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# Crop diversification across scales

## - implications for resource use and cropping systems sustainability

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# Crop diversification across scales - implications for resource use and cropping systems sustainability


## Abstract

The industrialization of agriculture and efforts to maximize yields of commodity crops are major drivers of biodiversity loss and disruption of ecosystems balance. To become more sustainable, agriculture needs to be aligned with the delivery of multiple ecosystem services, and reduce its dependency on external inputs and its negative environmental impacts. Increasing crop diversity may be a key strategy to promote multiple benefits and enhance the sustainable development of agroecosystems. More specifically, introducing crop diversification practices such as intercropping, cover crops, or diversified crop rotations may allow for efficient use of resources and enable the synergies of ecosystems processes and functions. In this thesis, I combined theoretical approaches and scientific methods along several scales to assess the sustainability of diversified cropping systems and increase the knowledge of complex cropping systems. The studies include a systematic review, field experiments, farmer interviews, sustainability assessments, and landscape analysis. I found that increasing crop diversity at field, farm, and landscape scales may enable synergies in these agroecosystems without causing yield reductions. Further, crop diversification showed promising effects on nutrient-use efficiency, reduced risk of nutrient losses and promoting associated biodiversity, thereby ensuring environmental sustainability and increasing the resilience of these diversified cropping systems. However, there are still several socio-economic factors that cause disadvantages in these diversified systems, demonstrating the need for increasing policy support or higher market demand for food produced in diversified cropping systems. The findings of this thesis support that increased crop diversity across spatial and temporal scales can contribute to resource-efficient production and enhance the delivery of ecosystem services, thus contributing to more sustainable cropping systems.



*Keywords:* complexity, cover crops, crop diversity, crop rotation, farmers perspectives, intercropping, interdisciplinary, landscape, nutrient use, sustainability.



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# Gröddiversifiering på olika skalor - betydelse för resursanvändning och odlingssystemens hållbarhet


## Sammanfattning

Jordbrukets industrialisering och insatser för skördemaximering i de vanligaste grödorna har orsakat förluster av biologisk mångfald och obalans i ekosystem. För att bli mer hållbart behöver jordbruket minska den negativa miljöpåverkan och beroendet av externa insatsmedel genom att förlita sig mer på ekosystemtjänster. Gröddiversifiering, att öka mångfalden av odlade grödor genom diversifierade växtföljder, samodling och mellangrödor, kan bidra till ökad resurseffektivitet och synergier med ekosystemtjänster. I min avhandling har jag kombinerat studier på olika skalor, med olika vetenskapliga metoder, för att utvärdera hållbarheten hos diversifierade odlingssystem och öka kunskapen om komplexa odlingssystem. Forskningen inkluderar systematisk litteraturgenomgång, fältförsök, intervjuer med lantbrukare, hållbarhetsutvärdering och landskapsanalys. Jag har visat att gröddiversifiering på fält-, gårds och landskapsnivå möjliggör synergier mellan olika funktioner i agroekosystemen utan att orsaka skördeminskningar. En ökad gröddiversitet visade sig ha positiva effekter för effektiv växtnäringsanvändning, minskade växtnäringsförluster och gynnande av biologisk mångfald, faktorer som ökar den miljömässiga hållbarheten och odlingssystemens resiliens. Det finns dock flera socio-ekonomiska faktorer som försvårar gröddiversifiering, och som visar att det behövs politiska styrmedel eller andra insatser för att öka marknadsefterfrågan av produkter från diversifierade odlingssystem. Resultaten i denna avhandling visar att en ökad gröddiversitet på olika skalor kan bidra till mer resurseffektiv produktion och generera ekosystemtjänster, och därmed öka odlingssystemens hållbarhet.


*Nyckelord:* gröddiversitet, hållbarhet, komplexitet, landskap, lantbrukares perspektiv, mellangrödor, samodling, tvärvetenskap, växtföljd, växtnäringsanvändning.



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# Diversificación de cultivos a diferentes escalas: importancia para el uso de recursos y la sostenibilidad de los sistemas de cultivo


## Resumen

La industrialización de la agricultura es una de las principales causantes de la pérdida de biodiversidad y la alteración del equilibrio de los ecosistemas. Para ser más sostenible, la agricultura debe estar alineada con la prestación de múltiples servicios ecosistémicos y reducir al mínimo los impactos ambientales negativos. El aumento de la diversidad de cultivos puede ser una estrategia clave para promover múltiples beneficios y mejorar la sostenibilidad. La introducción de prácticas de diversificación de cultivos, tales como cultivos intercalados, cultivos de cobertura o rotaciones diversificadas, permite un uso eficiente de los recursos y favorece las sinergias de los procesos y funciones de los ecosistemas. En esta tesis, se han combinado enfoques teóricos y métodos científicos a diferentes escalas para evaluar la sostenibilidad de los sistemas de cultivo diversificados. Estos incluyen a revisión sistemática, experimentos de campo, entrevistas a agricultores, evaluaciones de sostenibilidad y análisis del paisaje. Encontré que aumentar la diversidad de cultivos a nivel de la parcela, granja y en el paisaje puede permitir sinergias en estos agroecosistemas sin causar reducciones en el rendimiento. Además, la diversificación de cultivos mostró efectos prometedores sobre la eficiencia del uso de nutrientes, la reducción del riesgo en la pérdida de nutrientes y el fomento de la biodiversidad asociada, lo que garantiza la sostenibilidad ambiental y aumenta la resiliencia de estos sistemas de cultivo diversificados. Sin embargo, todavía hay varios factores socioeconómicos que causan desventajas de estos sistemas diversificados, lo que demuestra la necesidad de un mayor apoyo a través de políticas mas adecuadas, o al incremento en la demanda del mercado de alimentos producidos en sistemas de cultivo diversificados.



*Palabras clave*: complejidad, cultivos de cobertura, cultivos intercalados, diversidad de cultivos, perspectivas de los agricultores, interdisciplinariedad, paisaje, uso de nutrientes, rotación de cultivos, sostenibilidad.



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# Dedication

*To my beloved family and those who I met along the way.*

*“Our thought is universal, for it encompasses all that exists; that is, the visible and the invisible; the great mysteries hidden in Nature, and which until the present most of humankind have been unable to know, since they turn everything into chemistry and science, ignoring that everything, plants and stones included, has its spirit. And all this composes a thought that pervades the Universe; all is united like a breath. This is a thought that has not been made up by me; it is thousands of years old. ”*

**"Pagamentos" and Balance Mamo Zeukukuy**

Arhuaco Universe, Colombia

# Contents

# List of publications

This thesis is based on the work contained in the following papers, referred to by Roman numerals in the text:

I. Rodriguez*, C., Carlsson, G., Englund, J.-E., Flöhr, A., Pelzer, E., Jeuffroy, M.-H., Makowski, D. & Jensen, E.S. (2020). Grain legume-cereal intercropping enhances the use of soil-derived and biologically fixed nitrogen in temperate agroecosystems. A meta-analysis. *European Journal of Agronomy,* 118, 126077.

II. Rodriguez*, C., Dimitrova Mårtensson L.-M., Jensen, E.S., Carlsson, G. Combining crop diversification practices can benefit cereal production in temperate climates. (accepted)

III. Rodriguez*, C., Dimitrova Mårtensson L.-M., Zachrison M., Carlsson, G. Sustainability of diversified organic cropping systems– challenges identified by farmer interviews and multi-criteria assessments. (in review)

IV. Rodriguez*†, C., Lopez Hösel†, S., Dimitrova Mårtensson L.-M., Blennow, K. Is yield loss during drought correlated to landscape-level crop diversity? Development of enabling methodology for crop diversity studies with an application in Scania, Sweden. (manuscript)

 Paper II is in the very last step of the peer-review process at the time of printing, and the definitive version, to be published open access by Agronomy for Sustainable Development, may differ slightly.

*Corresponding author, †Equally contributing authors

The contribution of Carolina Rodriguez to the papers included in this thesis was as follows:

I. Conceptualization and methodology development with the co-authors, investigation, formal analysis, writing original draft.

II. Conceptualization with GC and ESJ, investigation with GC, formal analysis, visualization, writing original draft together with LMDM.

III. Conceptualization with GC, investigation, formal analysis, visualization, writing original draft with input from LMDM.

IV. Conceptualization and methodology development with the co-authors, investigation and formal analysis together with SHL and KB, visualization together with SHL, writing original draft together with LMDM.

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# Abbreviations

| | |
|---|---|
| CR | Critical realism |
| FAO | Food and Agriculture Organization of the United Nations |
| GHG | Greenhouse gas emissions |
| GIS | Geographical information system |
| HLPE | High-Level Panel of Experts for Food Security |
| IPBES | Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services |
| LEGATO | Legumes for the Agriculture of Tomorrow |
| MCDA | Multi-criteria decision aid method |
| N | Nitrogen |
| SAFA | Sustainability assessment of food and agricultural systems |
| SDGs | Sustainable Development Goals |
| SES | Socio-ecological system |
| SITES | Swedish Infrastructure for Ecosystem Science |

# 1. Setting the scene

> "Agriculture should be fundamentally redirected towards modes of production that are more environmentally sustainable and socially just"
>
> (De Schutter 2010, p. 3)[1]

## 1.1 Challenges of current cropping systems

Currently, 38% of the terrestrial land in the world is covered by agricultural activities (Steffen et al. 2015; DeClerck et al. 2016). Agriculture is the largest ecosystem of the Anthropocene (DeClerck et al. 2016) and is considered the largest driver of environmental change (Tilman et al. 2001) and responsible for affecting multiple planetary boundaries (Rockstrom et al. 2009). The negative impact on the environment by farming practices include the widespread degradation of land, the increase of greenhouse gas (GHG) emissions, 70% of freshwater consumption, loss of biodiversity (Ramankutty et al. 2008; Vermeulen et al. 2012; Campbell et al. 2017) and an adverse effect on the natural balance of ecosystems by the disturbance of nutrient cycles such as nitrogen and phosphorous (Gruber & Galloway 2008; Carpenter & Bennett 2011).

