. Although this concern also depends on economic inflation, and how much corn is sold, on the international market instead of the domestic market.

6.3.4.4. Minor constraints

Corn-soybean intercropping was shown to promote long-term environmental outcome by enhancing organic matter quality through carbon sequestration and improved water-use efficiency. However, there was limited evidence that corn-soybean intercropping mitigated GHG emissions. All corn-soybean intercropping experimental trials in SEBA were designed for potential and water-limited yields. This information is important to develop a production baseline, but reductive designed studies favoured sole cropping and hindered observations for facilitative capacities in intercropping systems. Minor changes to improve intercropping research include early-set producer engagement and other forms of experimental trials. Producer partnerships impact practices by making them more adoptable and practical to producers (Shennan 2008; Jackson et al. 2011). Encouraging producer partnerships with corn-soybean intercropping projects would broaden knowledge on land tenure, labour flexibility and yield gaps. However, producer engagement does involve some economic and risk challenges (INT A, E).

Altering experimental trial research, to focus more on input-use efficiency in intercropping systems would provide an opportunity to collect data on GHG emission reductions, keystone species habitat, ecosystem services, in-field ecological relationships, direct costs reductions, and indirect investment returns. Recently, the UIB research facility implemented a less conventional agroecological demonstration unit (UDAB) in the spring of 2017, where 40 ha of farmland was dedicated to studying agroecological principles and practices (INTA informa 2017). The UDAB site was created to investigate biophysical and economic indicators, in order to provide producers with information that can initiate agroecological transitions (INTA informa 2017). The UDAB is a promising initiative to create experimental designs, for enhancing intercropping facilitative relationships in modern intercropping systems.

6.3.5. Advancing sustainable-intensification framework for modernized cropping practices

This SI framework is a first attempt to holistically assess a modernized cropping practice within a given region through an interdisciplinary FSR approach. It is hoped a SI assessment can be moulded from this framework in future studies. It is recommended that future assessments have a greater emphasis on descriptors than scores. Scoring a cropping practice to be suitable for SI can: i) become meaningless when applied to different systems, regions, and circumstances; ii) have weighted bias towards specific indicators; iii) and decrease transparency as noted to be an issue for some sustainability assessments (Alrøe and Noe 2016; Hunter et al. 2017; Taluker et al. 2017). The benefits of using descriptors are: i) providing clarity by directly indicating a practice's sustainability and intensification features, ii) allowing for flexibility and transferability between cropping practice types, regional suitability, and local conditions; iii) encouraging continuous improvement and development of specific weaknesses; and iv) inviting the opportunity for interdisciplinary and transdisciplinary collaboration. There are hundreds of indicators that are appropriate for SI assessments, but not all are relative to a certain practice or place (Mahon et al. 2017; Weltin et al. 2018). Multiple scales of influence and circumstances affect how well a cropping practice fits as SI in one region or another. Thus, descriptors rather than scores – and using interdisciplinary/ transdisciplinary approaches – would provide more meaningful information on SI for producers, researchers, and policymakers.

6.4. CONCLUSION

The developed SI framework for cropping practices in combination with a broad scope interdisciplinary FSR approach was useful to holistically characterize corn-soybean intercropping in the SEBA Argentine Pampas. In this study, corn-soybean intercropping had both sustainable and intensification attributes, but had weak suitability as a SI for the studied region. The sustainability category – Diversity and Complexity and the intensification category – Increased Production, provided the strongest categorical rationale. The suitability of corn-soybean intercropping, as a SI practice in the SEBA region of Argentina, was constrained by limited growing degree days, social-political circumstances, technological advancements, and research limitations. A region with a supportive government and with greater than 2000 GDD would improve corn-soybean intercropping suitability, as a SI cropping practice.

The often neglected social and political dimensions of SI showed to be of great importance within the case-study, as these dimensions affected the suitability of corn-soybean intercropping. Moreover, limited knowledge and technology advancements are universal adoption barriers for intercropping. Intercropping will not meet its full capacity for resource use efficiency and increasing yields until research is dedicated to creating intercropping seed varieties, and design experiments for increased facilitative relationships between crop species.

CHAPTER 7

SUMMARY AND CONCLUSION

7.1. INTRODUCTION

Smallholders and modernized producers are incentivized to grow more using natural and synthetic resources more efficiently – and to minimizing the environmental impact of their agricultural activities – while ensuring their practices are economically viable and socially acceptable. Sustainable-intensification (SI) has been a recommended means for producers to perform this juggling act. Nevertheless, SI is difficult for producers to apply when instructions are obscure, and results from many studies do not look at SI in its entirety (Mahon et al. 2017; Weltin et al. 2018). Furthermore, researchers are still determining what is considered an SI practice (Dicks et al. 2018; Weltin et al. 2018) – suggesting SI is currently a concept than a readily applicable option.

There are many reasons to why it has been difficult to pin down which agricultural practices are considered SI. In general, agriculture is multi-faceted, because it combines both the natural and human-made realms that result in interconnections between distinctive disciplines. It is challenging for researchers to investigate agriculture activities broadly in a disciplinary sense, due to resource accessibility, time availability, and knowledge gap constraints; yet SI research necessitates looking at all dimensions (Mahon et al. 2017; Weltin et al. 2018). For instance, SI cropping practices depend on regional settings, past and current land management practices, producers decisions, and historical developments. These factors involve both the biophysical environment and social circumstances at various scales (Weltin et al. 2018). Since the 1990s, research on SI practices was more often conducted at the field-scale, limited to a number of growing seasons, to investigate biophysical features (Mahon et al. 2017).

This research approach is useful to gain in-depth knowledge on specific features of an SI practice. To complement the field-scale research Weltin et al. (2018) recommended applying multi-scalar research to understand the real-world impacts of SI cropping practices. For example, the collective decisions by producers on how they manage their fields can impact the environment, economy, or culture at larger scales. (e.g. water quality, greenhouse gas emissions, biodiversity, food security and international trade).

This doctoral research evaluated an emerging SI cropping practice, within the southeast Buenos Aires (SEBA) region of Argentina, in a multi and interdisciplinary manner incorporating both qualitative and quantitative methods at multiple scales. The following section restates the main research question of this dissertation with supporting findings and conclusions. Subsequently, this chapter reflects on the research contributions, shares research opportunities, and provides recommendations for future research on SI cropping practices and modernized corn (*Zea mays*)-soybean (*Glycine max*) intercropping.

7.2. DISSERTATION SUMMARY AND FINDINGS

This dissertation evaluated whether or not *modernized corn-soybean intercropping is a suitable sustainable-intensive cropping practice for the SEBA region?* Within the means of suitability, the cropping practice needed to be adoptable and practical to producers in the study region, and exhibit characteristics that defined SI. A broad-scale mixed-method approach influenced by the Farming System Research (FSR) was used to answer this main research question.

This dissertation found that corn-soybean intercropping at the time of the study was not a suitable SI cropping practice, for producers of the SEBA Pampas. The cropping practice had poor adoptability with respect to producers due to: i) national economic and political circumstances; ii) the inability to compete with sole-crop soybean economic and labour advantages; and iii) the subregion's cool climate that caused rigid planting-times and limited production (Chapter 3 and Chapter 5).

According to the developed framework, corn-soybean intercropping was characterized as a weak interpretation of SI (Chapter 6). However, the practice did exhibit a sustainability feature and an intensification feature. The corn-soybean intercropping practice provides a measure of sustainability through landscape, structural, crop species and soil biota diversity and complexity, and is a midway field-strategy to reduce soybean encroachment. Increased production was the intensification feature that corn-soybean intercropping demonstrated. The practice increased the length of the growing season, increased land-use intensity, maintained yields close to sole cropping, and improved yield quality in soybean.

Activities assessed for SI often have the social, political, and economic dimensions underutilized, with the biophysical aspects being the main foci. Within this case study, the main adoption barriers were associated with the socio-political and economic dimensions. This finding gives support to the importance of using holistic, interdisciplinary methods to study SI. Corn-soybean intercropping would likely have higher uptake in a warmer region with evenly distributed rainfall during the summer months, and where implemented policies provide support towards producers and incentivize SI innovations.

The field-scale study (Chapter 4) did not cover many of the categories identified in the developed SI framework but did provide data within one subcategory (mitigate GHG emissions and improve energy efficiency) of the "long-term environmental outcome" category. Also, this natural sciences study (Chapter 4), demonstrated the complexity involved in intercropping research and design. Intercropping systems within this study emitted similar soil-derived carbon dioxide (CO_2) emissions compared to sole crops. The 2:3 intercropping configuration had similar nitrous oxide (N_2O) emissions as the sole crops. In contrast, the 1:2 intercropping configuration had significantly higher N_2O emissions. Results indicate that 2:3 intercropping had more GHG mitigation potential than the 1:2 intercropping configuration. However, the 2:3 intercropping system did not display a meaningful reduction in cumulative GHG emissions (3% lower than combined sole crops). Similarly to my findings, Regehr et al. (2015) and Bichel et al. (2016) − who conducted carbon and nitrogen dynamics research at the same site − concluded that the 1:2 intercropping configuration was inferior to the 2:3 intercropping, in regards to components that affect long-term environmental outcomes.

Moreover, results from the natural sciences study brought attention to indicators within other categories of the SI framework; these categories were “Increased production” and “Chemical input mitigation”. The research site for corn-soybean intercropping at the UIB research station was designed to allow evaluation of potential yields (water, nutrient, and pest control sufficient) and on water-limited yields (nutrient and pest control sufficient). Fertilizers were added at the same rate for the sole-crop corn and the intercropping treatments, to avoid production bias. However, the sole-crop soybean treatment had no nitrogen fertilizer added as this would affect the legume’s nitrogen fixation capabilities. This land management design for intercropping investigations reflected poorly in the “Chemical input mitigation” category of the SI framework (Chapter 6). Alternatively, this intercropping research design supplied information to the “Increased production” category regarding yield progression, variability in yield, and land equivalent ratios. Previously research on corn-soybean intercropping within the SEBA region, the Pampas and internationally, predominantly studied biophysical variables at the field scale and their findings were useful to evaluate the cropping practice in other subcategories of the developed SI framework.

7.3. CONTRIBUTIONS TO RESEARCH

7.3.1. A conceptual framework for studying sustainable-intensification

The FSR approach has no set framework, but contains three core characteristics – systems thinking, multi/interdisciplinary perspectives and inclusions of social actors.

Comprehensively applying all three characteristics into a single dissertation is recognized as very challenging (Darnhofer et al. 2012, 17). The conceptual framework of this dissertation incorporated all three FSR characteristics to assess the adoptability and development of a potential SI cropping practice. The conceptual framework applied (Figure 1.1) was flexible and can be used to study the same cropping practice with different areas of emphasis (i.e. economic, policy, or technology). The conceptual framework demonstrated to be a useful mapping tool for this dissertation, with the potential to transcend and assist research groups that are multi-disciplinary, interdisciplinary, or transdisciplinary.

7.3.2. Development of the intercropping greenhouse gas interpretation tool

Global interest in mitigating GHG emissions from cultivated soil is a growing sustainability issue. Previous studies expressed there was potential for intercropping to mitigate GHG emissions. However, the crop type, configuration, row spacing, density, and added inputs affect the mitigation potential of the practice. The land equivalent ratio (LER) exists to evaluate the intensification of intercropping compared to sole cropping, and to my knowledge, there are no comparison calculations that focus on its performance for environmental sustainability features. In the natural sciences study (Chapter 4), the Intercropping GHG Interpretation (IGI) was presented as a ratio calculation to evaluate the GHG mitigation performance of intercropping, in comparison to the sum of crops grown using sole cropping. The IGI tool was useful in comparing various intercropping configurations during contrasting weather scenarios and at seasonal and monthly temporal scales. Within this case study, the IGI showed that the 1:2 corn-soybean intercropping configuration had poor GHG mitigation potential compared to the 2:3 configuration. Monthly IGI values identified periods when GHGs were higher or lower than sole cropping, and this information aids in identifying sources of emissions and modifying intercropping designs to have a lighter carbon footprint.

7.3.3. Gaining perspective during the emergence of modern intercropping

The social sciences study (Chapter 5) utilized perspectives from crop producers and agricultural practitioners to gain insight, on dimensions that are often underrepresented in SI literature (Alteiri 2017; Weltin et al. 2018). Most studies assessing producers' perspectives select participants who have already adopted the cropping practice being investigated, or selected a practice that has been well established regionally for many years. The social sciences study in this dissertation was unique compared to other perspective based cropping practices studies, as it focused on the emergence of participation in intercropping. The findings from this study gave insight into what motivates early adoption. In the case of SEBA producers, they were very responsive to introduced technologies (i.e. no-tillage, transgenic seeds, and double cropping), but their choice to adopt a practice was based on profitability, government restrictions, economic risks, and conveniences for outsourced labour. These insights on producer adoption aid in future research and developments for modernized corn-soybean intercropping, in SEBA and other more suitable regions. As well, these results inform developments of new and other potential SI cropping practices within the SEBA region.

7.3.4. Developed a framework to characterize sustainable-intensive cropping practices

There are no specific instructions on how to develop and implement SI practices because regional suitability needs to be considered. Without a structured framework, the concept of SI is ambiguous and can lead to obstructive policy making (Wezel et al. 2015). In this dissertation, a descriptive framework for characterizing features of SI in a cropping practice was created for these purposes: i) to be flexible with regional suitability and cropping practice type; ii) to incorporate multi-scales and scopes; and iii) to promote a balance between sustainability and intensification features of a cropping practice. Currently, this is the only SI framework that considers whether a practice is a weak or strong representation of SI. This preliminary framework is a tool that provides structure for both researchers and policymakers for when they are identifying why a cropping practice should be considered SI, and avoid greenwashed activities from using the term.

7.3.5. Holistically assessed modern corn-soybean intercropping as a sustainable-intensive cropping practice

Using the developed SI suitability framework, I was able to bridge the multiple dimensions (scales and disciplines) that are embedded in the concept of SI, to assess a cropping practice holistically. The findings from this assessment contribute to identifying regional suitability characteristics for corn-soybean intercropping; as well, identify main knowledge gaps, that if addressed, could improve the adoptability of the practice and enhance its SI features.