The industrialization of agriculture has significantly altered the land use in Europe, simplifying the landscapes and increasing the specialization of farming systems (Benton *et al.* 2003; Godfray *et al.* 2010). This industrialization was possible through the economic, political, and technological incentives that sought to increase agricultural productivity after the post-war in Europe (Gardner 1996). Indeed, the implementation of

[1] https://bit.ly/2Ldenmg accessed 9.12.20

“Green revolution” technologies, including intensive use of external inputs such as chemical fertilizers and pesticides, high-yielding cultivars, mechanization, and increasing livestock densities, boosted agricultural intensification and simplification of farming systems (Matson *et al.* 1997; Foley *et al.* 2005). In the last decades, several agricultural reforms have been implemented having as a consequence the narrow diversity of agricultural systems by increasing the genetic uniformity of crops, reducing the length of crop rotations, decreasing mixed farming systems, segregating product value chains[2], scaling up industrial and homogenous livestock systems and increasing the farm size (Shucksmith *et al.* 2005; Pe'er *et al.* 2014; IPES-Food 2016; Kuemmerle *et al.* 2016; Martin *et al.* 2016).

During the last 50 years, the number of farm holdings in Sweden has declined, particularly small and medium-sized farms, which has facilitated the expansion of large-scale farming systems (Björklund *et al.* 1999). Cereal production accounts for 39 % of the total crop production in the arable land (around 2.6 million hectares), while the numbers of farms with livestock production have decreased in the last decades, being the most affected dairy production (Statistics Sweden 2020b). The landscape simplification (Figure 1) has fundamental implications on biodiversity loss (Tscharntke *et al.* 2005) through both the increase of fragmentation and decreasing habitat heterogeneity and thus, affecting the function of the ecosystems (Benton *et al.* 2003).

Agriculture has to continue producing food, animal feed, and other raw materials necessary to supply the increasing population (FAO 2017). This agricultural production must be focused towards a more sustainable production (Tilman *et al.* 2002) with the goal of efficient use of resources, and supporting the restoration of the functions of agroecosystems (Cardinale *et al.* 2007). Agriculture is based on human-nature interactions, with inevitable disturbance of natural ecosystems. Nevertheless, it is fundamental to address both food security and environmental impact if the Sustainable Development Goals (SDGs) are to be fulfilled (DeClerck *et al.* 2016). Agriculture needs to be embedded in nature using new paths and approaches that help guide the agroecological transition towards sustainability by meeting both people and nature needs now and in the future (Levin & Clark 2010; Sen 2013).

[2] ‘segregation’ here is referring, e.g., to the animal feed production and rearing in separate farms, values chains, and regions (IPES-Food 2016)

*Figure 1.* Current agricultural systems in Sweden.

From top left corner: oilseed rape (photo: Julio Gonzalez, SLU), barley (photo: Jenny Svennås-Gillner, SLU), sugar beets in spring (photo: Georg Carlsson, SLU), winter wheat in autumn (photo: Mårten Svensson), Hay bales on a field (photo: Jenny Svennås-Gillner, SLU), bare soil in winter (photo: Georg Carlsson, SLU).

## 1.2 Re-designing current cropping systems towards more sustainable systems

There is a broad acknowledgment of transforming agri-food systems towards more sustainable systems. Although the discourse of sustainable agriculture has been debated for several years, its implementation has certainly been slow and unclear (Pretty 2008; Garnett *et al.* 2013; Bernard & Lux 2016). For instance, narratives of increasing food production by the continuation of technological innovations through sustainable intensification have been suggested by many actors (The Royal society 2009). In contrast, other scholars have claimed an overhaul of food systems challenges shifting to a deeper transformation of these systems by applying agroecology or agroecological intensification approaches (Wezel *et al.* 2015). The polarization in the debate of sustainable agriculture poses a barrier for agricultural policies and governance dynamics in the food systems (Hinrichs 2014; Anderson *et al.* 2019).

Some scholars acknowledge similarities in sustainable agriculture and agroecology by strengthening food security. However, there are concerns by many other actors regarding clear goals of sustainable intensification in addressing the environmental impacts of industrial agriculture (Wezel *et al.* 2015; IPES-Food 2016). On the other hand, agroecology provides a more holistic approach focusing on reduced external inputs, enhancing diversity, and political transformation supporting more environmental-friendly and socially fair food systems (Francis *et al.* 2003; Altieri *et al.* 2017). Further agroecological intensification is based on local knowledge and promotes participation and the local decision by designing and implementing practices aimed for long-term sustainability in a local context (Gliessman 2013). The High-Level Panel of Experts for Food Security (HLPE 2019) made an effort to combine a list of agroecological principles to enable a coherent understanding of the agroecology definitions that have been provided in recent years (Box 1).

### Box 1: Principles of Agroecology

Agroecology is described as a transdisciplinary, participatory and action-oriented approach across ecological, agricultural, food, nutritional and social sciences[1]

*Improve resource efficiency*

1. Recycling: use local renewable resources
2. Input reduction: reduce the dependency on external or purchased inputs

*Strengthen resilience*

3. Soil health: managing or enhancing soil organic matter and biological activity
4. Ensure animal health and welfare
5. Biodiversity: enhance the diversity of species, functions and genetic resources
6. Synergy: enhance ecological interactions, integration and complementary among components of agroecosystems
7. Economic diversification: diversity on-farm incomes

*Secure social equity*

Co-creation of knowledge: sharing of local and scientific knowledge and innovation, with emphasis on farmer-to-farmer exchange

8. Social values and diets: food systems based on identity, tradition, social and gender quality
9. Fairness: dignified and robust livelihoods
10. Connectivity: strengthened connection between producer and consumers
11. Land and natural resource governance: build up institutional governance to recognise family farmers and smallholder producers
12. Participation: encourage social participation in decision making by both producers and consumers

**Source:** HLPE (2019) report combined agroecological principles from several sources (Nicholls *et al.* 2016; CIDSE 2018; FAO 2018) and consolidated them in a list of 13 principles. **Notes: 1** (Méndez *et al.* 2013; Gliessman 2018; Wezel *et al.* 2020).

*Diversification of cropping systems*

Crop diversification practices go back to the origins of agriculture, particularly among indigenous communities. During the 19th century in Europe, the new husbandry model was characterized by the integrated use of animals and rotations. For example, the rotations included brassicas, cereals, legumes, and the integration of sheep and cattle grazing in the system (Vandermeer 2011). Diversification of cropping systems is a key agroecological principle that may enable the transition to more sustainable agricultural systems. For instance, increasing crop diversity could ensure food security and nutrition (FAO 2018) while enhancing resource use efficiency, reducing negative environmental impacts, and strengthening the resilience of the agroecosystems (Cardinale *et al.* 2007; Tamburini *et al.* 2020). Kremen *et al.* (2012) presented a conceptual framework of the diversified farming systems that "includes functional biodiversity[3] at multiple spatial and/or temporal scales through practices developed by traditional and/or agroecological scientific knowledge". Within this framework, diversified farming systems include practices such as inter-and multi-cropping (including agroforestry) and integration of livestock across the spatial scale. Cover crops, green manure, fallowing and crop rotations are related to both spatial and temporal scales. Further, incorporating non-crop plants in the field borders (hedgerow/buffer strips) is considered as spatial diversification.

Within this thesis, crop diversification practices included for evaluating the sustainability of cropping systems were limited mainly to intercropping, cover crops and green manures, and crop rotation (Table 1). However, some practices related to increased semi-natural habitat by diverse field margins were considered in **paper III** and landscape composition in **paper IV**. Further, Figure 2 illustrates the crop diversification practices included in this thesis.

[3] Functional biodiversity refers to the heterogeneity within crop stand on the expression of giving agroecosystem services (Moonen & Bàrberi 2008)

Table 1. Definitions of crop diversification practices.

Based on (Kremen et al. 2012; Gaba et al. 2014; Beillouin et al. 2019; Rosa-Schleich et al. 2019; Tamburini et al. 2020).

| | **Temporal scale** | **Spatial scale** | **Diversification practices** | **Definition** | **Benefits** | **Key references** |
|---|---|---|---|---|---|---|
| **Crop diversification** | Synchrony | Field | Intercropping | Simultaneous growth of two or more species in the same field during a specific period of time | Increase biodiversity, improve soil health and quality, increase nutrient use efficiency, reduce weed abundance, increase disease and pest control, support pollination, increase productivity and reduce external inputs (agrochemical and mineral fertilizer) | (Vandermeer 1989)<br>(Liebman & Dyck 1993)<br>(Trenbath 1993)<br>(Bedoussac *et al.* 2015)<br>(Hauggaard-Nielsen *et al.* 2001)<br>(Ofori & Stern 1987)<br>(Brooker *et al.* 2015)<br>(Cong *et al.* 2015) |
| | Asynchrony | Field | Cover crops and green manure | Crops no harvested (no for food and feed). Growing between periods of production of main crop---use for diverse purposes such as protecting soil from erosion, improving soil health and quality. Cover crop can be composed by plant species mixtures | Increase biodiversity, improve soil health and reduce soil erosion, improve nutrient management and water holding, reduce weed abundance, increase disease and pest control, support pollination, increase carbon sequestration, increase productivity and reduce external inputs and machinery | (Schipanski *et al.* 2014)<br>(Tonitto *et al.* 2006)<br>(Blanco-Canqui *et al.* 2015)<br>(Abdalla *et al.* 2019)<br>(Poeplau & Don 2015)<br>(Mitchell *et al.* 2013)<br>(Letourneau *et al.* 2011)<br>(Tribouillois *et al.* 2015) |
| | Asynchrony | Field | Diversified crop sequence/rotation | Temporal sequence of different crops grown on the same field. Crop sequences | Increase biodiversity, improve soil health, increase nutrient availability, reduce | (Duru *et al.* 2015)<br>(Bennett *et al.* 2012) |

| | | | | | | |
|---|---|---|---|---|---|---|
| | | | | can include grain crop, forages, cover crops and rotational grazing | weed abundance, increase disease and pest control, support pollination, increase carbon sequestration, increase productivity and reduce external inputs | |
| **Non-crop diversification** | Synchrony | Field | Diverse field margins | Non- crop vegetation in the field perimeter scale (e.g., flower and grass margins, buffer strips, hedgerow) | Increase biodiversity, support pollination and pest control, | (Marshall & Moonen 2002)<br>(Denys & Tscharntke 2002) |
| | | Landscape | Landscape heterogeneity | Landscape composition and configuration (e.g., perennial habitat diversity, semi-natural habitat cover, mosaics of crop types) | Increase biodiversity, support pollination and pest control. | (Veres *et al.* 2013)<br>(Sirami *et al.* 2019)<br>(Holland *et al.* 2016)<br>(Redlich *et al.* 2018b) |