7.4. STUDY OPPORTUNITIES

7.4.1. The array of research option and variations

Multi and interdisciplinary methods used to study FSR and the concept of SI are varied. These two subjects are multifaceted – and consequently demand extended time and effort from a researcher (trained in one discipline) to understand the assumptions, methodologies, and paradigms of other disciplines (Darnhofer et al. 2012, 16). This dissertation covered the breadth and depth of the subject matter. However, this case-study could have been evaluated in many other ways. For instance, one pathway could focus on an in-field study to reduce agrochemical inputs in intercropping systems, which would provide information for the input mitigation category of the SI framework. However, exploring this and other hypothetical pathways was outside the scope of this dissertation.

7.4.2. Regional suitability is time sensitive

Results from the developed SI framework are time sensitive due to factors related to regional suitability. At the time of the study (2011-2013), government intervention strongly affected corn-soybean intercropping adoptability. By 2015, the government changed and so did policies. New policies were supportive of producer and agricultural innovation; the Government of Argentina removed export taxes and levies on corn and wheat (*Triticum aestivum)*, provided debt relief programs for producers, and added equipment and technology investment incentives (Bronstien 2015; Williamson 2016). These changes in policies would affect producers' and practitioners' perceptions of the barriers and opportunities for intercropping adoption.

At the time of the present study, some indicators were unknown when assessing corn-soybean intercropping. The framework highlighted these research gaps, and future studies can respond to these remaining indicators. For example, the recently established (2017) agroecological demonstration unit (UDAB) in SEBA is a promising opportunity, for research on facilitative relationships in intercropping systems.

7.5. FUTURE RESEARCH AND RECOMMENDATIONS

7.5.1. Incorporate knowledge gaps in intercropping investigations

As mentioned previously, future intercropping studies are recommended to be more holistic. It is encouraged that corn-soybean intercropping experimental designs are modified to reach the goals of making the practice a stronger representation of SI. The two research gaps stressed throughout this dissertation was input mitigation research and enhancing intercropping technology for multi-cropping environments. Some technologies include: enhancing agroecological engineering to improve facilitative relationships in intercropping systems; the development of multi-cropping specific seed varieties; and constructing flexible autonomous mechanization that reduces labour requirements associated with intercropping. Research in both technology and input mitigation would contribute to developing more suitable SI cropping practices, and likely transform the Pampean agriculture regime.

7.5.2. Include social actors and political dimensions when developing sustainable-intensive cropping practices

This dissertation demonstrated that the socio-political dimension was strongly influential in the adoption of corn-soybean intercropping. Policies put in place created economic risks for crop producers and affected the profitability of the intercropping practice. The inclusion of the socio-political dimensions and producers participations, during early developments of novel SI cropping practices is greatly encouraged, to ensure adoptability under specific social circumstances. Collaborations between researchers, producers, and stakeholders have shown, in the past, to break down barriers that affected cropping practices introduced in Argentina (e.g. no-tillage and soybean production). Greater collaborations and investments in summer intercropping can resolve technology, labour efficiencies, and production issues associated with the practice.

7.5.3. Compare assessment results with other regions and other cropping practices

It would be interesting to apply the developed SI framework (Chapter 6) to corn-soybean intercropping within other Pampean regions. In particular, the northern Pampean regions (northern Buenos Aires, and Entre Rios and Cordoba provinces), where the climate is warmer and producers are capable of planting corn and soybean simultaneously. Studying modernized corn-soybean intercropping in other countries, such as China, the USA, or Uruguay would be beneficial, as they would have distinctive political and economic circumstances compared to Argentina. Additionally, comparing SI characterization results of corn-soybean intercropping with other cropping practices would be insightful, to determine which cropping practice best suits the SEBA region.

7.6. CONCLUDING REMARKS

This doctoral research used a mixed-method approach to overcome challenges in studying SI holistically and at multiple scales. Corn-soybean intercropping in SEBA was characterized as a weak SI cropping practice with poor adoptability within the Argentine Pampas subregion. Intercropping is an emerging practice within the Pampas. Continued research and investment towards intercropping give an opportunity for the practice to be a more suitable SI practice for Pampean crop producers, or crop producers from other regions. Economics, politics, and technology were the main facets that affected the practice's adoptability in the SEBA region. Identifying barriers within these facets help guide producers, researchers, and stakeholders towards solutions to improve the practice.

There is growing interest in modernized intercropping in Argentina, as well as in Europe, China, and Canada, as a way to increase production per land, area and time, improve yield quality, and minimize the environmental impact of agricultural activities. According to Borserup's (1987) theory, the increasing pressure of population growth is expected to generate more collaborations to solve problems and develop technologies to improve crop production. Intercropping has already demonstrated its ability to use natural resources efficiently. Continued breakthroughs and innovations will help modify intercropping, shaping the practice to be a viable strategy to aid future food security.

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9. APPENDICES

9.1. QUANTITATIVE STUDY DATA

Valid and missing data summaries

2011-2012 data summary Table 9.1.1
2012-2013 data summary Table 9.1.2

Seasonal variable descriptives

CO_2 emissions 2011-2012 and 2012-2013 Table 9.1.3
N_2O emissions 2011-2012 and 2012-2013 Table 9.1.4
Soil WFPS 2011-2012 and 2012-2013 Table 9.1.5
Soil temperature 2011-2012 and 2012-2013 Table 9.1.6

Weekly variable descriptives in 2011-2012

CO_2 emissions 2011-2012 Table 9.1.7
N_2O emissions 2011-2012 Table 9.1.8
Soil WFPS 2011-2012 Table 9.1.9
Soil temperature 2011-2012 Table 9.1.10

Weekly variable descriptives in 2012-2013

CO_2 emissions 2012-2013 Table 9.1.11
N_2O emissions 2012-2013 Table 9.1.12
Soil moisture 2012-2013 Table 9.1.13
Soil temperature 2012-2013 Table 9.1.14

Soil nitrogen concentrations descriptives 2012-2013 Table 9.1.15

Valid and missing data summaries

Table 9.1.1. Summary of valid and missing data for CO_2 emissions, N_2O emission, soil water-filled pore space, and soil temperature from the corn-soybean cropping system experimental site during November 2011-May 2012 at UIB, Balcarce, Argentina.

	Valid		Missing		Total	
2011-2012	N	%	N	%	N	%
CO_2 emissions	613	98.2	11	1.8	624	100
N_2O emissions Nov.- May	372	59.6	253	40.1	624	100
N_2O emissions Jan. - May	372	96.9	12	3.1	384	100
Water filled pore space	573	91.8	51	8.2	624	100
Soil temperature	623	99.8	1	0.2	624	100

Table 9.1.2. Summary of valid and missing data for CO_2 emissions, N_2O emission, soil water-filled pore space, and soil temperature from the corn-soybean cropping system experimental site during December 2012 - May 2013 at UIB, Balcarce, Argentina.

	Valid		Missing		Total	
2012-2013	N	%	N	%	N	%
CO_2 emissions	553	96.0	23	4.0	576	100
N_2O emissions Dec - May	558	96.9	18	3.1	576	100
N_2O emissions Jan - May	398	97.5	10	2.5	408	100
Water filled pore space	550	95.5	26	4.5	576	100
Soil temperature	551	95.7	25	4.3	576	100

Seasonal variable descriptives

Table 9.1.3. Descriptives for CO_2 emissions (kg C ha^{-1} d^{-1}) collected from chamber measurements in corn-soybean sole crops and intercrops in Balcarce, Argentina during growing seasons 2011-2012 and 2012-2013. Uppercase letters represent the comparison of treatment between growing seasons. Lowercase letters represent the analysis of treatments within a growing season. Non-matching letters indicate significant differences (α = 0.05 ; 95% confidence interval).

CO_2-C emissions descriptives (kg C ha^{-1} d^{-1})

					95% Mean C.I			
Treatment	N	Mean	SD	SE	L.B	U.B	Min.	Max.
Growing season 2011-2012								
Sole Corn	156	$27.7^{a,A}$	14.51	1.16	25.4	30.0	8.2	75.9
Sole Soybean	150	$29.9^{a,b,A}$	13.00	1.06	27.8	32.0	7.7	65.5
1:2 Intercrop	152	$32.7^{b,A}$	15.51	1.26	30.1	35.1	5.3	81.0
2:3 Intercrop	155	$28.9^{a,b,A}$	16.50	1.33	26.2	31.5	5.6	86.5
Total	613	29.7^{A}	15.02	0.61	28.5	30.9	5.4	86.5
Growing season 2012-2013								
Sole Corn	141	$24.3^{d,B}$	12.57	1.06	22.2	26.4	6.2	59.1
Sole Soybean	134	$26.3^{d,B}$	11.91	1.03	24.3	28.3	5.7	80.3
1:2 Intercrop	138	$25.6^{d,B}$	13.96	1.19	23.3	28.0	6.8	79.9
2:3 Intercrop	140	$23.8^{d,B}$	12.26	1.04	21.8	25.9	3.6	61.7
Total	553	25.0^{B}	12.71	0.54	23.9	26.1	3.6	80.3

Table 9.1.4. Descriptives for N_2O-N emissions (g N ha^{-1} d^{-1}) collected from chamber measurements in corn-soybean sole crops and intercrops in Balcarce, Argentina during growing seasons 2011-2012 and 2012-2013. Uppercase letters represent the comparison of treatment between growing seasons. The comparison between growing seasons was analyzed for sampling dates between Jan – May. Lowercase letters represent the analysis of treatments within a growing season. Non-matching letters indicate significant differences (α = 0.05 ; 95% confidence interval).

N_2O-N emissions descriptives (g N_2O-N $ha^{-1}d^{-1}$)

					95% Mean C.I			
Treatment	N	Mean	SD	SE	L.B	U.B	Min.	Max.
Growing season 2011-2012 (Jan 22 – May 7)								
Sole Corn	93	$6.7^{a,A}$	9.14	0.95	4.8	8.6	-6.1	40.1
Sole Soybean	92	$4.4^{a,A}$	5.83	0.61	3.2	5.6	-4.0	33.7
1:2 Intercrop	92	$10.5^{b,A}$	10.38	1.08	8.3	12.6	-2.6	44.1
2:3 Intercrop	95	$5.2^{a,A}$	6.39	0.66	3.9	6.5	-6.1	37.4
Total	372	6.7^{A}	8.44	0.44	5.8	7.5	-6.1	44.1
Growing season 2012-2013 (Jan 22- May 14)								
Sole Corn	101	$1.8^{d,B}$	2.70	0.27	1.3	2.4	-8.3	12.7
Sole Soybean	97	$4.0^{e,A}$	4.66	0.47	3.1	5.0	-4.7	20.2
1:2 Intercrop	99	$4.7^{d,e,B}$	7.63	0.77	3.2	6.2	-5.7	33.6
2:3 Intercrop	101	$2.8^{d,e,B}$	4.30	0.43	2.0	3.7	-3.9	26.6
Total	398	3.3^{B}	5.23	0.26	2.8	3.9	-8.3	33.6
Growing season 2012-2013								
Sole Corn	142	6.3^{d}	17.04	1.43	3.5	9.1	-8.3	154.2
Sole Soybean	135	$6.1^{d,e}$	8.77	0.75	4.6	7.6	-4.7	56.4
1:2 Intercrop	139	12.0^{e}	21.21	1.80	8.4	15.6	-5.7	170.1
2:3 Intercrop	142	$7.9^{d,e}$	17.88	1.50	4.9	10.8	-4.0	158.4
Total	558	8.1	17.03	0.72	6.7	9.5	-8.3	170.1

Table 9.1.5. Descriptives for soil water-filled pore space (WFPS) calculated from soil moisture content and bulk density (%) in corn-soybean sole crops and intercrops in Balcarce, Argentina during growing seasons 2011-2012 and 2012-2013. Uppercase letters represent the comparison of treatment between growing seasons. Lowercase letters represent the analysis of treatments within a growing season. Non-matching letters indicate significant differences (α = 0.05 ; 95% confidence interval).

Soil water-filled pore space (%)

					95% Mean C.I			
Treatment	N	Mean	SD	SE	L.B	U.B	Min.	Max.
------------------------------------Growing season 2011-2012----------------------------------								
Sole Corn	144	$30.7^{a,A}$	13.63	1.14	28.4	32.9	2.0	62.1
Sole Soybean	141	$29.6^{a,A}$	11.23	.94	27.8	31.5	1.2	54.6
1:2 Intercrop	144	$29.3^{a,A}$	12.48	1.04	27.3	31.4	3.3	55.9
2:3 Intercrop	144	$25.3^{b,A}$	12.74	.98	23.4	27.2	1.8	63.1
Total	574	28.7^{A}	12.44	.52	27.7	29.7	1.2	63.1
------------------------------------Growing season 2012-2013----------------------------------								
Sole Corn	137	$37.0^{d,B}$	12.37	1.06	34.9	39.1	8.5	63.3
Sole Soybean	138	$38.9^{d,B}$	12.87	1.10	36.8	41.1	11.0	67.9
1:2 Intercrop	138	$37.9^{d,B}$	11.82	1.01	35.9	39.9	11.2	63.4
2:3 Intercrop	137	$38.8^{d,B}$	11.90	1.02	36.8	40.8	8.4	66.3
Total	550	38.2^{B}	12.24	.52	37.1	39.2	8.4	67.9

Table 9.1.6. Descriptives for soil temperature (°C) collected in corn-soybean sole crops and intercrops in Balcarce, Argentina during growing seasons 2011-2012 and 2012-2013. Uppercase letters represent the comparison of treatment between growing seasons. Lowercase letters represent the analysis of treatments within a growing season. Non-matching letters indicate significant differences (α = 0.05 ; 95% confidence interval).

Soil temperature (°C)

					95% Mean C.I			
Treatment	N	Mean	SD	SE	L.B	U.B	Min.	Max.
------------------------------------Growing season 2011-2012----------------------------------								
Sole Corn	156	$25.2^{a,A}$	7.82	0.63	24.0	26.5	11.6	44.0
Sole Soybean	156	$25.9^{a,A}$	8.68	0.69	24.6	27.3	11.2	47.0
1:2 Intercrop	156	$25.6^{a,A}$	8.01	0.64	24.3	26.9	11.4	45.0
2:3 Intercrop	155	$25.7^{a,A}$	7.96	0.64	24.4	27.0	10.9	44.0
Total	623	25.6^{A}	8.11	0.32	25.0	26.3	10.9	47.0
------------------------------------Growing season 2012-2013----------------------------------								
Sole Corn	138	$21.4^{d,B}$	6.71	0.571	20.29	22.55	10.4	38.6
Sole Soybean	138	$22.8^{d,B}$	7.47	0.636	21.56	24.07	10.4	36.8
1:2 Intercrop	138	$22.4^{d,B}$	6.67	0.568	21.33	23.58	10.4	37.7
2:3 Intercrop	137	$21.3^{d,B}$	6.61	0.565	20.23	22.46	10.1	37.7
Total	551	22.0^{B}	6.88	0.293	21.43	22.58	10.1	38.6

Weekly variable descriptives in 2011-2012

Table 9.1.7. Descriptives for weekly CO_2-C emissions (kg CO_2-C ha^{-1} d^{-1}) collected during chamber measurements in corn-soybean sole crops and intercrops from December 2011-May 2012 in Balcarce, Argentina. C and S represent sole corn and sole soybean agroecosystems respectively, and 1:2 intercrop represents the intercropping design of 1-row corn to 2 rows soybeans, and 2:3 intercrop 2 rows corn and 3 rows soybeans. Non-matching letters indicate significant differences (α = 0.05 ; 95% confidence interval).

Date & Treatment		N	$\bar{x}$	S.D	S.E	Min	Max	Date & Treatment		N	$\bar{x}$	S.D	S.E	Min	Max
25-NOV-11	C	6	41.0^{ab}	8.70	3.55	31.8	55.5	03-JAN-12	C	6	23.7	2.62	1.07	19.6	26.7
	S	6	21.7^{b}	8.88	3.63	9.9	33.2		S	6	30.3	7.51	3.06	16.6	38.8
	1:2	6	47.3^{a}	13.67	5.58	28.6	61.4		1:2	6	32.4	8.21	3.35	15.9	38.4
	2:3	6	44.7^{a}	17.07	6.97	28.4	73.4		2:3	6	23.4	5.63	2.30	18.6	32.8
	Total	24	38.7	15.59	3.18	9.9	73.4		Total	24	27.4	7.20	1.47	15.9	38.8
29-NOV-11	C	6	49.6^{a}	11.05	4.51	31.5	60.4	12-JAN-12	C	6	26.0	7.92	3.23	16.4	34.7
	S	6	24.8^{b}	7.34	3.00	16.4	32.4		S	6	37.4	7.15	2.92	29.5	48.8
	1:2	6	49.3^{a}	10.32	4.21	33.0	60.8		1:2	6	39.4	14.27	5.83	12.6	50.6
	2:3	6	51.0^{a}	12.00	4.90	34.0	65.3		2:3	6	22.9	10.95	4.47	13.5	40.8
	Total	24	43.7	14.73	3.00	16.4	65.3		Total	24	31.4	12.16	2.48	12.6	50.6
04-DEC-11	C	6	48.1^{ab}	11.49	4.69	36.5	69.6	17-JAN-12	C	6	20.1	7.03	2.87	10.4	30.1
	S	6	24.8^{a}	14.62	5.97	7.7	45.0		S	6	25.2	11.08	4.52	15.5	44.5
	1:2	6	50.0^{ab}	18.42	7.52	32.5	81.0		1:2	6	24.5	5.52	2.25	15.2	29.1
	2:3	6	57.2^{b}	19.47	7.95	32.1	86.5		2:3	6	18.7	5.23	2.14	8.5	22.2
	Total	24	45.0	19.64	4.01	7.7	86.5		Total	24	22.1	7.62	1.55	8.5	44.5
08-DEC-11	C	6	34.6	14.48	5.91	25.6	63.5	22-JAN-12	C	6	50.0	13.83	5.65	37.6	75.8
	S	5	31.1	5.35	2.39	27.1	40.5		S	5	45.3	9.81	4.39	30.9	55.8
	1:2	6	36.9	11.82	4.83	21.1	52.2		1:2	6	52.5	4.89	2.00	44.8	57.7
	2:3	6	51.0	14.23	5.81	31.9	69.9		2:3	6	38.1	10.95	4.47	23.3	56.3
	Total	23	38.7	13.82	2.88	21.1	69.9		Total	23	46.5	11.25	2.34	23.3	75.8
14-DEC-11	C	6	28.6	7.60	3.10	19.9	40.8	31-JAN-12	C	6	23.8	2.85	1.16	20.3	27.9
	S	5	32.7	7.91	3.54	24.7	45.5		S	5	28.9	11.51	5.15	13.5	45.0
	1:2	6	45.9	7.19	2.94	34.5	55.2		1:2	5	27.1	6.63	2.96	16.5	33.0
	2:3	6	39.0	18.29	7.47	26.2	63.8		2:3	5	24.0	3.49	1.56	19.6	28.4
	Total	23	36.7	12.57	2.62	19.9	63.8		Total	21	25.9	6.67	1.46	13.5	45.0
20-DEC-11	C	6	39.4	4.95	2.02	30.8	44.3	07-FEB-12	C	6	20.2	6.45	2.63	12.9	31.1
	S	6	49.5	7.85	3.20	37.8	58.3		S	6	24.6	9.72	3.97	13.0	39.3
	1:2	6	54.3	8.93	3.64	38.7	63.2		1:2	5	28.3	6.51	2.91	18.0	34.4
	2:3	6	41.6	17.35	7.08	14.2	59.7		2:3	6	18.8	3.63	1.48	14.8	24.4
	Total	24	46.2	11.78	2.40	14.2	63.2		Total	23	22.7	7.46	1.55	12.9	39.3
27-DEC-11	C	6	23.4^{a}	5.53	2.26	15.8	31.0	16-FEB-12	C	6	16.2	3.24	1.32	11.0	20.3
	S	6	38.2^{b}	9.54	3.90	27.6	53.6		S	6	18.1	6.29	2.57	10.0	27.8
	1:2	6	29.5^{ab}	7.55	3.08	19.0	37.9		1:2	6	17.3	5.37	2.19	11.2	25.6
	2:3	6	27.3^{ab}	9.57	3.90	17.6	43.1		2:3	6	12.6	2.05	.83	10.3	15.3
	Total	24	29.6	9.46	1.93	15.8	53.6		Total	24	16.1	4.76	.97	10.0	27.8

Continuation of Table 9.1.7 - Descriptives for weekly CO_2-C emissions (kg CO_2-C ha^{-1} d^{-1}) 2011-2012.

Date & Treatment		N	$\bar{x}$	S.D	S.E	Min	Max	Date & Treatment		N	$\bar{x}$	S.D	S.E	Min	Max
22-FEB-12	C	6	38.6	5.66	2.31	33.2	47.2	03-APR-12	C	6	12.6	2.26	.92	9.7	15.4
	S	6	42.8	13.82	5.64	26.1	62.2		S	6	20.2	6.02	2.46	12.3	27.0
	1:2	6	45.2	9.89	4.04	28.7	56.5		1:2	6	19.3	5.00	2.04	12.3	25.7
	2:3	6	34.4	9.87	4.03	20.8	50.7		2:3	6	15.8	5.14	2.10	9.5	23.6
	Total	24	40.2	10.42	2.13	20.8	62.2		Total	24	17.0	5.46	1.11	9.5	27.0
28-FEB-12	C	6	29.4^{ab}	10.45	4.27	16.0	44.8	10-APR-12	C	6	18.4	8.36	3.41	12.4	35.0
	S	6	43.2^{a}	10.27	4.19	30.3	53.7		S	6	24.1	4.47	1.82	17.6	29.3
	1:2	6	32.9^{ab}	7.61	3.11	18.3	39.2		1:2	5	24.1	5.80	2.59	16.6	30.6
	2:3	6	25.3^{b}	5.52	2.25	16.9	31.6		2:3	6	17.5	5.76	2.35	12.8	25.3
	Total	24	32.7	10.58	2.16	16.0	53.7		Total	23	20.9	6.63	1.38	12.4	35.0
06-MAR-12	C	6	53.8	11.49	4.69	30.6	61.8	16-APR-12	C	6	13.6^{a}	2.14	.87	9.9	16.1
	S	6	51.6	10.38	4.24	37.3	65.5		S	5	23.1^{b}	5.94	2.66	15.9	30.4
	1:2	6	47.7	5.89	2.41	38.5	52.9		1:2	6	18.1^{ab}	3.74	1.53	13.6	23.5
	2:3	6	48.8	13.70	5.59	34.9	68.9		2:3	6	14.4^{a}	4.23	1.73	9.8	20.9
	Total	24	50.5	10.31	2.11	30.6	68.9		Total	23	17.0	5.34	1.11	9.8	30.4
13-MAR-12	C	6	24.4	11.27	4.60	10.4	44.5	24-APR-12	C	6	14.5	5.87	2.40	8.4	25.0
	S	6	34.9	10.86	4.43	16.2	44.6		S	6	13.8	2.32	.95	10.7	17.5
	1:2	6	30.8	11.32	4.62	17.0	46.4		1:2	6	12.9	5.08	2.07	6.3	18.2
	2:3	6	25.0	8.14	3.32	16.1	36.4		2:3	6	12.7	7.56	3.09	6.8	26.8
	Total	24	28.8	10.73	2.19	10.4	46.4		Total	24	13.5	5.22	1.07	6.3	26.8
22-MAR-12	C	6	25.6	3.49	1.42	22.2	31.3	03MAYY-12	C	6	13.3	4.71	1.92	8.2	21.4
	S	5	31.2	6.48	2.90	21.8	39.4		S	6	16.9	4.86	1.98	7.8	20.7
	1:2	6	31.1	5.29	2.16	24.8	39.8		1:2	6	12.6	6.35	2.59	5.3	21.1
	2:3	6	28.4	9.46	3.86	13.2	38.6		2:3	6	12.9	6.79	2.77	5.6	23.2
	Total	23	29.0	6.54	1.36	13.2	39.8		Total	24	13.9	5.64	1.15	5.3	23.2
27-MAR-12	C	6	20.9	6.62	2.70	10.3	30.4	07-MAY-12	C	6	11.1^{a}	1.79	.73	8.6	13.9
	S	6	26.1	10.43	4.26	15.0	40.5		S	6	18.4^{b}	3.95	1.61	13.1	23.3
	1:2	5	20.6	8.62	3.85	8.2	32.5		1:2	6	11.5^{ac}	2.83	1.16	7.3	14.9
	2:3	6	26.3	12.85	5.25	8.9	47.0		2:3	6	17.5^{bc}	4.46	1.82	11.4	23.9
	Total	23	23.6	9.66	2.01	8.2	47.0		Total	24	14.6	4.68	.96	7.3	23.9

Table 9.1.8. Descriptives for weekly N_2O-N emissions (g N_2O-N ha^{-1} d^{-1}) that were collected during chamber measurements in corn-soybean sole crops and intercrops from January 2012-May 2012 in Balcarce, Argentina. C and S represent sole corn and sole soybean agroecosystems respectively, and 1:2 intercrop represents intercropping design of 1 row corn to 2 rows soybeans, and 2:3 intercrop 2 rows corn and 3 rows soybeans. Non-matching letters indicate significant differences (α = 0.05 ; 95% confidence interval).