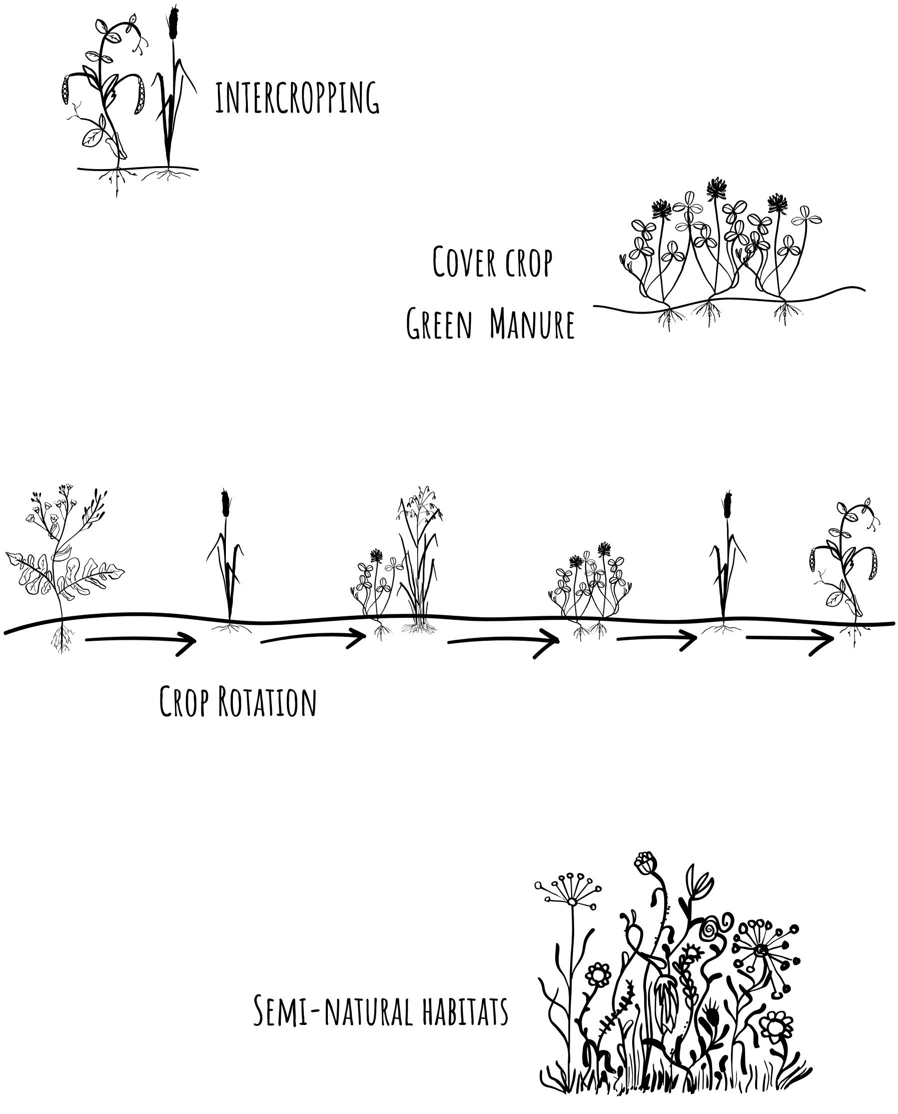


*Figure 2.* Illustration of crop diversification practices

## 1.3 Understanding the gaps for agroecological transition

The Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services (IPBES) Global Assessment recognizes the importance of agroecological approaches and cross-sectoral integrated landscape as pathways to transform current agricultural production systems, thus enabling food security while conserving biodiversity both inclusively and equitably. Furthermore, the assessment highlighted the need for engagement by all the actors related to the specific landscape to resolve trade-offs among objectives, certification, agri-environmental schemes, and research on agroecological intensification practices (IPBES 2019).

In recent years, diversified farming and cropping systems have already been recognized for enhancing the sustainability of agricultural systems and maintaining the provisioning of ecosystem services (Kremen & Miles 2012). There is empirical evidence showing win-win conditions by both agricultural production and the environment of on-farm diversity (Davis *et al.* 2012; Valkama *et al.* 2015; Kleijn *et al.* 2019). Besides, diversified farming systems may also improve several social and economic aspects of the agricultural enterprise (Kremen *et al.* 2012). However, Jensen *et al.* (2015) highlighted the shortage of understanding of the potential of intercropping in the organic and conventional farming systems. Furthermore, interactions in the supply chain and marketing conditions might create barriers that limit the adoption of diversified systems among farmers (Iles & Marsh 2012). In the case of Europe, other barriers and lock-ins have been identified which limited the adoption of crop diversification practices, such as the added value of alternative and minor crops, lack of knowledge of the complex and diversified system, limitation of adapted inputs, and marketing and poor development of technologies and innovations adapted to these diversified systems (Meynard *et al.* 2018; Morel *et al.* 2020).

Agroecological research on crop diversification practices offers opportunities to investigate and address knowledge gaps about the functions and services of diversified cropping systems and may contribute to alleviating barriers that farmers face when trying to implement diversification practices. With the growing interest in meeting sustainability goals, it was possible to systematically study the effects of crop diversification on the spatial and temporal scales having in mind socio-ecological frames.

Some concepts and terms are widely used in research about food and agricultural systems. To increase clarity and readability, I have included a list of key concepts used in this thesis (Table 2).

Table 2. Glossary of terms used in the thesis

| **Terms** | **Definition** |
|---|---|
| Socio-ecological systems (SES) | Complex and dynamic systems linking ecosystems and human society (Berkes & Folke 1998; Folke *et al.* 2005) |
| Cropping system | Cropping system refers to the choice of crops and set of field-level management practices applied to each crop which are part of the same crop rotation. |
| Farming system | Farming system refers to the entire farm organisation and the interaction between their subcomponents (or enterprises). |
| Crop diversity | Crop diversity refers to all diversity within and among wild and domesticated crop species (Wood & Lenné 1999). |
| Crop diversification | The effort to increase the diversity of crops (including annual and perennial) through e.g., crop rotation, multiple cropping, varietal mixture (Hufnagel *et al.* 2020). |
| Ecosystem services | The benefits that organisms provide to humans (Millennium Ecosystem Assessment 2005). |
| Interdisciplinary | "Interdisciplinary is a means of answering questions that cannot be satisfactorily addressed using single methods or approaches." (Klein 1990). |
| Transdisciplinary | "Transdisciplinarity is a reflexive, integrative, method-driven scientific principle aiming at the solution or transition of societal problems and concurrently of related scientific problems by differentiating and integrating knowledge from various scientific and societal bodies of knowledge." (Lang *et al.* 2012) |
| Monocropping | Growing a single plant species in a given field. Continuous monocropping growing the same crop species year after year (Garland *et al.* 2021). |
| Associated diversity | The diversity that persists in agricultural settings, but is not directly chosen (e.g., soil biota, wild pollinators, natural pest enemies, etc.); governed by ecological processes that allow these organisms to persist in agricultural settings (Wood *et al.* 2015). |

## 1.4 Research focus, aim and questions

There is strong scientific evidence demonstrating that diversified farming systems provide a broad range of ecological and social services (Bacon *et al.* 2012; Kremen & Miles 2012). However, there is a lack of support for implementing diversified farming systems to a larger extent. Policy, financial support, and research have mainly focused on increasing the productivity of commodity crops, with limited attention to the adoption of diversified cropping systems services (Kremen & Miles 2012). With the negative effect on the environment by agricultural systems and climate change, there is a need to transform towards more sustainable food systems, securing food and ecosystems through more efficient use of natural resources. Limited awareness and difficulties in evaluating the benefits of diversified cropping systems constrain the adoption of these practices. **The overall goal of my research was to improve the understanding of how diversified cropping systems enhance sustainability in a local context, with particular attention to the benefits, trade-offs, and hinders for implementation of diversification practices in cropping systems in the Scania region, southern Sweden.** The aim of this thesis is to increase the knowledge on complex systems by exploring the effects of crop diversification practices on the spatial and temporal scales in functions and services of agroecosystems through the inclusion of the following sustainability criteria: nutrient use efficiency, weed control, land use, and feasibility. In doing so, we hope to generate knowledge and guidelines for the design, implementation, and management of diversified cropping systems. Accordingly, the overarching research question addressed in the present thesis is:

> *Do crop diversification practices have the potential to enhance the sustainability of agricultural production systems?*

The following, more specific research questions are addressed in the papers included in this thesis (Figure 3):

1. Which synergistic and antagonistic effects do different crop diversification practices have on ecosystem services in farmland?
2. Which are the social, economic, and environmental impacts that strengthen or constrain diversified cropping systems?
3. How is the landscape composition in the agricultural region of Scania, and how is it related to crop productivity?

4. What are the perceptions farmers may have for implementing crop diversification practices?

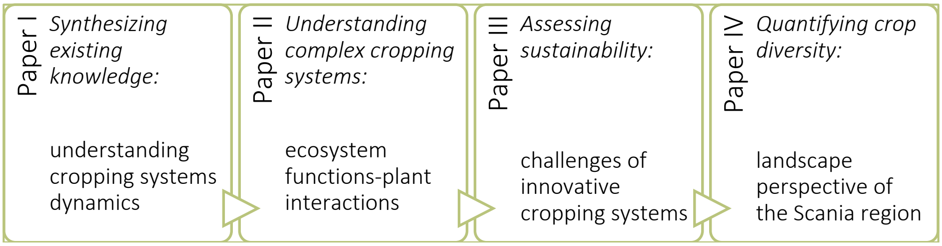


*Figure 3*. Overview of the papers included in this thesis and their analytical focus with respect to the theoretical framework on complex and socio ecological systems.

**Paper I** provides an evidence-based synthesis of crop diversification, specifically how intercropping influences the use of N resources by grain legumes and cereal plants in temperate agroecosystems.
**Paper II** examines how crop diversification influences the performance of crops in crop rotation sequences of grain legumes and cereals, with and without the integration of cover crops, in terms of crop yield, weed suppression and the use of N resources.
**Paper III** presents sustainability assessments of farm-based data on diversified cropping systems, describing the strengths and challenges in the sustainability of organic cropping systems.
**Paper IV** shows the geographical representation of landscape crop diversity in the Scania region and explores how crop diversity affects agriculture's ability to withstand and produce crops even under changing climate.