Date & Treatment		N	$\bar{x}$	S.D	S.E	Min	Max	Date & Treatment		N	$\bar{x}$	S.D	S.E	Min	Max
22-JAN-12	C	6	21.3^{a}	9.36	3.82	8.6	33.2	22-MAR-12	C	6	4.1	2.52	1.02	1.8	7.9
	S	5	11.6^{ab}	5.07	2.67	4.2	16.4		S	5	2.1	2.27	1.01	-.4	4.7
	1:2	6	17.2^{ab}	6.80	2.76	4.5	23.2		1:2	5	11.7	7.78	3.48	-.5	19.9
	2:3	6	7.8^{b}	4.91	2.01	.6	15.8		2:3	6	4.7	2.45	1.00	2.1	6.6
	Total	23	14.6	8.33	1.74	.6	33.2		Total	22	5.5	5.30	1.13	-.5	19.9
31-JAN-12	C	6	5.0	3.92	1.60	-.4	10.5	27-MAR-12	C	6	3.4	3.72	1.52	-2.9	6.6
	S	5	2.3	4.65	2.08	-1.3	10.2		S	6	.9	5.47	2.23	-2.5	11.7
	1:2	5	3.9	4.46	1.99	-2.0	7.8		1:2	5	9.5	6.42	2.87	1.4	18.9
	2:3	5	1.8	4.88	2.18	-3.3	9.8		2:3	6	4.3	2.76	1.13	.5	8.4
	Total	21	3.3	4.32	0.94	-3.3	10.5		Total	23	4.3	5.35	1.11	-2.9	18.9
07-FEB-12	C	6	2.2	.74	.30	.8	2.9	03-APR-12	C	6	1.1	3.19	1.30	-1.7	6.4
	S	6	2.2	1.02	.42	1.3	3.6		S	6	3.9	3.87	1.58	-2.2	8.5
	1:2	5	6.2	6.30	2.82	-.6	14.8		1:2	6	3.4	2.76	1.13	-1.1	6.5
	2:3	6	2.6	6.68	2.73	-6.1	14.1		2:3	6	4.9	4.52	1.84	-2.2	11.9
	Total	23	3.2	4.52	.94	-6.1	14.8		Total	24	3.3	3.69	.75	-2.2	11.9
16-FEB-12	C	5	3.5	5.95	2.66	-2.6	12.1	10-APR-12	C	5	.4	4.86	2.17	-4.7	7.6
	S	6	.3	2.20	.90	-3.7	2.4		S	6	3.1	4.01	1.09	-2.3	9.7
	1:2	6	2.4	3.74	1.53	-1.7	7.4		1:2	6	8.0	4.50	2.37	2.9	13.6
	2:3	6	2.4	1.77	.72	-.6	4.2		2:3	6	2.0	5.33	2.53	-3.6	12.1
	Total	23	2.1	3.57	0.74	-3.7	12.1		Total	23	3.5	5.23	1.87	-4.7	13.6
22-FEB-12	C	6	19.9	9.84	4.02	7.5	32.6	16-APR-12	C	6	5.2	5.82	2.37	-.1	16.1
	S	6	15.2	10.45	4.27	3.9	33.7		S	5	5.3	5.66	2.53	-1.2	11.1
	1:2	6	16.3	3.45	1.41	11.2	20.7		1:2	6	6.5	4.58	1.87	1.9	14.8
	2:3	6	7.2	4.36	1.78	.6	14.1		2:3	6	3.7	3.03	1.23	-.9	6.0
	Total	24	14.6	8.60	1.76	.6	33.7		Total	23	5.2	4.63	.97	-1.2	16.1
28-FEB-12	C	6	10.9^{ab}	6.70	2.74	1.46	21.6	24-APR-12	C	6	$-.3^{a}$	4.53	1.85	-4.1	8.3
	S	6	5.9^{a}	8.88	3.62	.7	23.9		S	6	6.1^{b}	2.05	.84	2.8	7.8
	1:2	6	23.4^{b}	7.85	3.21	16.3	33.0		1:2	6	2.1^{ab}	3.12	1.28	-1.0	7.2
	2:3	6	11.0^{ab}	5.06	2.07	5.0	17.5		2:3	6	$.7^{a}$	1.28	.52	-.9	2.4
	Total	24	12.8	9.45	1.93	.7	33.0		Total	24	2.2	3.74	.76	-4.1	8.3
06-MAR-12	C	5	22.3^{a}	12.26	5.48	7.5	40.1	03-MAY-12	C	6	.7	3.98	1.62	-6.1	4.9
	S	6	1.7^{b}	3.52	1.44	-4.1	4.9		S	6	3.0	2.36	.96	-.7	6.2
	1:2	6	29.4^{a}	8.91	3.64	17.7	44.1		1:2	6	2.7	2.65	1.08	-.5	6.3
	2:3	6	18.1^{ab}	11.20	4.57	7.4	37.3		2:3	6	3.6	1.45	.59	2.0	6.3
	Total	23	17.7	13.74	2.86	-4.1	44.1		Total	24	2.5	2.81	.57	-6.1	6.4
13-MAR-12	C	6	6.9^{a}	4.22	1.72	.9	13.8	07-MAY-12	C	6	1.3^{ab}	2.02	.83	-.9	3.7
	S	6	4.0^{b}	2.44	1.00	-.2	6.6		S	6	3.9^{a}	1.96	.80	1.9	6.7
	1:2	6	22.7^{a}	12.05	4.92	7.2	36.8		1:2	6	$.6^{ab}$	2.55	1.04	-2.6	4.1
	2:3	6	8.1^{ab}	7.23	2.95	1.6	20.6		2:3	6	$-.7^{b}$	1.64	.67	-3.5	1.1
	Total	24	10.4	10.15	2.07	-.2	36.8		Total	24	1.3	2.58	.53	-3.5	6.7

Table 9.1.9. Descriptives for weekly soil water-filled pore space (%) that was calculated from moisture content measurements collected during chamber measurements in corn-soybean sole crops and intercrops from November 2011-May 2012 in Balcarce, Argentina. C and S represent sole corn and sole soybean agroecosystems respectively, .and 1:2 intercrop represents the intercropping design of 1 row corn to 2 rows soybeans, and 2:3 intercrop 2 rows corn and 3 rows soybeans. Means with same superscripted letters indicated no significant differences between treatments at α = 0.05 and 95% confidence interval (C.I).

Date & Treatment		N	$\overline{X}$	S.D	S.E	Min	Max	Date & Treatment		N	$\overline{X}$	S.D	S.E	Min	Max
25-NOV-11	C	6	24.9	2.48	1.01	22.1	29.1	03-JAN-12	C	6	16.4^{ab}	2.82	1.15	14.5	21.4
	S	6	34.9	9.73	3.97	24.0	45.7		S	6	20.8^{b}	3.08	1.26	15.6	24.6
	1:2	6	22.7	2.13	.87	19.0	25.3		1:2	6	17.0^{ab}	3.10	1.27	14.2	21.8
	2:3	6	24.1	9.27	3.79	17.0	42.0		2:3	6	15.6^{a}	1.36	.55	14.2	17.8
	Total	24	26.6	8.13	1.66	17.0	45.7		Total	24	17.5	3.22	.66	14.2	24.6
29-NOV-11	C	6	34.9	5.49	2.24	29.5	42.1	12-JAN-12	C						
	S	6	36.6	10.80	4.41	21.5	50.0		S						
	1:2	6	30.4	6.50	2.65	24.7	42.8		1:2						
	2:3	6	29.0	5.87	2.40	22.4	37.2		2:3						
	Total	24	32.7	7.67	1.57	21.5	50.0		Total						
04-DEC-11	C	6	27.0	6.21	2.54	20.0	34.7	17-JAN-12	C	6	16.2^{a}	1.20	.49	14.2	17.6
	S	6	31.0	3.41	1.39	26.9	35.5		S	6	21.3^{b}	2.04	.83	19.0	24.3
	1:2	6	31.2	3.83	1.56	28.1	36.9		1:2	6	17.7^{a}	2.16	.88	15.4	20.4
	2:3	6	31.5	7.22	2.95	21.8	40.2		2:3	6	17.8^{a}	1.76	.72	16.4	20.2
	Total	24	30.2	5.38	1.10	20.0	40.2		Total	24	18.2	2.57	.52	14.2	24.3
08-DEC-11	C	6	19.4	5.50	2.25	11.3	24.7	22-JAN-12	C						
	S	6	26.0	5.30	2.16	20.2	32.4		S						
	1:2	6	23.1	5.38	2.20	16.3	29.4		1:2						
	2:3	6	19.8	4.09	1.67	15.3	27.4		2:3						
	Total	24	22.1	5.50	1.12	11.3	32.4		Total						
14-DEC-11	C	6	33.6^{ab}	5.32	2.17	27.9	41.4	31-JAN-12	C	6	20.6^{ab}	.75	.30	19.9	21.7
	S	6	37.7^{a}	7.09	2.89	25.9	47.5		S	4	25.3^{b}	5.05	2.53	22.6	32.9
	1:2	6	32.5^{ab}	5.29	2.16	26.1	37.9		1:2	6	20.7^{ab}	2.02	.82	17.4	22.8
	2:3	6	25.3^{b}	1.74	.71	22.2	26.7		2:3	6	19.2^{a}	1.38	.57	17.1	20.5
	Total	24	32.3	6.67	1.36	22.2	47.5		Total	22	21.1	3.12	.67	17.1	32.9
20-DEC-11	C	6	25.1^{a}	3.31	1.35	20.4	28.5	07-FEB-12	C	6	7.2^{a}	.86	.35	6.2	8.7
	S	6	29.8^{a}	5.01	2.05	23.0	35.6		S	6	10.8^{b}	1.55	.63	8.9	12.5
	1:2	6	23.8^{ab}	3.76	1.53	20.3	29.2		1:2	6	7.9^{a}	1.46	.59	6.2	9.9
	2:3	6	18.9^{b}	1.32	.54	17.6	21.2		2:3	6	7.5^{a}	1.02	.42	5.9	8.8
	Total	24	24.4	5.19	1.06	17.6	35.6		Total	24	8.4	1.88	.38	5.9	12.5
27-DEC-11	C	6	12.4^{a}	5.60	2.29	5.6	20.3	16-FEB-12	C	6	5.9	3.35	1.37	2.0	10.0
	S	6	21.4^{b}	4.56	1.86	14.6	28.4		S	6	4.0	3.24	1.32	.0	9.0
	1:2	6	18.1^{b}	4.82	1.97	13.9	26.5		1:2	6	5.0	1.51	.61	3.3	7.4
	2:3	6	7.0^{a}	4.09	1.67	1.8	11.7		2:3	6	5.5	1.86	.76	2.2	7.3
	Total	24	14.7	7.20	1.47	1.8	28.4		Total	24	5.1	2.55	.52	.0	10.0

Continuation of Table 9.1.9 - Descriptives for weekly soil water-filled pore space (%) 2011-2012.

Date & Treatment		N	$\bar{x}$	S.D	S.E	Min	Max	Date & Treatment		N	$\bar{x}$	S.D	SE	Min	Max
22-FEB-12	C	6	45.4	2.39	.98	41.3	48.7	03-APR-12	C	6	27.7	6.22	2.54	20.0	37.0
	S	6	38.0	8.99	3.67	22.8	46.4		S	6	18.2	2.48	1.01	15.4	22.6
	1:2	6	40.4	4.67	1.90	31.4	44.4		1:2	6	22.8	4.31	1.76	18.8	31.3
	2:3	6	39.1	4.07	1.66	35.3	44.5		2:3	6	21.1	7.68	3.13	12.5	34.6
	Total	24	40.7	5.96	1.22	22.8	48.7		Total	24	22.5	6.23	1.27	12.5	37.0
28-FEB-12	C	6	47.6	4.66	1.90	41.6	54.6	10-APR-12	C	6	43.0^{a}	2.58	1.05	39.7	46.5
	S	6	41.6	5.49	2.24	32.7	48.3		S	6	39.4^{a}	4.06	1.66	33.8	45.6
	1:2	6	43.3	6.30	2.57	34.5	53.4		1:2	6	37.4^{ab}	5.20	2.12	32.2	46.8
	2:3	6	41.3	3.66	1.49	37.1	45.8		2:3	6	31.4^{b}	5.61	2.29	25.0	38.4
	Total	24	43.5	5.42	1.11	32.7	54.6		Total	24	37.8	6.02	1.23	25.0	46.8
06-MAR-12	C	6	49.1	8.34	3.41	40.6	62.1	16-APR-12	C	6	35.9^{a}	3.10	1.27	30.3	38.1
	S	6	45.7	7.87	3.21	32.3	54.6		S	6	30.7^{a}	4.33	1.77	23.3	35.5
	1:2	6	51.4	5.00	2.04	44.2	55.9		1:2	6	30.8^{a}	5.35	2.19	23.4	36.9
	2:3	6	46.7	9.57	3.91	38.0	63.1		2:3	6	21.4^{b}	3.53	1.44	16.3	25.3
	Total	24	48.2	7.68	1.57	32.3	63.1		Total	24	29.7	6.59	1.35	16.3	38.1
13-MAR-12	C	6	37.0	4.98	2.03	29.7	42.8	24-APR-12	C	6	45.6	2.45	1.00	42.6	48.9
	S	6	31.7	12.72	5.19	17.2	46.9		S	6	41.5	3.36	1.37	36.2	45.6
	1:2	6	33.5	9.59	3.92	25.3	49.2		1:2	6	40.6	2.90	1.18	38.6	46.2
	2:3	6	25.9	4.10	1.67	18.4	30.6		2:3	6	41.5	3.52	1.44	37.5	46.3
	Total	24	32.0	9.00	1.84	17.2	49.2		Total	24	42.3	3.51	.72	36.2	48.9
22-MAR-12	C	6	40.6^{a}	3.32	1.36	34.4	43.5	03-MAY-12	C	6	38.1^{a}	5.54	2.26	30.4	43.5
	S	6	24.8^{b}	5.06	2.07	17.2	29.5		S	6	27.1^{b}	5.84	2.39	18.7	36.0
	1:2	6	41.8^{a}	5.13	2.10	34.4	49.2		1:2	6	32.2^{ab}	2.59	1.06	27.3	34.7
	2:3	6	29.0^{b}	4.15	1.69	25.1	36.6		2:3	6	25.2^{b}	5.50	2.25	18.8	35.2
	Total	24	34.0	8.55	1.75	17.2	49.2		Total	24	30.6	6.94	1.42	18.7	43.5
27-MAR-12	C	6	42.0^{ab}	10.59	4.32	29.2	57.9	07-MAY-12	C	6	40.8^{a}	8.17	3.34	27.1	47.8
	S	6	36.3^{a}	5.73	2.34	27.2	43.7		S	6	30.5^{ab}	6.64	2.71	21.3	37.6
	1:2	6	49.3^{b}	3.25	1.33	44.6	53.0		1:2	6	30.2^{b}	5.20	2.12	24.7	38.9
	2:3	6	40.4^{ab}	.96	.39	38.8	41.4		2:3	6	22.5^{b}	2.47	1.01	19.1	25.3
	Total	24	42.0	7.57	1.55	27.2	57.9		Total	24	31.0	8.69	1.77	19.1	47.8

Table 9.1.10. Descriptives for weekly soil temperature (°C) that were collected during chamber measurements in corn-soybean sole crops and intercrops from November 2011-May 2012 in Balcarce, Argentina. C and S represent sole corn and sole soybean agroecosystems respectively, and 1:2 intercrop represents intercropping design of 1 row corn to 2 rows soybeans, and 2:3 intercrop 2 rows corn and 3 rows soybeans. Non-matching letters indicate significant differences (α = 0.05 ; 95% confidence interval).

Date & Treatment		N	$\overline{x}$	S.D	S.E	Min	Max	Date & Treatment		N	$\overline{x}$	S.D	SE	Min	Max
25-NOV-11	C	6	34.9^{a}	1.02	.41	33.6	36.6	12-JAN-12	C	6	28.0	.00	.00	28.0	28.0
	S	6	32.9^{b}	.82	.34	31.6	33.8		S	6	28.3	.26	.11	28.0	28.5
	1:2	6	34.4^{ab}	.76	.31	33.6	35.5		1:2	6	28.4	.38	.15	28.0	29.0
	2:3	6	33.1^{ab}	1.42	.58	31.4	34.6		2:3	6	28.3	.41	.17	28.0	29.0
	Total	24	33.8	1.29	.26	31.4	36.6		Total	24	28.3	.33	.07	28.0	29.0
29-NOV-11	C	6	33.1	1.47	.60	31.5	35.1	17-JAN-12	C	6	42.6^{a}	1.07	.44	41.5	44.0
	S	6	34.2	0.78	.32	33.0	35.1		S	6	45.4^{b}	1.28	.52	44.0	47.0
	1:2	6	31.2	2.18	.89	28.7	34.1		1:2	6	42.8^{a}	2.16	.88	39.5	45.0
	2:3	6	33.9	1.58	.64	31.9	35.8		2:3	6	42.3^{a}	.98	.40	41.5	44.0
	Total	24	33.1	1.84	.38	28.7	35.8		Total	24	43.3	1.86	.38	39.5	47.0
04-DEC-11	C	6	32.9	1.13	.46	31.6	34.9	22-JAN-12	C	6	25.2	.41	.17	24.5	25.5
	S	6	32.3	2.37	.97	29.2	35.4		S	6	25.0	.00	.00	25.0	25.0
	1:2	6	32.1	3.25	1.33	27.8	36.3		1:2	6	25.3	.61	.25	24.5	26.0
	2:3	6	34.7	1.64	.67	33.5	37.8		2:3	6	25.2	.93	.38	24.0	26.0
	Total	24	33.0	2.33	.48	27.8	37.8		Total	24	25.2	.56	.12	24.0	26.0
08-DEC-11	C	6	27.2^{a}	1.14	.46	26.1	29.3	31-JAN-12	C	6	27.2	.68	.28	26.0	28.0
	S	6	29.7^{b}	1.78	.73	26.7	31.7		S	6	26.7	.41	.17	26.0	27.0
	1:2	6	29.1^{ab}	1.17	.48	26.7	29.6		1:2	6	27.7	.82	.33	26.0	28.0
	2:3	6	27.2^{ab}	.55	.22	26.1	27.5		2:3	6	27.1	.38	.15	26.5	27.5
	Total	24	28.3	1.62	.33	26.1	31.7		Total	24	27.1	.67	.14	26.0	28.0
14-DEC-11	C	6	26.1^{a}	1.81	.74	24.1	29.4	07-FEB-12	C	6	34.7	.52	.21	34.0	35.5
	S	6	31.3^{b}	1.51	.62	29.2	33.1		S	6	34.7	.41	.17	34.0	35.0
	1:2	6	31.3^{b}	4.07	1.66	28.0	39.1		1:2	6	35.0	.32	.13	34.5	35.5
	2:3	6	28.6^{ab}	1.49	.61	26.9	30.7		2:3	6	34.7	.26	.11	34.5	35.0
	Total	24	29.3	3.19	.65	24.1	39.1		Total	24	34.8	.39	.08	34.0	35.5
20-DEC-11	C	6	31.1	3.71	1.52	26.2	34.7	16-FEB-12	C	6	31.1^{ab}	.91	.37	29.6	32.1
	S	6	36.8	3.35	1.37	34.0	41.6		S	6	30.1^{b}	.79	.32	29.4	31.4
	1:2	6	32.1	4.66	1.90	27.3	38.6		1:2	6	32.2^{a}	1.47	.60	31.1	35.0
	2:3	6	34.9	2.54	1.04	32.7	38.3		2:3	6	31.3^{ab}	.49	.20	30.9	32.1
	Total	24	33.7	4.10	.84	26.2	41.6		Total	24	31.2	1.19	.24	29.4	35.0
27-DEC-11	C	6	34.9^{a}	1.50	.61	33.0	36.6	22-FEB-12	C	6	21.6^{ab}	2.10	.86	19.0	24.0
	S	6	41.6^{b}	1.71	.70	38.6	43.5		S	6	19.0^{b}	1.23	.50	18.0	20.6
	1:2	6	35.8^{a}	2.00	.82	32.3	37.5		1:2	6	20.7^{ab}	2.38	.97	18.9	24.2
	2:3	6	34.8^{a}	1.46	.60	32.8	37.0		2:3	6	22.3^{a}	1.62	.66	20.3	24.8
	Total	24	36.8	3.24	.66	32.3	43.5		Total	24	20.9	2.15	.44	18.0	24.8
03-JAN-12	C	6	29.4	.50	.20	28.8	30.0	28-FEB-12	C	6	20.6^{a}	.29	.12	20.1	21.0
	S	6	29.3	.44	.18	29.0	30.1		S	6	20.4^{a}	.43	.17	20.1	21.2
	1:2	6	29.6	.33	.13	29.2	30.1		1:2	6	21.5^{b}	.37	.15	21.1	22.2
	2:3	6	29.2	.48	.20	28.5	30.0		2:3	6	21.0^{ab}	.48	.20	20.4	21.7
	Total	24	29.4	.45	.09	28.5	30.1		Total	24	20.9	.59	.12	20.1	22.2

Continuation of Table 9.1.10 - Descriptives for weekly soil temperature (°C) 2011-2012.

Date & Treatment		N	$\overline{X}$	S.D	S.E	Min	Max	Date & Treatment		N	$\overline{X}$	S.D	S.E	Min	Max
06-MAR-12	C	6	26.0	1.87	.76	23.4	28.8	10-APR-12	C	6	17.9	.26	.11	17.6	18.3
	S	6	23.6	1.32	.54	22.1	25.9		S	6	18.7	1.08	.44	17.8	20.6
	1:2	6	24.9	2.42	.99	23.2	28.8		1:2	6	18.4	.55	.22	17.8	19.4
	2:3	6	27.0	3.43	1.40	22.8	30.2		2:3	6	19.0	.77	.31	18.4	20.2
	Total	24	25.4	2.57	.53	22.1	30.2		Total	24	18.5	.81	.17	17.6	20.6
13-MAR-12	C	6	17.6	.80	.33	16.8.	18.6	16-APR-12	C	6	18.8	.68	.28	18.2	20.1
	S	6	17.3	.75	.31	16.1	18.3		S	6	19.3	.77	.32	18.5	20.6
	1:2	6	17.3	.88	.34	16.2	18.3		1:2	6	19.4	.88	.36	18.6	21.1
	2:3	6	17.1	1.51	.62	15.4	19.2		2:3	6	19.4	1.58	.64	17.3	20.8
	Total	24	17.3	.98	.20	15.4	19.2		Total	24	19.2	1.00	.20	17.3	21.1
22-MAR-12	C	6	17.6	.85	.35	16.8	18.8	24-APR-12	C	6	12.1	.38	.15	11.6	12.7
	S	6	17.4	.80	.33	16.1	18.3		S	6	11.9	.56	.23	11.2	12.4
	1:2	6	18.0	1.54	.63	16.2	20.3		1:2	6	11.8	.35	.14	11.4	12.2
	2:3	6	17.0	1.29	.53	15.4	18.6		2:3	6	11.8	.81	.33	10.9	13.0
	Total	24	17.5	1.14	.23	15.4	20.3		Total	24	11.9	.53	.11	10.9	13.0
27-MAR-12	C	6	14.1	.39	.16	13.6	14.7	03-MAY-12	C	6	15.8	2.20	.90	12.4	17.4
	S	6	13.6	.69	.28	12.7	14.3		S	6	16.1	2.64	1.08	13.3	19.9
	1:2	6	14.0	.41	.17	13.4	14.5		1:2	6	14.8	1.73	.71	12.7	17.0
	2:3	6	14.0	.98	.40	12.9	15.3		2:3	6	15.7	2.75	1.12	12.3	18.7
	Total	24	13.9	.64	.13	12.7	15.3		Total	24	15.6	2.25	.46	12.3	19.9
03-APR-12	C	6	18.4	.99	.41	17.3	19.8	07-MAY-12	C	6	17.4^{a}	.59	.24	16.9	18.2
	S	6	20.2	1.39	.57	19.0	22.7		S	6	18.9^{b}	.48	.19	18.2	19.5
	1:2	6	20.2	1.08	.44	18.5	21.1		1:2	6	17.8^{ab}	.75	.30	17.2	19.1
	2:3	6	19.0	2.15	.88	15.7	21.3		2:3	5	18.3^{ab}	.57	.26	17.6	19.0
	Total	24	19.4	1.58	.32	15.7	22.7		Total	23	18.1	.79	.16	16.9	19.5

Weekly variable descriptives in 2012-2013

Table 9.1.11. Descriptives for weekly CO_2-C emissions (kg CO_2-C ha^{-1} d^{-1}) that were collected during chamber measurements in corn-soybean sole crops and intercrops from December 2012 -May 2013 in Balcarce, Argentina. C-S and S-S represent sole corn and sole Soybean agroecosystems respectively, and 1:2 intercrop represents intercropping design of 1 row corn to 2 rows soybean, and 2:3 intercrop 2 rows corn and 3 rows soybean. Non-matching letters indicate significant differences (α = 0.05 ; 95% confidence interval).

Date & Treatment		N	$\bar{x}$	S.D	S.E	Min	Max	Date & Treatment		N	$\bar{x}$	S.D	S.E	Min	Max
11-DEC-12	C	6	29.0	7.01	2.86	15.9	36.8	29-JAN-13	C	6	26.7	5.60	2.29	20.8	34.9
	S	6	34.1	9.09	3.71	21.0	42.9		S	6	24.7	4.82	1.97	17.3	31.7
	1:2	6	35.0	13.11	5.35	16.9	48.3		1:2	5	29.0	7.87	3.52	21.6	39.7
	2:3	5	33.3	9.39	4.20	20.3	42.8		2:3	6	29.5	6.25	2.55	23.3	37.3
	Total	23	32.8	9.53	1.99	15.9	48.3		Total	23	27.4	6.04	1.26	17.3	39.7
19-DEC-12	C	6	34.5	8.36	3.41	20.4	41.8	5-FEB-13	C	6	28.1	5.17	2.11	22.6	37.1
	S	6	27.3	5.40	2.21	20.8	33.4		S	6	36.2	9.44	3.85	21.1	47.9
	1:2	6	30.6	9.03	3.69	12.5	36.7		1:2	6	30.8	5.20	2.12	26.4	39.8
	2:3	6	25.2	5.47	2.23	17.2	33.0		2:3	6	28.2	8.65	3.53	20.2	43.3
	Total	24	29.4	7.66	1.56	12.5	41.8		Total	24	30.8	7.65	1.56	20.2	47.9
24-DEC-12	C	6	46.8	12.32	5.03	26.9	57.4	14-FEB-13	C	6	30.2	8.77	3.58	21.9	40.9
	S	4	48.2	25.07	12.53	19.3	80.3		S	6	29.8	9.44	3.85	22.5	47.4
	1:2	6	46.5	24.14	9.85	24.0	79.5		1:2	5	27.1	5.66	2.53	22.1	35.1
	2:3	5	44.5	16.40	7.33	21.3	60.8		2:3	6	37.4	4.88	1.99	33.2	46.5
	Total	21	46.4	18.25	3.98	19.3	80.3		Total	23	31.3	8.01	1.67	21.9	47.4
28-DEC-12	C	5	28.3	10.46	4.68	14.2	37.3	21-FEB-13	C	6	17.5	2.86	1.17	14.5	22.4
	S	4	40.8	3.09	1.55	37.6	44.3		S	6	22.8	4.77	1.95	14.7	29.5
	1:2	4	26.6	8.37	4.19	14.3	32.3		1:2	6	18.6	5.51	2.25	11.7	27.2
	2:3	5	30.9	8.07	3.61	21.8	43.2		2:3	6	19.0	1.40	.57	16.7	20.8
	Total	18	31.4	9.19	2.17	14.2	44.3		Total	24	19.5	4.24	.87	11.7	29.5
03-JAN-13	C	6	39.5	11.03	4.50	28.8	53.6	26-FEB-13	C	5	31.9	15.54	6.95	20.9	59.1
	S	5	33.5	11.78	5.27	21.8	49.9		S	5	23.1	8.62	3.86	13.1	29.7
	1:2	5	52.4	18.76	8.39	34.3	79.9		1:2	6	25.6	7.85	3.20	17.3	34.4
	2:3	6	28.3	11.16	4.56	17.0	43.5		2:3	5	28.3	10.88	4.87	15.6	37.6
	Total	22	38.0	15.29	3.26	17.0	79.9		Total	21	27.1	10.63	2.32	13.1	59.1
09-JAN-13	C	6	42.2	9.30	3.79	32.1	58.8	02-MAR-13	C	6	19.2	2.94	1.20	14.9	22.7
	S	6	37.2	12.03	4.91	23.0	50.9		S	6	32.2	10.04	4.10	18.1	48.1
	1:2	6	41.9	11.84	4.84	21.8	53.5		1:2	6	24.4	9.32	3.80	17.2	41.9
	2:3	6	37.3	14.47	5.91	23.5	61.7		2:3	6	19.0	7.11	2.90	9.9	29.6
	Total	24	39.6	11.50	2.34	21.8	61.7		Total	24	23.7	9.16	1.87	9.9	48.1
15-JAN-13	C	6	27.6	8.86	3.62	16.2	41.1	12-MAR-13	C	6	12.6	1.30	.53	11.5	14.6
	S	6	29.7	7.64	3.12	17.7	37.5		S	5	16.1	3.77	1.69	12.1	20.8
	1:2	6	37.2	9.70	3.96	21.4	45.2		1:2	6	12.5	4.47	1.82	6.8	18.6
	2:3	6	32.3	5.76	2.35	25.1	42.4		2:3	6	14.2	4.84	1.98	9.6	22.5
	Total	24	31.7	8.41	1.72	16.2	45.1		Total	23	13.8	3.86	.80	6.8	22.5
22-JAN-13	C	6	38.7	10.74	4.38	24.9	57.1	21-MAR-13	C	5	23.1	8.63	3.86	12.4	35.2
	S	6	33.3	10.92	4.46	19.0	48.8		S	6	32.4	11.73	4.79	13.7	45.7
	1:2	6	33.1	6.19	2.53	24.3	41.6		1:2	6	27.7	7.45	3.04	14.7	35.9
	2:3	6	37.9	13.58	5.54	21.5	60.7		2:3	6	24.1	9.86	4.03	15.6	42.9
	Total	24	35.7	10.31	2.10	19.0	60.7		Total	23	27.0	9.67	2.02	12.4	45.7

Continuation of Table 9.1.11 - Descriptives for weekly CO_2-C emissions (kg CO_2-C ha^{-1} d^{-1}) 2012-2013.