## 1.5 Contribution to sustainability science

*Sustainability science* is an emerging field that focuses on the dynamic of human-environment interactions across scales (Kates *et al.* 2001; Jerneck *et al.* 2010), seeking to solve both general and complex issues through evidence-supported solutions (Wiek & Lang 2016) that bridges different disciplines from natural and social science (inter-and transdisciplinary). In fact, sustainability science implements a holistic approach to better understand the current problems affecting modern society. It thereby applies both problem-driven and solution-oriented research methods, tailoring particular and context-based issues. Further, sustainability science translates research into action to achieve sustainable development goals (SDGs) through promoting social learning and participatory action-oriented research (Miller *et al.* 2013). In this thesis, the challenge was to understand the complexity of agricultural systems and the issues related to their impact on the environment to make it possible to refer to both environmental and social dimensions concerning sustainability. Doing my thesis in this field allowed me to identify some of the unsustainable farming practices of the current agricultural systems and how they can be improved by the implementation of crop diversification practices. Further, this work hopes to generate transformative knowledge and guidelines on re-designing cropping systems for enhanced sustainability, tackle socio-ecological issues of agri-food systems, and contribute to solving problems such as climate change adaptation and mitigation. The thesis also includes studies on the values and individual beliefs of the farmers who were implementing these practices.

In the following section, I introduce the theoretical background where I integrated different theoretical views and perspectives to understand the complexity of cropping systems.

# 2. Theoretical framing and key concepts

In this chapter, I first present a section on complex theory and socio-ecological systems, focusing on the intertwined human-nature systems. Further, I specify the interaction between spatial and temporal scales of diversified cropping systems, thus emphasizing key measures towards more sustainable farming systems. Finally, I navigate between key concepts and principles of sustainability.

## 2.1 Theories of complex and socio-ecological systems

The theoretical framing of this thesis lies at the interface between complex systems theories and socio-ecological systems (SES). I drew from both fields to formulate my analytical approach to improve the theoretical and applied understanding of diversified cropping systems within the dynamic context of sustainable food systems, innovation and ecosystem services across temporal and spatial scales.

I have aimed towards integrating different perspectives, on one hand understanding agri-food systems as diverse but also complex systems that include different actors, such as producers, sellers, distributors, consumers and governmental institutions, across all the processes. On the other hand, drawing from SES, these complex systems are influenced by social and environmental factors/drivers, which determine how the activities and practices are performed (Figure 4). Complex systems are further seen as:

> "A large network with no central control which raises complex collective behavior and adaptation through learning/evolution." (Mitchell 2009)[4]

Socio-ecological systems are based on complex adaptive systems, and represent a coherent set of dynamic interactions shared by interlinked ecosystems and human societies (Berkes & Folke 1998). These interactions occur across multiple spatial and temporal scales (Gunderson & Holling 2002), motivating the focus on crop diversification across scales in this thesis. The SES is composed of the ecological and social subsystems, of which the first encompasses the ecosystem's dynamics and interactions between the species and their habitats. The social subsystem is focused on the dynamics between individuals, groups, and society in general (McGinnis & Ostrom 2014). Further, these individuals are connected in networks governed by rules and regulations and characterized by constant and dynamic learning where new knowledge is generated (Folke *et al.* 2005; Clark *et al.* 2016).

Considering nature and societal interactions between different scales can help explain context-based challenges for sustainable food systems. The scale interactions between processes and multiple actors may influence the resilience of SES (Walker *et al.* 2004). For example, on a global scale, the uncertainty of economic performance of new/alternative crops (different from those in systems based on mainstream crops) will influence farmers' decisions to diversify or not diversify their cropping system (Sadok *et al.* 2008; Tilman *et al.* 2011; Morel *et al.* 2020). In another context, this interaction will create opportunities to facilitate coordination from the downstream levels of the value chain (e.g., reducing logistical cost from minor crops within processing firms and help the positioning of products from diversified systems with the end consumer) (Meynard *et al.* 2018). Furthermore, crop diversification practices may enhance the heterogeneity in the landscape, thus increasing associated biodiversity and developing rural areas (Benton *et al.* 2003; Fahrig *et al.* 2011; Kleijn *et al.* 2019).

Since a SES is formed by many parts that interact to build up a more complex entity, my intention is to explore the dynamics of these components using a holistic approach rather than focusing on each part. Therefore, I have applied theories from several disciplines, in particular ecology and

[4] Introduction about concepts and theories of complexity in 20th century science.

sociology. This interdisciplinary approach sought to go across the social and ecological dimensions of sustainability science. Ostrom (2009) has highlighted the relevance of including both natural and social science to better understand the SESs. In this thesis, I used SES to help understand the human sources of ecological change. Further, following Walker *et al.* (2004), I see the relevance to understand the driving forces for human motivation actions. However, I do not claim to have based my research on the causes underlying the driven forces. Instead, I tried to understand the effect of direct human activities, through the increase in crop diversity at field and farm scale, on the direct and indirect changes in the ecosystem, thus the capacity of the system to provide goods and services.

Farming landscapes are considered socio-ecological systems, shaped by many natural and human-driven processes (Petrosillo *et al.* 2015; Gaba *et al.* 2020). The SES approach gives a broader perspective of complex systems to help understanding synergies and trade-offs in different domains and at different scales, linking both human and natural systems (Leslie *et al.* 2015). For example, **paper I**, examined how crop diversification at the spatial scale (in particular intercropping) is associated with the sustainability of cropping systems through the efficient use of resources and (e.g., increasing the potential to contribute to the reduction of greenhouse gas emissions). Further, the effect of crop diversification at both the spatial and temporal scale was relevant in **paper II**, which analyzed how the implementation of these different practices impacted several ecosystem functions and services. Moving from the field, the SES provides a framework to scale up to the farm level to better understand social and environmental drivers influencing crop choice and crop management (**paper III and IV**). Having SES as a starting point, I thus provide the potential for a better understanding of the complexities and dynamic interactions associated with diversified cropping systems. I focus particularly on how including the ecological and social dimensions in the cropping systems in sustainability assessments are key to a holistic understanding of these systems.

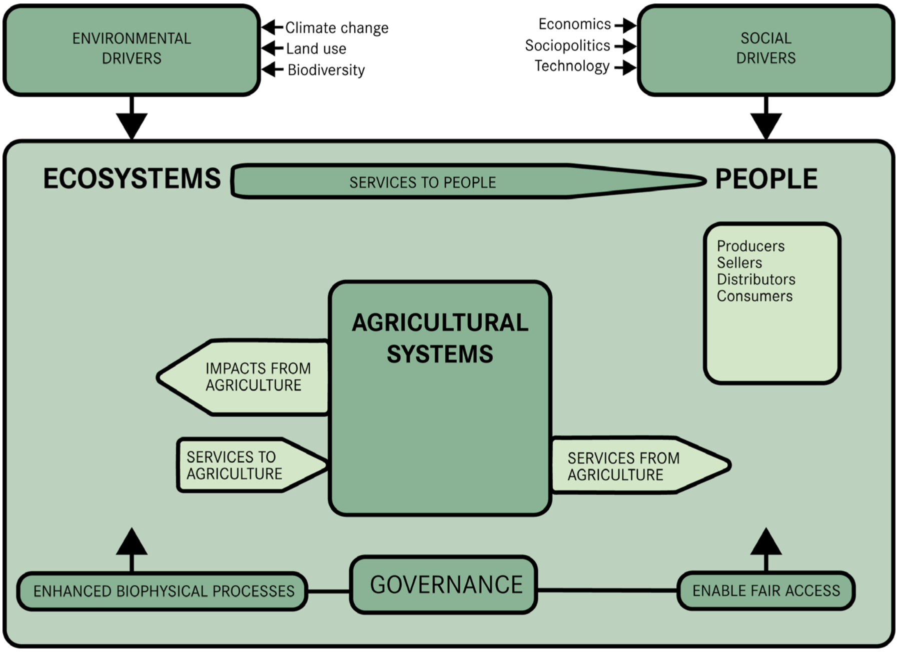


*Figure 4.* The agricultural systems are represented as the interlinkage of components of a socio-ecological system. Figure adapted from (DeClerck *et al.* 2016).

## 2.2 Sustainability: from principles to transformation

Sustainability is a broad and complex discipline with roots in forestry, political economy, social justice, and conservationism ideas (Purvis *et al.* 2018). The term sustainable development gained recognition after the Brundtland Commission of the United Nations in 1983, intending to reach a global agreement to harmonize economic prosperity with ecological health and social equity. The most common definition of sustainable development[5] is *"development that meets the needs of the present without compromising the ability of future generations to meet their own needs."* With human decision-making included, sustainability makes an effort to achieve the transformation of a social paradigm through an ethical view on economic

[5] Published in the *Our common future* report by the World Commission on Environment and Development 1987. Our common future, report. Oxford: Oxford University Press. World Commission on Environmental Development, 1987.

growth and industrialization, bringing a holistic approach of many components such as human well-being, ecosystems, technological development, and institutional change (Edwards & Orr 2005).

In parallel with the socio-ecological complex systems, I refer to the third core principle[6] of sustainability expressed by Ben-Eli (2018) as the way to *"ensure that essential diversity of all forms of life in the biosphere is maintained"*. This principle implies that the use of land should target not only the reduction of any human disturbance on other forms of life but also include the promotion of the capacity of the systems to increase the biodiversity[7] in areas of high degree/level of human habitation. This thesis focuses on the benefits brought by increasing plant diversity in farming systems and is thus aligned with this principle of life and biodiversity.

Agriculture has been coined as the human activity to produce food, feed, fuel, and raw materials through the use of natural resources. The activities vary from the field scale (interconnectedness between soil, water, and plants), farm-scale (crop and livestock production), regional scale (natural resource and land use), and global scale (trade markets and food security) (Smith & McDonald 1998). Sustainable agriculture is contextualized on the management of natural resources by individuals, ecosystem dynamics, and the orientation of technological and institutional changes to ensure human needs (Altieri 1995; Kloppenburg 2010). Emerging forms of alternative management of agricultural production have made it challenging to bring consensus to the definition of sustainable agriculture. Due to the impact of the agri-food systems on the sustainability and the planetary boundaries (Steffen *et al.* 2015; Rockstrom *et al.* 2017) and the failure of policies to reduce environmental deterioration (Foley *et al.* 2011), there is a call for shifting the paradigm of maximized productivity to adopt instead the SES approach involving both environmental sustainability and social wellbeing (Schipanski *et al.* 2016; Bennett 2017). Indeed, scientific knowledge must develop to support policies that promote sustainability transitions and participation and increased local decisions that achieve fundamental changes in our society. This thesis emphasizes the importance of considering cropping systems, not in isolation but as interlinked within the systems

[6] There are five core principles described by Ben-Eli (2018), where he clustered them as material, economic, life, social, and spiritual domains. We focused in this thesis mainly on the domain of life.

[7] Biodiversity is coined from biological diversity and defined as the variety of all forms of life, from genes to species, through to the broad scale of ecosystems (Faith 2020).

components and socio-environmental drivers affecting the systems. To achieve this, I integrated the pillars of sustainability to analyze the potential of these diversified cropping systems in the environmental, economic, and social dimensions. In particular, I aimed to understand the processes and relations of the components of the system when applying diversification practices and how this impacts the environment and affects the viability of the farm economy, and other impacts that may benefit society as well. Despite the progress on theories on transition, transformation, and change theory, in this thesis, I did not include such theories, but I acknowledge along with this study the role of social actors in human-nature linked systems and the capacity to drive change from both SES and agroecology approaches (Ollivier *et al.* 2018). Considering this, I intend to provide an understanding of the importance of diversified systems and as evidence to support further policy-making decisions.

# 3. Methodology

The methodological approach is based on mixed methods and interdisciplinary research, combining quantitative and qualitative analysis, literature reviews, and sustainability assessments. To identify, quantify and evaluate the impact of crop diversification at the regional level, I initially performed a meta-analysis. Second, I evaluated diversification practices using field experiments. Thirdly, synergies and trade-offs resulting from diversification measures and farmer perceptions and motivations towards these measures were analyzed. Lastly, a landscape analysis and farmer interviews provided further insights into regional patterns of crop diversification.

## 3.1 Overall research approach

*Ontological and epistemological starting points*

My research is influenced by critical realism (CR) since this particular approach is applied in sustainability science and intends to join both positivism and social constructivism (Archer *et al.* 2013; Nastar *et al.* 2018). Critical realism originated as a critique against the positivist school of natural science. In the ontological domain, CR postulates a realist view of being, and the epistemological domain encompasses relativism knowledge (Bhaskar 2008), proposing that there is a world that exists and is independent of objectives, structures, and our general knowledge. Furthermore, CR distinguishes what is real (biophysical reality) and the observations or mental constructions about the world. CR recognizes that our knowledge is never unmediated by its dependence on the contemporary time period and culture. *"What must the world be like for science to be possible?"* or *"what must science be like to give us knowledge of intransitive objects (...)?"* (Bhaskar

2008, p.13). CR states that one domain of the stratified reality is empirically reachable and defines science as a way to determine events and causal mechanisms that are hidden or unseen. In brief, it is not easy to assume that our theories are entirely objective reflections of the truth. However, CR is critical in considering that even though the knowledge can be partially socially constructed, it is compatible with the idea of different valid perspectives on reality (Maxwell 2012). Considering the scope of my research contradictions in the socio-ecological and technological system may influence the paradigms and views of the actors within the food system, considered as a social construction.

## 3.2 Methods applied

The main methods in this thesis can be categorized as systematic reviews, empirical analyses, quantitative and qualitative methods of data collection, landscape analysis, and sustainability assessments (Table 2). I have used a mixed methodology approach that combined methods from different disciplines, enabling me to explore and obtain the insights presented in this thesis.

A systematic review was used to deductively identify nitrogen use efficiency in intercropping systems (**paper I**). Data was extracted from field-scale studies presented in published papers to quantify the $N_2$ fixation and acquisition of soil-derived nitrogen by intercropped cereal and legumes plants. The search string returned 811 articles. A screening process excluding 222 articles reporting tropical climates resulted in 589 potentially relevant papers. The papers were systematically selected following specific criteria, including temperate locations, reporting enough information about nitrogen fixation and soil nitrogen acquisition, and include management practices. The final data set was based on 29 articles, including results of 72 experiments.

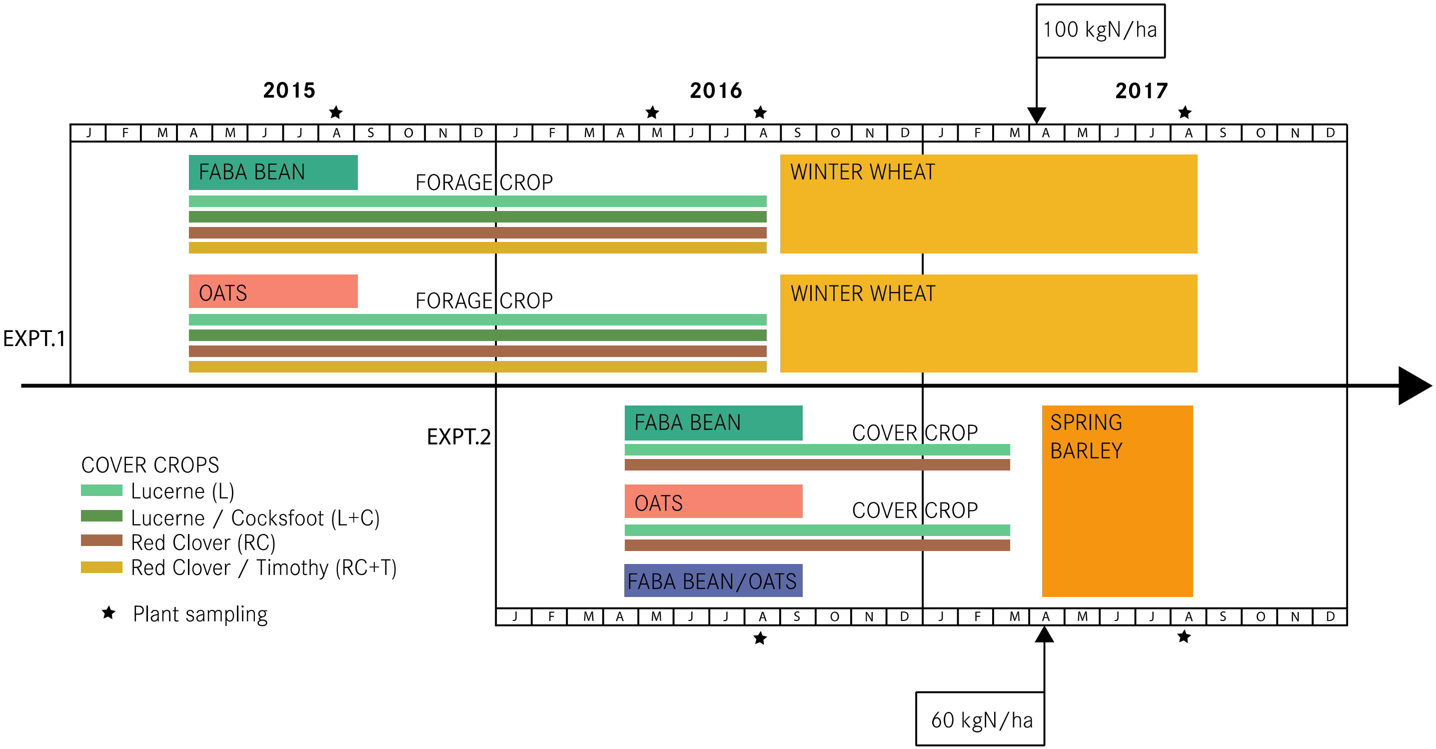


*Figure 5.* Illustration of field experiments.

**Paper II** is based on field experiments, which examined how the combination of crop diversification practices such as intercropping and cover crops influenced the performance of an arable crop sequence in terms of crop grain yield, crop and weed biomass, and nitrogen acquisition. The field experiments were carried out in SITES Lönnstorp research station, SLU, Alnarp (55.65N, 13.06E) in 2015-2017. The experiments were part of the European project LEGATO (Legumes for the Agriculture of Tomorrow), and each experiment integrated several degrees of crop diversification. Each experiment was a complete randomized block design with four replicates and consisted of 12×2 m plots for each crop sequence. Crop grain yield, crop biomass, weed biomass, and nitrogen acquisition were measured at harvest of each of the preceding and cover crop as well as the subsequent cereal. Figure 5 illustrates the different crops included in the field experiments.

A mix of quantitative and qualitative methods was used in **paper III**. The aim was to capture farmers' perceptions on crop diversification practices in organic production and to assess how sustainable those diversified systems are. I used a multi-criteria decision aid method (MCDA) and a sustainability assessment framework built on the SAFA guidelines to illustrate the social, economic, and environmental aspects of the cropping systems. A field experiment representing a diverse cropping system and cropping systems from commercial farms were compared to a reference system which was an example of a moderately diversified arable cropping system in the Scania region. **Paper IV** included a landscape analysis to map the geographical distribution of crop diversity in Scania. The biodiversity Shannon index was used to calculate crop diversity in the region and assisted in identifying spatial patterns within the region. Furthermore, crop yield data under normal climate conditions and abiotic disturbance were included to identify possible correlations with crop diversity.

*Interviews*

Semi-structured interviews were used to gain in-depth information about crop management practices in the farming systems and enable further understanding of the driving forces behind those approaches (**paper III**). Interviews have been used to get detailed insights and experiences from the participants involved. Five farmers were interviewed from different farming systems such as arable cropping systems, animal production, and mixed farming. The interviews explored motivation for crop diversity and identified ecosystem services provided by the current cropping systems and provided information on possible opportunities and obstacles for further inclusion of crop diversification practices.

*Study area*

Scania (Box 2) acts as the case study for **paper III** and **IV**. Scania is the southernmost county in Sweden (Figure 6).

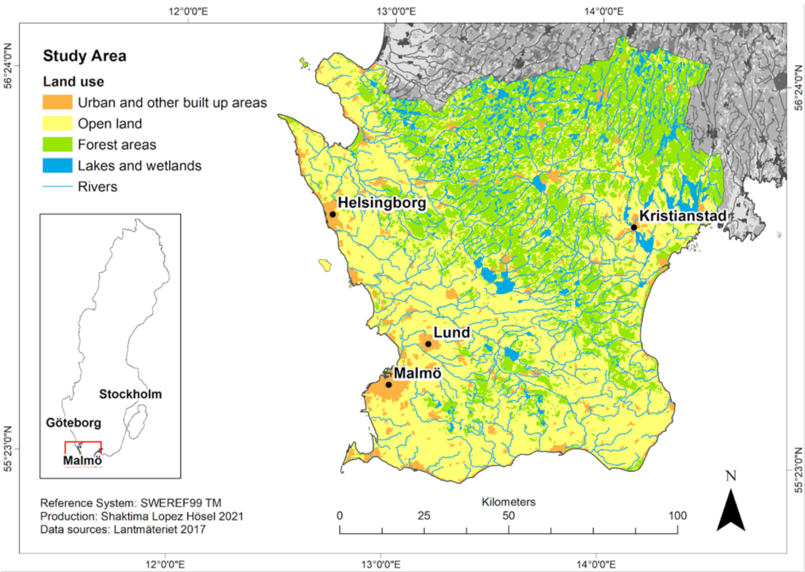


*Figure 6.* The study area and primary land use of the County of Scania, Sweden.