Date & Treatment		N	$\bar{x}$	S.D	S.E	Min	Max	Date & Treatment		N	$\bar{x}$	S.D	S.E	Min	Max
27-MAR-13	C	6	12.2	1.29	.53	10.7	14.2	24-APR-13	C	6	13.4	2.47	1.01	8.8	15.7
	S	6	14.2	5.28	2.16	5.7	20.1		S	6	20.4	5.13	2.09	12.9	25.7
	1:2	6	13.6	3.77	1.54	9.6	19.1		1:2	6	14.9	4.48	1.83	9.6	23.1
	2:3	6	14.0	4.85	1.98	9.6	22.5		2:3	6	15.9	4.67	1.91	10.4	22.2
	Total	24	13.5	3.90	.80	5.7	22.5		Total	24	16.1	4.82	.98	8.8	25.7
3-APR-13	C	6	16.1	6.37	2.60	10.5	27.8	30-APR-13	C	6	16.4	2.52	1.03	13.8	20.5
	S	6	16.5	6.39	2.61	9.6	25.7		S	6	21.8	6.40	2.61	11.6	28.0
	1:2	6	18.8	7.50	3.06	9.3	27.3		1:2	6	18.3	7.73	3.16	9.2	32.1
	2:3	6	16.0	6.89	2.81	10.7	27.3		2:3	6	14.7	4.10	1.68	9.6	19.6
	Total	24	16.9	6.45	1.32	9.3	27.8		Total	24	17.8	5.85	1.19	9.2	32.1
10-APR-13	C	6	16.2	2.59	1.06	12.1	18.5	7-MAY-13	C	6	10.5	1.96	.80	7.3	13.0
	S	5	16.0	6.06	2.71	7.1	22.5		S	6	13.6	4.47	1.83	6.7	19.0
	1:2	6	16.1	3.36	1.37	11.2	20.4		1:2	6	10.3	2.77	1.13	7.5	14.3
	2:3	6	15.5	5.12	2.09	9.9	23.4		2:3	6	9.0	4.38	1.79	3.6	16.2
	Total	23	15.9	4.10	.85	7.1	23.4		Total	24	10.9	3.75	.76	3.6	19.0
17-APR-13	C	6	12.7	1.21	.49	11.7	14.5	14-MAY-13	C	6	12.6	4.30	1.75	6.1	19.1
	S	5	16.3	3.63	1.62	12.3	20.4		S	5	17.0	6.30	2.82	7.5	22.8
	1:2	6	13.6	3.66	1.49	9.5	18.8		1:2	5	14.1	2.56	1.14	10.6	17.8
	2:3	6	14.2	4.82	1.97	9.6	22.4		2:3	6	10.3	4.87	1.99	5.3	18.5
	Total	23	14.1	3.57	.74	9.5	22.4		Total	22	13.3	5.00	1.07	5.3	22.8

Table 9.1.12. Descriptives for weekly N_2O-N emissions (g N_2O-N ha^{-1} d^{-1}) chamber measurements collected in corn-soybean sole crops and intercrops from December 2012-May 2013 in Balcarce, Argentina. C-S and S-S represent sole corn and sole Soybean agroecosystems respectively, and 1:2 intercrop represents the intercropping design of 1-row corn to 2 rows soybean, and 2:3 intercrop 2 rows corn and 3 rows soybean. Non-matching letters indicate significant differences ($\alpha = 0.05$; 95% confidence interval).

Date & Treatment		N	$\bar{x}$	S.D	S.E	Min	Max	Date & Treatment		N	$\bar{x}$	S.D	S.E	Min	Max
11-DEC-12	C	6	7.9	6.15	2.51	1.3	19.2	3-JAN-13	C	6	20.0^{a}	8.88	3.62	10.4	33.2
	S	6	3.7	3.36	1.37	-2.6	6.1		S	5	10.4^{a}	7.53	3.37	.6	19.1
	1:2	5	6.6	3.52	1.57	2.1	9.8		1:2	5	47.6^{b}	1.56	.70	46.1	49.7
	2:3	6	6.6	9.90	4.04	-3.8	19.5		2:3	6	17.4^{a}	9.46	3.86	6.7	30.3
	Total	23	6.2	6.18	1.29	-3.8	19.5		Total	22	23.4	15.63	3.33	.6	49.7
19-DEC-12	C	6	5.4	1.52	.62	3.0	6.9	9-JAN-13	C	6	6.2^{a}	2.35	.96	3.5	9.2
	S	6	4.9	3.85	1.57	-2.3	9.3		S	6	9.0^{a}	3.98	1.62	3.9	13.8
	1:2	6	4.0	4.91	2.01	-.4	11.9		1:2	6	27.3^{b}	12.89	5.26	9.8	43.8
	2:3	6	4.6	5.78	2.36	-4.1	13.4		2:3	6	9.8^{a}	4.68	1.91	4.0	16.1
	Total	24	4.7	4.07	.83	-4.1	13.4		Total	24	13.1	10.85	2.21	3.5	43.8
24-DEC-12	C	6	14.0	6.87	2.81	6.1	23.4	15-JAN-13	C	6	3.0^{a}	3.10	1.27	-.7	8.2
	S	4	7.6	6.18	3.09	4.3	16.9		S	6	8.9^{a}	7.24	2.95	2.1	19.7
	1:2	6	21.7	9.07	3.70	10.5	36.0		1:2	6	23.8^{b}	6.59	2.69	13.9	33.2
	2:3	5	18.0	8.65	3.87	10.4	31.7		2:3	6	8.6^{a}	6.37	2.60	2.8	21.0
	Total	21	15.9	8.90	1.94	4.3	36.0		Total	24	11.1	9.67	1.97	-.7	33.2
28-DEC-12	C	5	74.2	56.18	25.12	9.6	154.2	22-JAN-13	C	6	3.2^{a}	5.10	2.08	-1.9	12.7
	S	5	38.9	18.47	8.26	14.1	56.4		S	6	12.0^{a}	6.00	2.45	4.2	20.2
	1:2	6	78.6	51.38	20.97	35.4	170.1		1:2	6	23.3^{b}	10.07	4.11	7.7	33.6
	2:3	6	76.1	44.36	18.11	40.8	158.4		2:3	6	8.4^{a}	9.73	3.97	-2.6	26.6
	Total	22	67.9	44.99	9.59	9.6	170.1		Total	24	11.7	10.64	2.17	-2.6	33.6

Continuation of Table 9.1.12. - Descriptives for weekly N_2O-N emissions (g N_2O-N ha^{-1} d^{-1}) 2012-2013.

Date & Treatment		N	$\bar{x}$	S.D	S.E	Min	Max	Date & Treatment		N	$\bar{x}$	S.D	S.E	Min	Max
29-JAN-13	C	6	2.9^a	2.77	1.13	-.4	6.6	27-MAR-13	C	6	2.0	2.08	.85	-1.3	4.1
	S	6	2.0^a	2.31	.94	-.7	4.7		S	6	2.3	2.15	.88	.2	5.7
	1:2	5	15.1^b	7.82	3.50	4.5	26.2		1:2	6	.0	2.72	1.11	-4.1	3.9
	2:3	6	3.2^a	4.73	1.93	-1.7	10.8		2:3	6	1.5	.74	.30	.8	2.8
	Total	23	5.4	6.82	1.42	-1.7	26.2		Total	24	1.5	2.12	.43	-4.1	5.7
5-FEB-13	C	5	1.0^a	5.71	2.55	-8.3	5.7	3-APR-13	C	6	2.4	1.20	.49	1.4	4.7
	S	6	4.7^a	3.59	1.47	-.6	9.2		S	6	2.5	.79	.32	.9	3.1
	1:2	6	13.3^b	10.00	4.08	-.6	23.3		1:2	6	2.2	2.68	1.09	-1.8	5.3
	2:3	6	3.8^a	4.32	1.76	-1.8	10.8		2:3	6	2.4	2.16	.88	.5	5.1
	Total	23	5.9	7.62	1.59	-8.3	23.3		Total	24	2.4	1.74	.36	-1.8	5.3
14-FEB-13	C	6	2.8	2.44	.99	.5	7.3	10-APR-13	C	6	3.1	2.86	1.17	.2	6.8
	S	6	3.2	5.49	2.24	-2.7	12.0		S	5	.4	1.50	.67	-.9	2.3
	1:2	5	1.8	4.20	1.88	-5.7	4.2		1:2	6	.6	1.59	.65	-1.3	2.8
	2:3	6	5.3	6.32	2.58	-3.7	14.2		2:3	6	1.2	2.41	.98	-1.6	4.8
	Total	23	3.4	4.70	.98	-5.7	14.2		Total	23	1.4	2.32	.48	-1.6	6.8
21-FEB-13	C	6	2.4	2.00	.81	-.3	5.8	17-APR-13	C	6	2.2	2.33	.95	-1.3	5.2
	S	6	2.7	3.22	1.31	-1.4	6.8		S	5	4.0	4.55	2.03	.2	11.1
	1:2	6	5.3	2.87	1.17	1.0	9.4		1:2	6	.9	2.82	1.15	-4.1	3.9
	2:3	6	5.7	6.54	2.67	1.0	18.2		2:3	6	1.5	.72	.30	.8	2.8
	Total	24	4.0	4.07	.83	-1.4	18.2		Total	23	2.1	2.88	.60	-4.1	11.1
26-FEB-13	C	6	.5	1.66	.68	-2.3	2.3	24-APR-13	C	6	$.1^a$	2.40	.98	-3.2	4.0
	S	5	.9	1.94	.87	-.7	4.0		S	6	6.7^b	3.36	1.37	3.7	13.1
	1:2	6	5.7	3.51	1.43	2.1	11.5		1:2	6	$.6^a$	2.40	.98	-2.7	3.4
	2:3	5	5.0	5.82	2.60	-3.9	10.1		2:3	6	$.3^a$	2.35	.96	-3.4	3.7
	Total	22	3.0	4.09	.87	-3.9	11.5		Total	24	1.9	3.76	.77	-3.4	13.1
2-MAR-13	C	6	2.2	1.89	.77	-1.4	3.8	30-APR-13	C	6	$.4^a$	2.29	.94	-2.5	4.3
	S	6	.7	2.80	1.14	-4.7	3.0		S	6	9.2^b	5.65	2.31	3.1	16.9
	1:2	6	1.7	3.34	1.36	-3.3	6.2		1:2	6	3.2^{ab}	1.75	.71	.1	5.1
	2:3	6	2.4	2.48	1.01	-1.1	5.8		2:3	6	1.6^a	1.32	.54	-.3	3.4
	Total	24	1.7	2.59	.53	-4.7	6.2		Total	24	3.6	4.61	.94	-2.5	16.9
12-MAR-13	C	6	2.2	2.32	.95	-1.3	5.2	7-MAY-13	C	6	.9	1.97	.80	-2.0	3.6
	S	5	4.5	5.54	2.48	.2	13.7		S	6	5.2	3.79	1.55	1.8	11.4
	1:2	6	- .7	3.07	1.25	-4.1	3.9		1:2	6	2.1	3.20	1.31	-1.8	7.0
	2:3	6	1.5	.73	.30	.8	2.8		2:3	6	.6	2.39	.98	-1.1	4.6
	Total	23	1.7	3.54	.74	-4.1	13.7		Total	24	2.2	3.29	.67	-2.0	11.4
21-MAR-13	C	6	1.5	2.92	1.19	-1.0	6.9	14-MAY-13	C	6	1.0	1.62	.66	-.9	3.0
	S	6	1.5	1.52	.62	-1.1	3.2		S	5	5.4	5.61	2.51	-.1	14.4
	1:2	6	4.1	2.37	.97	1.5	8.0		1:2	5	1.3	1.65	.74	-.6	3.2
	2:3	6	2.3	1.40	.57	.7	4.1		2:3	6	1.9	1.95	.80	-.2	5.3
	Total	24	2.4	2.27	.46	-1.1	8.0		Total	22	2.3	3.33	.71	-.9	14.4

Table 9.1.13. Descriptives for weekly water-filled porosity space (%) that were collected during chamber measurements in corn-soybean sole crops and intercrops from December 2012-May 2013 in Balcarce, Argentina. C-S and S-S represent sole corn and sole soybean agroecosystems respectively, and 1:2 intercrop represents the intercropping design of 1 row corn to 2 rows soybean, and 2:3 intercrop 2 rows corn and 3 rows soybean. Non-matching letters indicate significant differences (α = 0.05 ; 95% confidence interval).