Adapted from GSD-Map of Sweden, (Swedish Land Survey 2018), reproduced under the Creative commons CC0 1.0 Universal license.

### Box 2: Scania region

The total arable land in Scania is around 987 000 hectares and corresponds to 39% of the national arable land. The Agricultural activities based on cereal production are concentrated on the open plains in the southwest, where soils generally have relatively high clay content[1] and high soil fertility[2]. The organic production comprises 37 000 hectares, corresponding to 6.7% of the total organic production area in Sweden. Mixed farming and livestock production are distributed along with the northern and eastern parts of the region, while forest areas are mainly in the northern part of the region. Crop rotations are characterized by stockless crop production, mixed crop-livestock production, or vegetable production.

*Swedish Agricultural policy*

The current agricultural policy[3] in the region is primarily set by the Common Agricultural Policy of the EU. Within the first pillar of the CAP, the greening component[4] of the direct payments to farmers sets a minimum level of crop diversity and aims to improve the conditions for associated biodiversity via so called Ecological Focus Areas. Within the second pillar of the CAP[5], farmers can obtain support for organic production and practices that have positive environmental impacts such as management and conservation of semi-natural meadows and pastures and the establishment of buffer zones to reduce nutrient losses to water.

**Source:** Statistics Sweden (Statistics Sweden 2020a), Government policy (Government Office of Swedish 2018), and Swedish Board of Agriculture. **Notes:**
**1** (Piikki & Söderström 2019) **2** (Soinne *et al.* 2020) **3** https://bit.ly/3h1aM8c accessed 04.05.21 **4** https://bit.ly/3eSPwir accessed 06.05.21. **5** https://bit.ly/2QJtmY1 accessed 06.05.21

Table 3. Description of the methodological elements used in each paper.

| Papers | Methods | Data | Purpose | Type of analysis | Scale |
|---|---|---|---|---|---|
| **I** | Systematic review | Quantitative | Quantify the use of nitrogen resource in intercropping systems | Meta-analysis (mixed effect models) | Field |
| **II** | Empirical analysis | Quantitative | Quantify crop yield, weed biomass and nitrogen acquisition of different crop diversification practices | Field experiments. ANOVA (mixed effect models) | Field |
| **III** | Interviews | Mixed | Identify farmers' perceptions | Interview transcripts were thematically analyzed | Farm |
| | Sustainability assessments | | Assess the sustainability of diversified cropping systems in organic production | multi-criteria decision aid method (MCDA) and sustainability assessment framework | |
| **IV** | Landscape analysis | Quantitative | Mapping spatial patterns | GIS analysis | Landscape |
| | | | Calculate crop diversity | Biodiversity Shannon index | |
| | | | Calculate spatial autocorrelation | Semi-variogram models | |
| | | | Correlate crop diversity with crop yield data from standard climate and under drought conditions | Linear regression | |

# 4. Summary of the results

## 4.1 Diversified cropping systems: Synergies and trade-offs

*Research question 1: Which synergistic and antagonistic effects do different crop diversification practices have on ecosystem services in farmland?*

### 4.1.1 Field scale

A systematic review of intercropping systems is presented in **paper I,** applied to temperate conditions and specific to grain legumes and cereal combinations. The study provided a quantitative synthesis of this particular crop diversification practice and its influence on crop N acquisition. Besides giving an overview of the effects of intercropping on symbiotic $N_2$ fixation and soil N acquisition, this analysis helps identify key factors that may affect the crop N acquisition by combining a large number of studies. I have thereby assessed the state of knowledge regarding the complementary functioning of diversified cropping systems by implementing intercropping practices and provided up-to-date findings that can help stakeholders such as policy makers to assess information relevant for new policies. The results show that:

- Intercropping practices increased the grain legume reliance on biological $N_2$ fixation and reduced the acquisition of soil-derived N by the grain legume.
- Intercropped cereals were acquiring relatively greater amounts of soil-derived N than cereals growing as sole crops.
- Complementarity of nitrogen use was enhanced in intercrops, suggesting that soil nitrogen pools can be utilized more efficiently by implementing this practice.

- Effects of intercropping on nitrogen use were influenced by management factors such as choice of legume species, intercrop composition, and fertilization rate.

Several crop diversification practices were assessed to determine how they influence the performance of arable crop sequences in **paper II**. By increasing the complexity of cropping systems through the combination of different species in space and time, I explored how agroecosystem functions and services related to productivity, weed suppression, and nitrogen use resources of crops in the crop rotation sequences are affected by using crop diversification practices. In this paper, I study several practices such as replacing cereal crops by grain legumes in the preceding crops, and by adding different combinations of forage and cover crops. The main insights:

- Introducing undersown cover crops in the main crops (grain legume or cereal) does not reduce the yield of the preceding crop.
- Undersown grasses as cover crops and in forage crop mixtures may benefit by having a grain legume as preceding crop, while the growth of forage legumes was often positively influenced by a cereal preceding crop.
- Subsequent crops (in this case cereals) were positively influenced by legumes cover crops while the effect of grain legumes as preceding crops were less pronounced in the subsequent cereal.
- Cover crops had no significant effect on weed biomass in the preceding and subsequent cash crops.

## 4.2 Assessing the sustainability of diversified cropping systems

*Research question 2: Which are the social, economic and environmental impacts that strengthen or constrain diversified cropping systems?*

### 4.2.1 Field and Farm scale

**Paper III** assesses the sustainability of diversified cropping systems in organic production using a multi-criteria decision aid method and a sustainability assessment framework. Commercial farms and field experiments were included in the assessment, which identified strengths and challenges in the sustainability of organic cropping systems. This paper describes how crop diversification practices may increase sustainability and how the inclusion of social, economic, and environmental aspects helped to understand the farming system dynamics and address synergies and trade-offs. Furthermore, the study applied various methods to identify barriers to crop diversification practices at the farm level. Main points of **paper III** that contribute to this thesis:

- Organic production systems already include high plant diversity at the field and farm scale.
- Environmental sustainability at field experiments and commercial farms is high, indicating efficient use of resources, positive effects on associated biodiversity, and low pollution risks.
- Lack of inclusive markets and local value chains, and low recognition of the benefits of diversified cropping systems by society are cross-cutting barriers that limit the economic sustainability of these systems.
- Sustainability assessments are key tools to identify challenges of complex cropping systems and quantify the socio-economic and environmental factors affecting the overall sustainability of these systems.
- Simple tools for monitoring sustainability in farming systems are scarce or even missing, and developing easy-to-use tools would stimulate transition towards more sustainable agriculture.

## 4.3 Crop diversity at the landscape

*Research question 3: How is the landscape composition in the agricultural region of Scania, and how is it related to crop productivity?*

### 4.3.1 Landscape scale

As a reaction to the industrialization of agriculture and the simplification of landscapes, there are expectations and hopes for developing sustainable agri-food systems that increase the diversity in farming systems. **Paper IV** describes the spatial pattern and distribution of crop diversity at the landscape scale. This paper provides an overview of the role of crop diversity in crop production, specifically under abiotic disturbances. The paper finds the correlation between crop diversity and crop yield in the landscape scale. The main insights:

- Landscape-level crop diversity correlated positively with cereal crop yields.
- Landscape-level effects of the 2018 drought on yield can differ between crops.
- The effect of crop diversity on yield was not significant but with a tendency for less reduced yield with increasing crop diversity, particularly for winter wheat.
- We develop a methodology for using the Shannon diversity index as an indicator of crop diversity on a spatial scale and related to crop production under climate change.

## 4.4 Implementing crop diversification practices

*Research question 4: What are the perceptions farmers may have for implementing crop diversification practices?*

**Paper III** interrogates the farmers' perceptions and motivations on implementing crop diversification practices. The analysis identified factors and drivers that influence the farmers' choices of crops and implementation of crop diversification practices. Looking across practices, systems, and scales allowed for a critical understanding of farmers' values and needs. Further, this study may help to overcome the barriers to enhancing sustainable cropping systems. The results revealed the following advantages and disadvantages of crop diversification, as perceived by farmers:

+ Reducing reliance on external inputs.
+ Efficient use of resources (water, nutrients, fuel).
+ Reduce effects of pests and diseases.
+ Increasing associated biodiversity.
+ Increase soil carbon input and thus improve soil organic matter.
+ Mitigating climate change by increasing carbon sequestration.
- Market demand and sale opportunities of alternative crops and minor crops.
- Intensity of work.

- Limitation and lack of coordination in the value chain, explicitly supporting new or alternative crops.
- Variability of grain yield (of alternative crops), e.g., in grain legumes.
- Technological lock-ins, e.g., lack of machinery developed to diversified and complex systems.
- Rural and agricultural policies, i.e., lack of incentives to farmers to increase crop diversification to a larger scale.
- Lack of knowledge on complex systems, e.g., implementation of cover crops, alternative crops, and highly diversified crop rotations.

# 5. Contributions and reflections

In theoretical community ecology, one of the main problems is understanding how “the niches of particular species in a biological community are divided, tacitly assuming that they certainly must be divided if the species are living together” (Vandermeer 2011). In diversified cropping systems, this ecological mechanism is applied in practice by cultivating plant species that complement each others’ niches. Much of my work consists of increasing the understanding of how combining crop diversification practices may enhance the sustainability of farming systems by using different methodologies to analyze complexity in farming systems and advance the understanding of socio-economic and environmental hinders for implementing of such practices.

To the question “*Do crop diversification practices have the potential to enhance the sustainability of agricultural production systems?'‘,* the four papers suggest that increasing crop diversity by including or combining crop diversification practices is likely to enhance sustainability. The thesis provides a novel understanding of the ecological theory of diversified cropping systems and offers a conceptual way of connecting these agroecosystems with socio-economic drivers from local to landscape scale. It acknowledges the impact of humans on the composition of landscapes and thus claims for the relevance of crop diversity (**paper IV**). It provides a synthesis, either describing the possible mechanism of plant-plant interactions, e.g., by intercropping (**paper I**) and crop sequences (**paper II**), or conceptualizing the cropping systems and their diversity and sustainability in a food systems context (**paper III**). These perspectives allow for increased knowledge and discuss synergies, trade-offs, and hinders for implementing crop diversification practices, particularly the relevance of having adequate tools to deal with such complexity.

## 5.1 From field to landscape: the contribution of diversified cropping systems

Crop diversification has been practiced for a long time in farming systems. With the great focus on sustainable, ecological intensification, and agroecological perspectives, crop diversification practices have become vital elements in the global research agenda[8]. A large part of studies on crop diversification practices are mainly focusing on single practices, and there is scarce evidence of the combination of several practices. In our first attempt evaluating crop diversification, we synthesize some of the benefits of intercropping used as a single practice (**paper I**). We demonstrated that implementing intercropping systems of legumes-cereals stimulates the N use efficiency by complementarity in plant traits, thus using different niches (Gaba *et al.* 2014). However, this benefit will be more evident in soils with low N availability, since the cereal is usually more competitive for inorganic N (Jensen 1996; Hauggaard-Nielsen & Jensen 2001) the legumes are forced to depend primarily on the symbiotic $N_2$ fixation at low soil N levels (Hauggaard-Nielsen *et al.* 2009a; Bedoussac & Justes 2010).

Widening the scope to include both spatial and temporal scales, the integration of several diversification practices in the cropping systems did not show a strong influence on the performance of the different crop components in a crop sequence, particularly for crop productivity, weed control, and N acquisition (**paper II**). The complexity in diversified cropping systems did not allow us to easily observe the mechanisms behind the functioning of these systems or plant-plant interactions. However, we could highlight that replacing cereals with grain legumes earlier in the crop sequence and including either forages or cover crops, did not have any penalty for crop productivity or N resources acquisition in the subsequent cereal. Furthermore, we could also argue for a tendency of weed reduction in the same subsequent crop. Different dynamics may have occurred along with the different components in the crop sequences, as consequences of various ecological mechanisms such as competition, complementarity, facilitation, and compensation. For example, previous studies have shown that cover crops may provide several benefits, including the facilitation of inputs of biologically fixed N, weed reduction, soil carbon sequestration, nutrient retention, and reduced risk of soil erosion (Hauggaard-Nielsen *et al.*

[8] An example in the European Union https://bit.ly/3erlpzN

2009b; Hunter *et al.* 2019). Furthermore, the less responsive effect of the subsequent cereals by the inclusion of cover crops as sole crops or in mixtures may be driven for lower N recovery efficiency (Doltra & Olesen 2013), or due to the competition for soil N by the cover crop or short-term N immobilization when incorporating cover crop biomass (Hauggaard-Nielsen *et al.* 2009b), especially, under low availability of N in the soil. Since it is more likely that N availability for the subsequent crops depends mainly on the N accumulation provided by the preceding legume crops (Bergkvist *et al.* 2011).

**Paper III** provides an overview of the overall sustainability of the diversified cropping systems. It reveals the potential of crop diversification practices to strengthen environmental benefits such as soil quality improvement, climate impact, and resource use efficiency. This is in line with recent syntheses, which demonstrate that agricultural diversification practices such as crop mixtures and crop rotations, among others, have a positive effect on soil quality, crop yield, nutrients regulation, C sequestration as well as associated biodiversity (Tamburini et al. 2020; Beillouin et al. 2021). For instance, increasing crop diversity (by integrating intercropping, cover crops, or green manure) may be an efficient solution to enhance crop production with low use of N inputs, thus reducing fossil energy consumption (Jensen et al. 2011; Jeuffroy et al. 2013). Although many of the positive benefits of organic production are attributed to the non-use of synthetic fertilizers and pesticides, it is relevant to explore further improvements of organic cropping systems via practices that increase via both crop and non-crop components of the agricultural landscape.

Increasing compositional heterogeneity in the landscape resulted in a positive correlation with crop yield, specifically for cereals (**paper IV**). This evidence that increasing crop diversity tends to promote the capacity of certain crops to withstand abiotic disturbance is novel and deserves more attention to be able to understand the different factors influencing these effects or the underlying mechanisms. The positive effects of crop diversity on several ecosystem services in the landscapes have been described before (Batáry *et al.* 2011; Redlich *et al.* 2018a; Sirami *et al.* 2019). My thesis contributes to the existing research in landscape heterogeneity by highlighting the relevance of increasing crop diversity and the risk for reducing crop productivity under climate change. This means that, e.g., promoting practices such as longer rotations could ameliorate adverse effects from climate disturbances, thus increasing agricultural resilience (Bowles *et al.* 2020; Marini *et al.* 2020), and crop yield stability (Renard & Tilman 2019). The results from this study demonstrated that there is a great opportunity for improving resource-efficient production, enhancing ecosystem services, and contributing to more sustainable cropping systems by increasing on-farm crop diversity across spatial and temporal scales.

## 5.2 Studying complex cropping systems

A central aspect in this thesis has been to integrate complex theory to understand farming systems and the socio-ecological dynamics in terms of synergies, trade-offs, and challenges of implementing crop diversification practices. This thesis contributes to understanding the complex interactions between crop species and management (**paper I and II**), but the ability to represent such ecological complexity in a practical way for integration into farmers management is still basic or lacking.

Paper **III** improves the understanding of socio-ecological dynamics that contribute to further knowledge in implementing crop diversification practices. Furthermore, **paper IV** advances the relationship between crop diversity and crop productivity in the landscape and the indirect effects of farmers' decisions on crop choice. Complex interactions among people and the environment are the factors that characterize agroecosystems. For instance, identifying the social, economic, and environmental challenges by farmers or other stakeholders in the agri-food systems and assessing their motivation provides the opportunity to set up new norms of sustainability requirements for crop production. At the same time, the possibility for sustainable development depends on changing the perception of human society regarding complex systems. Attention should be directed to change the perception of where society and nature are coevolving in the biosphere (Petrosillo *et al.* 2015), for example, by increasing the recognition that farmers receive when managing and maintaining these diversified agricultural landscapes. Understanding agroecosystems means allowing for the integration of ecological processes and socio-political structures that control agricultural systems. Since the adaptation of crop diversification practices is based on local conditions, it might be relevant to include other factors that we did not cover in this thesis to fully understand these complex dynamics and driving forces that may transform current systems to more sustainable agricultural systems.

## 5.3 Barriers for implementing crop diversification practices

Diversified cropping systems have a significant potential role in the transition to a more sustainable agricultural and food systems. However, there are still many challenges for the implementation of these practices in farming systems. Several barriers may be listed, such as shortage of farmer (and advisor) knowledge on the crop management for highly diversified systems, lack of market flexibility and poor establishment of a local market for alternative and minor crops, among others. It is likely that the solution is not only at the farm level but expands to other sectors of the food system. It is essential to connect different stakeholders from the food system sector to build up tools and technologies that enable the involvement of consumers and other actors, to support farmers access to evolving markets and overcome knowledge gaps related to crop diversification. Research has to comprise interdisciplinary teams who focus on farmers' needs to provide them with noticeable alternatives approaching the local conditions and promoting farm-led innovation. Therefore, our studies help to understand how combining crop diversification practices influence the dynamics of the agroecosystem functions and understanding the values and beliefs behind the farmers' decisions in the transition towards more sustainable farming systems. Other points that can be interesting to develop in the future to overcome barriers for implementing crop diversification are listed below:

- Increase knowledge of agroecosystem dynamics when combining crop diversification practices in both short and long-term perspectives, including different environmental conditions.
- Communicate the importance of increased crop diversity to the several stakeholders in the food systems and scaling up to the political agenda recognizing the benefits of diversified cropping systems in delivering ecosystem services.
- Illustrate how the choice of crop diversification practices and their combination may enhance synergies or have the potential to reduce trade-offs.

- Improve suitable varieties adapted to temperate conditions or potential to develop native species for agricultural purposes (e.g., local legumes or landrace species).

## 5.4 Research approach reflections

Several aspects outlined in the different parts of this thesis presented limitations that must be reflected on to provide more outstanding quality and the possibility to be applicable to further socio-ecological and agroecological research.

A question regarding the depth of expertise a researcher should have in sustainability science always arises. *Should the researcher be a generalist or a specialist?* Studies on socio-ecological interactions may require many scientific knowledge sources. However, doctoral education still lacks support in orienting scholars to address issues of complex nature, particularly sustainability challenges, somehow understanding the intuitive process of balancing deep methodological grounding and epistemological agility to engage in rigorous sustainability science (referring to interdisciplinarity and transdisciplinary research) (Haider *et al.* 2018). This thesis attempts to look through various disciplines to create awareness and to simplify a message, trying to get science into policy. Exploring the sustainability of cropping systems means that I have to rely on a wider range of theories, concepts, and methodologies, broaden myself from literature, field experiments, participatory research, and moving across scales. However, it is always stimulating to acquire skills and knowledge to be applied not only in the same field but also to address questions in another field; a professor said in a lecture on working with scientists and policymakers, *"retrospectoscope is a power tool."*

I here describe some of the issues that arose during this journey. Starting with **paper I**, searching literature on intercropping (focused on local climatic conditions), most of the research has been focused on peas and we find a lack of research on the use of, e.g., other legumes. However, this opens opportunities to extend the research to other species that are suitable for these local conditions. It is also valuable to highlight the lack of information and data reported in published articles, limiting the possibility to perform more synthesis in this specific topic. In the case of field experiments in **paper II**, here I reflect on the limitations in the experimental setup and lack of belowground measurements, that would have allowed more detailed analyses of ecological mechanisms in response to studied combinations of crop diversification practices. However, here I would like to highlight the lack of financial support in research on organic production and even more limited to agroecology.

Evaluating sustainability based on the available tools can constrain what type of systems that can be evaluated and limits the evaluation to certain specific indicators of sustainability. **In paper III**, I acknowledge that we were missing appropriate indicators for organic production. However, in this thesis, other factors were equally important such as motivating stakeholders, following the activities of farmers to understand their perspectives, testing tools, learning skills in many aspects such as social, economic, and environmental. In addition, in the analysis of the landscape (**paper IV**), the work was based mainly on publicly available data. This factor is relevant because it limits the ecosystem services that can be evaluated, but it also elucidates ideas to develop tools that help to monitor the sustainability of agricultural landscapes.