Date & Treatment		N	$\overline{x}$	S.D	S.E	Min	Max	Date & Treatment		N	$\overline{x}$	S.D	S.E	Min	Max
11-DEC-12	C	6	30.9	6.86	2.80	21.4	39.2	5-FEB-13	C	6	29.4^{a}	2.15	.88	25.4	31.8
	S	6	32.1	4.53	1.85	24.1	37.3		S	6	20.4^{b}	6.02	2.46	14.5	29.8
	1:2	6	30.8	4.77	1.95	24.9	37.3		1:2	6	27.9^{ab}	5.41	2.21	21.7	35.7
	2:3	6	31.6	5.38	2.20	22.5	38.6		2:3	6	30.1^{a}	4.92	2.01	24.1	37.9
	Total	24	31.4	5.12	1.05	21.4	39.2		Total	24	26.9	6.01	1.23	14.5	37.9
19-DEC-12	C	6	29.0	6.08	2.48	17.7	34.4	14-FEB-13	C						
	S	6	31.3	1.44	.59	29.4	33.2		S						
	1:2	6	31.3	7.88	3.22	18.9	40.5		1:2						
	2:3	6	30.4	7.96	3.25	22.5	43.3		2:3						
	Total	24	30.5	6.05	1.24	17.7	43.3		Total						
24-DEC-12	C	6	27.4	4.23	1.73	23.8	34.2	21-FEB-13	C	6	13.8	5.73	2.34	8.9	23.3
	S	6	30.3	2.74	1.12	27.7	33.8		S	6	17.9	4.80	1.96	13.3	26.3
	1:2	6	31.6	4.62	1.89	23.4	36.0		1:2	6	15.3	4.37	1.78	11.2	23.6
	2:3	6	28.7	3.32	1.36	25.1	34.7		2:3	6	22.0	4.93	2.01	14.5	29.4
	Total	24	29.5	3.89	.79	23.4	36.0		Total	24	17.2	5.61	1.15	8.9	29.4
28-DEC-12	C	6	55.5	5.32	2.17	49.1	63.3	26-FEB-13	C	6	23.8^{a}	3.69	1.50	20.1	30.2
	S	6	60.5	4.92	2.01	53.2	67.3		S	6	40.5^{b}	9.70	3.96	28.3	57.6
	1:2	6	53.6	5.48	2.24	48.0	60.7		1:2	6	33.0^{ab}	6.48	2.65	21.6	41.2
	2:3	6	57.5	5.53	2.26	49.4	64.4		2:3	6	35.1^{ab}	11.88	4.85	22.0	54.5
	Total	24	56.8	5.61	1.15	48.0	67.3		Total	24	33.1	10.07	2.06	20.1	57.6
03-JAN-13	C	6	33.4	5.70	2.32	26.7	42.1	02-MAR-13	C	6	42.8	4.71	1.92	35.9	48.9
	S	6	33.4	6.57	2.68	23.3	41.6		S	6	47.9	5.78	2.36	38.6	55.2
	1:2	6	25.4	4.25	1.74	21.0	33.0		1:2	6	47.2	4.75	1.94	42.2	55.4
	2:3	6	32.1	6.56	2.64	22.7	39.2		2:3	6	46.7	5.35	2.18	40.7	54.9
	Total	24	31.8	6.39	1.30	21.0	42.1		Total	24	46.2	5.22	1.07	35.9	55.4
09-JAN-13	C	6	35.3	4.94	2.02	30.0	43.9	12-MAR-13	C	6	42.2	4.81	1.96	34.3	47.9
	S	6	35.0	6.25	2.55	24.5	43.6		S	6	46.8	5.92	2.42	39.8	56.6
	1:2	6	33.7	3.09	1.26	29.3	37.5		1:2	6	47.8	3.74	1.53	44.6	53.6
	2:3	6	35.1	6.74	2.75	25.7	43.2		2:3	6	46.4	3.19	1.30	42.4	50.2
	Total	24	34.8	5.12	1.04	24.5	43.9		Total	24	45.8	4.76	.97	34.3	56.6
15-JAN-13	C	5	19.7	1.87	.84	17.0	22.0	21-MAR-13	C	6	43.3	3.23	1.32	38.4	47.2
	S	6	22.5	4.00	1.63	17.4	27.3		S	6	47.8	4.33	1.77	41.7	53.6
	1:2	6	24.7	7.58	3.09	16.7	36.7		1:2	6	42.0	4.67	1.90	35.7	48.0
	2:3	6	25.2	5.17	2.11	18.6	30.9		2:3	6	47.8	6.94	2.83	40.1	59.1
	Total	23	23.2	5.30	1.10	16.7	36.7		Total	24	45.2	5.35	1.09	35.7	59.1
22-JAN-13	C	6	42.1	4.97	2.03	35.1	48.7	27-MAR-13	C	6	45.2	4.82	1.97	39.6	51.6
	S	6	34.0	4.05	1.65	26.5	38.1		S	6	47.7	4.51	1.84	40.7	52.8
	1:2	6	33.1	5.71	2.33	26.1	41.1		1:2	6	46.6	6.09	2.49	40.4	53.0
	2:3	6	35.6	6.65	2.71	25.7	45.6		2:3	6	46.5	4.16	1.70	40.2	50.7
	Total	24	36.2	6.21	1.27	25.7	48.7		Total	24	46.5	4.70	.96	39.6	53.0
29-JAN-13	C	6	16.7	7.61	3.11	8.5	30.0	3-APR-13	C	6	56.7	3.67	1.50	53.0	62.9
	S	6	20.1	8.46	3.46	11.0	29.8		S	6	59.1	7.99	3.26	44.1	67.9
	1:2	6	23.3	4.61	1.88	17.5	28.9		1:2	6	57.5	4.58	1.87	50.1	63.4
	2:3	6	19.5	6.73	2.75	8.4	26.9		2:3	5	60.8	6.07	2.71	51.2	66.3
	Total	24	19.9	6.95	1.42	8.4	30.0		Total	23	58.4	5.61	1.17	44.1	67.9

Continuation of Table 9.1.13. Descriptives for water-filled porosity space (%) 2012-2013

Date & Treatment		N	$\bar{x}$	S.D	S.E	Min	Max	Date & Treatment		N	$\bar{x}$	S.D	S.E	Min	Max
10-APR-13	C	6	45.2	4.82	1.97	39.6	51.6	30-APR-13	C	6	48.6	1.85	.75	45.2	50.4
	S	6	47.7	4.51	1.84	40.7	52.8		S	6	49.7	5.55	2.27	43.6	56.5
	1:2	6	46.6	6.09	2.49	40.4	53.0		1:2	6	49.9	4.35	1.78	42.6	56.1
	2:3	6	46.5	4.16	1.70	40.2	50.7		2:3	6	46.8	6.10	2.49	35.6	53.8
	Total	24	46.5	4.70	.96	39.6	53.0		Total	24	48.8	4.61	.94	35.6	56.5
17-APR-13	C	6	37.9	5.24	2.14	31.8	44.2	7-MAY-13	C	6	45.5	4.28	1.75	40.1	49.5
	S	6	40.2	7.54	3.08	31.0	50.1		S	6	48.8	3.06	1.25	43.6	52.6
	1:2	6	43.9	5.29	2.16	35.1	51.1		1:2	6	48.2	8.73	3.56	36.7	59.0
	2:3	6	44.7	5.96	2.43	34.5	50.0		2:3	6	49.3	3.98	1.62	43.7	52.8
	Total	24	41.7	6.35	1.30	31.0	51.1		Total	24	48.0	5.32	1.09	36.7	59.0
24-APR-13	C	6	37.1	8.24	3.36	25.4	46.3	14-MAY-13	C	6	47.2	8.22	3.36	33.0	57.9
	S	6	40.2	5.05	2.06	33.1	46.3		S	6	41.5	7.94	3.24	29.1	48.9
	1:2	6	38.0	3.44	1.40	34.7	44.2		1:2	6	39.7	5.08	2.07	31.2	43.8
	2:3	6	37.4	6.66	2.72	27.7	44.9		2:3	6	40.0	5.48	2.24	33.6	47.5
	Total	24	38.2	5.83	1.19	25.4	46.3		Total	24	42.1	7.08	1.44	29.1	57.9

Table 9.1.14. Descriptives for weekly soil temperature (°C) that were collected during chamber measurements in corn-soybean sole crops and intercrops from December 2012-May 2013 in Balcarce, Argentina. C-S and S-S represent sole corn and sole Soybean agroecosystems respectively, and 1:2 intercrop represents the intercropping design of 1 row corn to 2 rows soybean, and 2:3 intercrop 2 rows corn and 3 rows soybean. Non-matching letters indicate significant differences (α = 0.05 ; 95% confidence interval).

Date & Treatment		N	$\bar{x}$	S.D	S.E	Min	Max	Date & Treatment		N	$\bar{x}$	S.D	S.E	Min	Max
11-DEC-12	C	6	35.7	1.34	.55	34.4	37.7	03-JAN-13	C	6	25.1	1.69	.69	23.9	27.7
	S	6	34.9	2.02	.82	32.2	36.8		S	6	28.0	1.80	.73	25.3	29.8
	1:2	6	34.8	1.42	.58	32.6	36.4		1:2	6	27.0	3.19	1.30	24.2	32.4
	2:3	6	35.7	.96	.39	33.9	36.7		2:3	6	24.6	2.99	1.22	22.3	29.8
	Total	24	35.3	1.45	.30	32.2	37.7		Total	24	26.2	2.74	.56	22.3	32.4
19-DEC-12	C	6	27.7	1.89	.77	26.0	30.5	09-JAN-13	C	6	24.9^{a}	2.23	.91	22.4	28.3
	S	6	28.5	1.91	.78	25.9	30.3		S	6	31.2^{b}	1.64	.67	29.2	34.0
	1:2	6	27.3	1.34	.55	26.0	29.3		1:2	6	30.0^{b}	2.55	1.04	27.5	33.9
	2:3	6	28.9	2.65	1.08	25.2	31.1		2:3	6	24.3^{a}	1.34	.55	22.6	25.7
	Total	24	28.1	1.98	.40	25.2	31.1		Total	24	27.6	3.61	.74	22.4	34.0
24-DEC-12	C	6	36.5	2.26	.92	32.7	38.6	15-JAN-13	C	6	28.4^{a}	.57	.23	27.8	29.1
	S	6	34.9	.65	.27	34.0	35.5		S	6	33.6^{c}	1.17	.48	32.2	35.2
	1:2	6	35.8	1.90	.77	33.5	37.7		1:2	6	30.9^{b}	1.76	.72	28.8	33.7
	2:3	6	35.0	1.93	.79	32.8	37.7		2:3	5	28.6^{a}	1.14	.51	27.3	29.8
	Total	24	35.6	1.79	.37	32.7	38.6		Total	23	30.4	2.44	.51	27.3	35.2
28-DEC-12	C	6	24.4	.82	.34	23.3	25.6	22-JAN-13	C	6	25.6^{a}	.57	.23	24.9	26.6
	S	6	23.9	.33	.14	23.4	24.4		S	6	32.3^{b}	1.09	.45	30.2	33.2
	1:2	6	24.1	1.33	.54	22.3	26.1		1:2	6	27.6^{a}	1.17	.48	25.3	28.6
	2:3	6	23.6	1.05	.43	21.8	24.8		2:3	6	25.4^{a}	1.45	.59	23.8	28.1
	Total	24	24.0	.95	.19	21.8	26.1		Total	24	27.7	3.04	.62	23.8	33.2

Continuation of Table 9.1.14. – Descriptives for weekly soil temperature (°C) 2012-2013.

Date & Treatment		N	$\bar{x}$	S.D	S.E	Min	Max	Date & Treatment		N	$\bar{x}$	S.D	S.E	Min	Max
29-JAN-13	C	6	24.0^{a}	.78	.32	23.2	25.0	02-MAR-13	C	6	17.9	.72	.29	17.0	19.1
	S	6	27.7^{b}	.56	.23	26.6	28.1		S	6	17.6	.74	.30	17.1	19.0
	1:2	6	25.5^{c}	.60	.25	25.0	26.3		I- 1:2	6	18.4	.67	.27	17.6	19.1
	2:3	6	26.0^{c}	.64	.26	25.3	27.0		I- 2:3	6	18.0	.83	.34	17.3	19.5
	Total	24	25.8	1.45	.30	23.2	28.1		Total	24	18.0	.76	.16	17.0	19.5
5-FEB-13	C	6	23.6^{a}	1.53	.62	22.0	26.2	12-MAR-13	C	6	15.5	.27	.11	15.0	15.7
	S	6	29.1^{b}	2.10	.86	27.0	33.0		S	6	15.7	.85	.35	15.0	16.8
	1:2	6	25.1^{a}	1.29	.53	23.0	26.3		I- 1:2	6	16.0	.36	.15	15.6	16.5
	2:3	6	22.8^{a}	1.56	.64	21.2	25.7		I- 2:3	6	15.5	.17	.07	15.3	15.8
	Total	24	25.1	2.91	.59	21.2	33.0		Total	24	15.7	.51	.10	15.0	16.8
14-FEB-13	C							21-MAR-13	C	6	20.0	.58	.24	19.4	21.0
	S								S	6	19.8	.43	.18	19.3	20.4
	1:2								I- 1:2	6	20.8	.54	.22	19.8	21.2
	2:3								I- 2:3	6	19.8	.78	.32	18.8	20.8
	Total								Total	24	20.1	.69	.14	18.8	21.2
21-FEB-13	C	6	22.2	.81	.33	21.5	23.6	27-MAR-13	C	6	16.2	.81	.33	15.0	17.3
	S	6	23.1	1.50	.61	21.8	25.2		S	6	16.2	.86	.35	15.2	17.6
	1:2	6	23.2	1.04	.42	22.1	24.6		1:2	6	17.6	.79	.32	16.5	18.9
	2:3	6	22.6	.52	.21	22.2	23.6		2:3	6	16.8	.95	.39	15.9	18.5
	Total	24	22.8	1.05	.21	21.5	25.2		Total	24	16.7	1.00	.20	15.0	18.9
26-FEB-13	C	6	16.4^{a}	.61	.25	15.8	17.2	03-APR-13	C	6	20.3^{a}	.49	.20	19.4	20.7
	S	6	17.0^{ab}	.63	.26	16.0	17.9		S	6	19.7^{a}	.41	.17	19.1	20.3
	1:2	6	17.8^{b}	.54	.22	16.9	18.5		1:2	6	21.1^{b}	.47	.19	20.3	21.6
	2:3	6	16.8^{a}	.31	.13	16.2	17.0		2:3	6	19.7^{a}	.43	.17	19.4	20.4
	Total	24	17.0	.73	.15	15.8	18.5		Total	24	20.2	.72	.15	19.1	21.6

Monthly soil nitrogen concentration descriptives

Table 9.1.15. Soil nitrogen concentrations (Kg N ha^{-1}) at 0-15 cm depth for corn-soybean sole crop and intercropping system treatments.

Treatment	2012-2013 Nitrogen soil concentrations (Kg N ha^{-1})				
	N	NH_4^+	NO_3^-	Total Inorganic N	NO3 : NH4 ratio
		------------------------December 11, 2012 (Pre-fertilizer)------------------------			
Sole Corn	3	5.7 ± 1.79	43.1 ± 11.17	48.8 ± 10.63	11.5 ± 6.55
Sole Soybean	3	3.8 ± 1.66	69.5 ± 12.18	73.4 ± 13.40	22.5 ± 5.50
1:2 Intercrop	3	3.9 ± 2.04	42.8 ± 21.55	46.6 ± 19.52	29.3 ± 20.05
2:3 Intercrop	3	3.8 ± 1.28	84.1 ± 24.72	88.0 ± 25.93	22.9 ± 3.61
		---------------------December 19, 2012 (Pre-fertilizer)-------------------------			
Sole Corn	3	6.0 ± 2.96	43.8 ± 11.29	49.7 ± 12.96	9.6 ± 3.56
Sole Soybean	3	1.2 ± 0.28	13.5 ± 12.67	14.7 ± 12.94	7.9 ± 6.97
1:2 Intercrop	3	2.2 ± 0.53	12.7 ± 12.13	14.9 ± 12.43	4.7 ± 4.32
2:3 Intercrop	3	2.7 ± 1.05	41.6 ± 10.65	44.3 ± 10.79	22.9 ± 13.20
		------------------------------December 24, 2012--------------------------------------			
Sole Corn	3	8.9 ± 7.02	38.0 ± 20.78	46.9 ± 22.75	10.3 ± 9.20
Sole Soybean	3	9.6 ± 3.34	62.5 ± 1.31	72.1 ± 4.27	9.8 ± 4.73
1:2 Intercrop	3	4.7 ± 0.43	61.8 ± 6.52	66.6 ± 6.85	13.1 ± 0.86
2:3 Intercrop	3	4.1 ± 1.60	50.0 ± 24.44	54.1 ± 25.64	11.0 ± 6.12
		------------------------------December 28, 2012--------------------------------------			
Sole Corn	3	0.8 ± 0.83	3.1 ± 2.94	3.9 ± 3.75	0.9 ± 1.42
Sole Soybean	3	0.7 ± 0.27	0.6 ± 0.01	1.2 ± 0.28	1.2 ± 0.44
1:2 Intercrop	3	0.2 ± 0.09	9.4 ± 8.40	9.6 ± 8.45	32.0 ± 30.51
2:3 Intercrop	3	1.5 ± 0.60	5.5 ± 3.48	7.0 ± 3.94	2.9 ± 1.48
		------------------------------January 16, 2013---			
Sole Corn	3	1.6 ± 0.72	5.9 ± 3.98	7.6 ± 4.70	2.9 ± 0.92
Sole Soybean	3	2.7 ± 1.54	26.9 ± 2.34	29.6 ± 3.18	18.8 ± 9.74
1:2 Intercrop	3	2.9 ± 1.05	16.2 ± 2.83	19.1 ± 3.37	7.8 ± 3.75
2:3 Intercrop	3	1.5 ± 0.55	12.7 ± 5.50	14.2 ± 5.53	10.0 ± 5.37
		-------------------------------February 27, 2013--------------------------------------			
Sole Corn	3	6.0 ± 1.90	7.9 ± 1.52	13.9 ± 2.87	1.5 ± 0.34
Sole Soybean	3	2.1 ± 0.32	11.6 ± 6.75	13.7 ± 6.45	6.7 ± 4.66
1:2 Intercrop	3	0.9 ± 0.35	7.4 ± 3.27	8.2 ± 3.27	10.8 ± 6.61
2:3 Intercrop	3	3.5 ± 1.96	7.6 ± 1.10	11.1± 1.45	6.1 ± 4.04
		--------------------------------March 20, 2013---			
Sole Corn	3	2.6 ± 0.10	8.2 ± 4.49	10.9 ± 5.12	4.1 ± 1.59
Sole Soybean	3	2.0 ± 0.92	1.8 ± 1.09	3.8 ± 1.99	0.9 ± 0.18
1:2 Intercrop	3	3.4 ± 0.31	6.5 ± 1.03	9.9 ± 1.03	1.9 ± 0.38
2:3 Intercrop	3	11.7 ± 4.29	11.8 ± 2.82	23.4 ± 5.66	1.3 ± 0.36
		-----------------------------April 23, 2013---			
Sole Corn	3	12.5 ± 3.63	10.4 ± 2.75	22.8 ± 5.87	0.9 ± 0.26
Sole Soybean	3	7.8 ± 1.17	10.3 ± 1.72	18.1 ± 0.73	1.4 ± 0.38
1:2 Intercrop	3	8.6 ± 0.59	6.2 ± 2.03	14.8 ± 1.46	0.7 ± 0.27
2:3 Intercrop	3	13.2 ± 2.25	6.3 ± 2.36	19.5 ± 3.58	0.5 ± 0.20
		--------------------------------May 13, 2013---			
Sole Corn	3	14.5 ± 0.65	15.5 ± 1.85	30.0 ± 2.34	1.1 ± 0.10
Sole Soybean	3	15.5 ± 1.52	16.6 ± 1.24	31.8 ± 1.60	1.1 ± 0.15
1:2 Intercrop	3	19.4 ± 5.84	16.8 ± 2.64	36.2 ± 8.48	0.9 ± 0.11
2:3 Intercrop	3	26.3 ± 6.37	16.9 ± 2.88	43.2 ± 8.72	0.7 ± 0.09

9.2 QUALITATIVE STUDY DATA

Table 9.2. Articles published that obtained land equivalent ratios (LERs) for sustainable intensive summer intercrops in the southeast Buenos Aires region, Argentina.

Article	Season	Location	LER
Corn-Soybean Intercropping			
Monzon et al. 2014	2004-2008	Balcarce, BA	0.86-1.08
Echarte et al. 2011	2005-2006	Balcarce, BA	0.96-1.13
Coll et al. 2012	2005-2007	Balcarce BA	1.03-1.05
Chapter 4	2011-2013	Balcarce, BA	0.82-1.27*
Sunflower – Soybean Intercropping			
Coll et al. 2012	2005-2007	Balcarce BA	0.97-1.24
Echarte et al. 2011	2006-2007	Balcarce BA	0.93-1.31
de la Fuenta et al. 2014	2007-2008	Tandil, BA	1.27

* Rainfed yields. all other LER values were from irrigated sites.

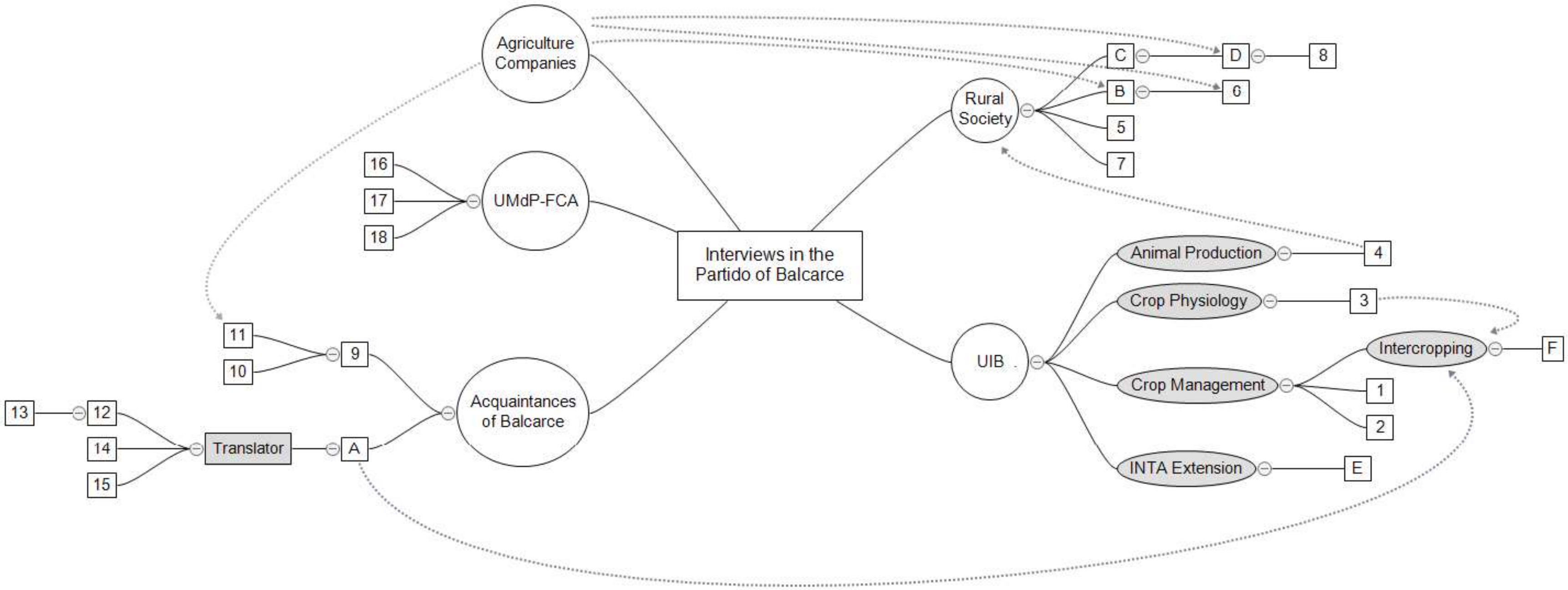

Figure 9.2. A cognitive map of acquiring interviewed participants. White circles represent main introduction facilities to participants. UMdP-FCA, UIB, and AACREA denote University of Mar del Plata Faculty of Agriculture Sciences, Balcarce Integrated Unit, and Argentina Association of Region Consortiums for Agriculture Experimentation, respectively. Shaded ellipses represent departments within the UIB. White squares with numbers signify those who participated in the semi-structured interviews, white squares with letters represent those who participated in extended interviews. Solid lines indicate direct connections from snowball sampling. The translator (grey rectangle) translated most interviews and aided in referring participants. Dotted lines indicate indirect connections determined during interviews

9.3 INTERDISCIPLINARY STUDY DATA

Table 9.3.1. Cross-referencing multiple discipline resources in sustainability categories for characterizing modernized corn-soybean intercropping as a sustainable-intensive cropping practice in the southeast Buenos Aires Pampas.

Sustainable-intensive parameters	**Supporting sources**		
	Intercropping literature related to case-study	**Case study findings & experience**	**Supportive interview quotes for subcategory**
Sustainability categories			
Knowledge intensity			
Sufficient research available on practice	Caviglia 2009	Chapter 5	A, D
Resources publicly available for practice	N//A	Chapter 5 Field notes	A,B,D,E,2, 8, 10, 18
Farmer networks	Calviño and Monzon 2009; Monzon et al. 2014	Chapter 3 & 5	A, B, D, 1,2,3,4,9,10,18
Socio-political suitability			
Government support	Caviglia et al. 2004; Calviño and Monzon 2009	Chapter 3 & 5;	A, B, C, D, E, F, 3, 4, 6, 7, 8, 9, 11, 14, 15, 16
Community & infrastructure support	N/A	Chapter 3;& 5	A, B, C, D, E, F
Amend to land tenure conditions	Cavligia and Andrade 2010	Chapter 3 & 5	A ,B, C, D, E, F, 1, 3, 9, 2, 16
Diversity & complexity			
Production & landscape diversity	Calviño and Monzon 2009	Chapter 4, 5; Field notes	A, C, D, E, F, 2, 3
Market diversification	Coll et al. 2012 Monzon et al., 2014	Chapter 3 & 4;	B, C, D, E, 1, 3, 12
Species diversity & welfare	Bichel et al. 2016; Bichel et al. 2017;	N/A	E
Long-term environmental outcomes			
Improve water use efficiency & water quality	Valenzuela et al. 2009; Dyer 2010; Coll et al. 2012;	Chapter 5;	A, C, E, F, 3
Enhance soil organic matter & soil fertility	Regehr et al.2015; Bichel et al. 2016; Novelli et al, 2017; Oelbermann et al. 2017	Chapter 4; Field notes	D, E,1
Mitigate GHG emission & improve energy efficiency	Dyer 2010;	Chapter 4; Field notes	N/A

Table 9.3.2. Cross-referencing multiple discipline resources in intensification categories for characterizing corn-soybean intercropping as a sustainable-intensive cropping practice in the southeast Buenos Aires Pampas.

Sustainable -intensive parameters	**Supporting sources**		
	Articles that specifically relate to case-study examination	**Case study findings & experience**	**Related interview quotes for subcategory**
Intensification categories			
Chemical input mitigation			
Improve pesticide use efficiency	N/A	Chapter 4 & 5; Field notes	A, 1, 16
Improve fertilizer-use efficiency	N/A	Chapter 4; Field notes	A, D, F, 1, 2, 3, 9, 16
Improve herbicide efficiency	N/A	Chapter 2; Field notes	A, D, F, 3, 6, 16
Labour & technology efficiency			
Technology accessible & affordable to producers	Calviño and Monzon, 2009; Monzon et al. 2014	Chapter 3 & 5; Field notes;	A, B, F, 3, 4
Permits labour flexibility & efficiency	Calviño and Monzon, 2009	Chapter 5; Field notes;	A, 1, 10, 13, 18
Ideal technology existent for practice	Caviglia 2009 Andrade et al. 2012; Agrositio 2015	Chapter 5	A, D, E, 2, 6, 9, 12
Increased production			
Increase crop & landscape intensity	Caviglia 2009; Caviglia & Andrade 2010; Echarte et al. 2011; Monzon et al. 2014	Chapter 2 & 5; Field notes	A, D, E, F, 3
Closing yield gaps	yieldgap 2014	Chapter 2 4; Field notes;	D, E, F
Improving yield quality	Caviglia 2005; Cambareri 2013	N/A	N/A
Short-term profitability			
Reduce natural & manmade risks	Monzon et al. 2014 ,	Chapter 3, 4 & 5; Field notes;	A, B, C, D, F, 2, 6, 8, 9, 19
Affordable initial fixed costs	Calviño and Monzon 2009; Cambareri 2013; Monzon et al. 2014	Chapter 3 & 5;	A, C, D, F, 1, 2, 9, 10, 17
Practice provides competitive income for producers	Coll et al. 2012; Cambareri 2013; Monzon et al. 2014	Chapter 5;	A, B, D, E, 2, 4, 5,13