In summary, the results of this thesis provide important insights into the contribution of diversified cropping systems and represent a step in the direction of transforming agricultural systems. Further, this thesis has connected sustainability science to agronomic and socio-ecological studies of diversified cropping systems.

# 6. Conclusions and future perspectives

Achieving sustainable food systems that adequately meet current population needs without compromising future well-being requires a research agenda that integrates agroecology, equity between global and local food systems, cultural dimensions of food and agriculture, and human health (Vandermeer *et al.* 2018). As an agroecologist, I aimed to improve our understanding of how diversified cropping systems can enhance sustainability. Indeed, assessing diversified cropping systems is critical for understanding their performance and design strategies for steering agricultural landscapes towards increased sustainability. The thesis has demonstrated the capacity of a diversified cropping system to enhance sustainability. The integration of crop diversification practices highlighted many benefits, particularly to the environment. However, there is a need for greater focus on more aspects that can cover several mechanisms in complex socio-ecological systems to gain insights into the consequences of land use.

Crop diversification practices have been recognized as a way to support functional biodiversity across spatial and temporal scales. Therefore, the results from this study provide further insights and reinforce the argument about promoting synergies in the agroecosystems. I demonstrated, for example, that combining crop diversification practices did not have yield penalties or other trade-offs in crop performance. Further research will be needed to understand better the functions and mechanisms linked in plant-plant interactions in longer crop rotations, highlighting both synergies and trade-offs. Such understanding can help provide advice to the farmers to increase the implementation of crop diversification practices to a larger extent.

The thesis further demonstrated the benefits of diversified cropping systems using commercial farms. However, increasing crop diversity at the field and farm level showed the socioeconomic challenges of these systems. This effect indicates a need for policy strategies that can support agricultural systems to overcome these challenges by promoting inclusive and local markets, strengthening the local value chains, and disseminating the benefits of diversifying cropping/farming systems to a broader audience.

Increased landscape heterogeneity can reduce the negative impact of having homogeneous cover in the agricultural landscape (Batáry *et al.* 2011; Sirami *et al.* 2019). The thesis demonstrated the positive correlation between landscape-level crop diversity and cereal crop yields. Increasing crop diversity may further benefit the competitive advantages of farming systems to face abiotic disturbances due to climate change. These benefits could considerably improve the functioning of agroecosystem and thereby enhance the resilience of agricultural systems.

Given the complex nature of agricultural systems and the many challenges to enhance the sustainability of these systems, further research would be needed to promote the implementation of crop diversification practices. As a starting point, there is a need for integrative agricultural systems research to build up from knowledge across different research disciplines and include public institutions, private food sectors, and civil spheres. This type of transdisciplinary collaboration can contribute to addressing complex and fundamental societal challenges by bridging the gap between problem solving and scientific innovation (Lang *et al.* 2012), creating knowledge embracing all disciplines. Secondly, research for developing simple sustainability assessment tools that are easily accessible and can be used by e.g., farmers, advisors or the public in general, will shorten the gap between theoretical evaluations and practical implementation of more sustainable practices. For instance, the sustainability assessment may support the design and implementation of long-term monitoring of sustainable practices and benchmarking farming performance on several scales. Third, increasing research on complex and agroecological systems will allow a better understanding of the multiple dynamic interactions happening in the agroecosystems. Finally, opening up to more participatory and collaborative research, it is possible to impact policy to overcome these current challenges. If successfully implemented, the findings in this thesis, along with the future research and action suggested here, will stimulate a sustainable agricultural development where ecosystem services from diversified cropping systems increase resource use efficiency and contribute to more resilient food systems.

# References


Abdalla, M., Hastings, A., Cheng, K., Yue, Q., Chadwick, D., Espenberg, M., Truu, J., Rees, R.M. & Smith, P. (2019). A critical review of the impacts of cover crops on nitrogen leaching, net greenhouse gas balance and crop productivity. *Glob Chang Biol,* 25(8), 2530-2543. https://doi.org/10.1111/gcb.14644

Altieri, M. (1995). *Agroecology: the science of sustainable agriculture*. 2 edition. Boulder, CO: Westview Press

Altieri, M., Nicholls, C. & Montalba, R. (2017). Technological Approaches to Sustainable Agriculture at a Crossroads: An Agroecological Perspective. *Sustainability,* 9(3). https://doi.org/10.3390/su9030349

Anderson, C.R., Bruil, J., Chappell, M.J., Kiss, C. & Pimbert, M.P. (2019). From Transition to Domains of Transformation: Getting to Sustainable and Just Food Systems through Agroecology. *Sustainability,* 11(19). https://doi.org/10.3390/su11195272

Archer, M., Bhaskar, R., Collier, A., Lawson, T. & Norrie, A. (2013). *Critical Realism: Essential Readings*. Taylor and Francis. https://doi.org/10.4324/9781315008592

Bacon, C.M., Getz, C., Kraus, S., Montenegro, M. & Holland, K. (2012). The Social Dimensions of Sustainability and Change in Diversified Farming Systems. *Ecology and Society,* 17(4). https://doi.org/10.5751/es-05226-170441

Batáry, P., Fischer, J., Báldi, A., Crist, T.O. & Tscharntke, T. (2011). Does habitat heterogeneity increase farmland biodiversity? *Frontiers in Ecology and the Environment,* 9(3), 152-153. https://doi.org/10.1890/11.Wb.006

Bedoussac, L., Journet, E.-P., Hauggaard-Nielsen, H., Naudin, C., Corre-Hellou, G., Jensen, E.S., Prieur, L. & Justes, E. (2015). Ecological principles underlying the increase of productivity achieved by cereal-grain legume intercrops in organic farming. A review. *Agronomy for Sustainable Development,* 35(3), 911-935. https://doi.org/10.1007/s13593-014-0277-7

Bedoussac, L. & Justes, E. (2010). The efficiency of a durum wheat-winter pea intercrop to improve yield and wheat grain protein concentration depends on N availability during early growth. *Plant and Soil,* 330(1-2), 19-35. https://doi.org/10.1007/s11104-009-0082-2

Beillouin, D., Ben-Ari, T. & Makowski, D. (2019). Evidence map of crop diversification strategies at the global scale. *Environmental Research Letters,* 14(12), 123001. https://doi.org/10.1088/1748-9326/ab4449

Beillouin, D., Ben-Ari, T., Malézieux, E., Seufert, V. & Makowski, D. (2021). Benefits of crop diversification for biodiversity and ecosystem services. *bioRxiv*, 2020.09.30.320309. https://doi.org/10.1101/2020.09.30.320309

Ben-Eli, M.U. (2018). Sustainability: definition and five core principles, a systems perspective. *Sustainability Science,* 13(5), 1337-1343. https://doi.org/10.1007/s11625-018-0564-3

Bennett, A.J., Bending, G.D., Chandler, D., Hilton, S. & Mills, P. (2012). Meeting the demand for crop production: the challenge of yield decline in crops grown in short rotations. *Biological Reviews of the Cambridge Philosophical Society,* 87(1), 52-71. https://doi.org/10.1111/j.1469-185X.2011.00184.x

Bennett, E.M. (2017). Changing the agriculture and environment conversation. *Nat Ecol Evol,* 1(1), 18. https://doi.org/10.1038/s41559-016-0018

Benton, T.G., Vickery, J.A. & Wilson, J.D. (2003). Farmland biodiversity: is habitat heterogeneity the key? *Trends in Ecology & Evolution,* 18(4), 182-188. https://doi.org/10.1016/s0169-5347(03)00011-9

Bergkvist, G., Stenberg, M., Wetterlind, J., Båth, B. & Elfstrand, S. (2011). Clover cover crops under-sown in winter wheat increase yield of subsequent spring barley—Effect of N dose and companion grass. *Field Crops Research,* 120(2), 292-298. https://doi.org/10.1016/j.fcr.2010.11.001

Berkes, F. & Folke, C. (1998). *Linking social and ecological systems : management practices and social mechanisms for building resilience*. Cambridge, UK: Cambridge University Press.

Bernard, B. & Lux, A. (2016). How to feed the world sustainably: an overview of the discourse on agroecology and sustainable intensification. *Regional Environmental Change,* 17(5), 1279-1290. https://doi.org/10.1007/s10113-016-1027-y

Bhaskar, R. (2008). *A realist theory of science* 3rd edition. Oxon, UK: Routledge.

Björklund, J., Limburg, K.E. & Rydberg, T. (1999). Impact of production intensity on the ability of the agricultural landscape to generate ecosystem services: an example from Sweden. *Ecological Economics,* 29(2), 269-291. https://doi.org/10.1016/s0921-8009(99)00014-2

Blanco-Canqui, H., Shaver, T.M., Lindquist, J.L., Shapiro, C.A., Elmore, R.W., Francis, C.A. & Hergert, G.W. (2015). Cover Crops and Ecosystem Services: Insights from Studies in Temperate Soils. *Agronomy Journal,* 107(6), 2449-2474. https://doi.org/10.2134/agronj15.0086

Bowles, T.M., Mooshammer, M., Socolar, Y., Calderón, F., Cavigelli, M.A., Culman, S.W., Deen, W., Drury, C.F., Garcia y Garcia, A., Gaudin, A.C.M., Harkcom, W.S., Lehman, R.M., Osborne, S.L., Robertson, G.P., Salerno, J., Schmer, M.R., Strock, J. & Grandy, A.S. (2020). Long-Term Evidence Shows that Crop-Rotation Diversification Increases Agricultural Resilience to Adverse Growing Conditions in North America. *One Earth,* 2(3), 284-293. https://doi.org/10.1016/j.oneear.2020.02.007

Brooker, R.W., Bennett, A.E., Cong, W.F., Daniell, T.J., George, T.S., Hallett, P.D., Hawes, C., Iannetta, P.P., Jones, H.G., Karley, A.J., Li, L., McKenzie, B.M., Pakeman, R.J., Paterson, E., Schob, C., Shen, J., Squire, G., Watson, C.A., Zhang, C., Zhang, F., Zhang, J. & White, P.J. (2015). Improving intercropping: a synthesis of research in agronomy, plant physiology and ecology. *New Phytologist,* 206(1), 107-117. https://doi.org/10.1111/nph.13132

Campbell, B.M., Beare, D.J., Bennett, E.M., Hall-Spencer, J.M., Ingram, J.S.I., Jaramillo, F., Ortiz, R., Ramankutty, N., Sayer, J.A. & Shindell, D. (2017). Agriculture production as a major driver of the Earth system exceeding planetary boundaries. *Ecology and Society,* 22(4). https://doi.org/10.5751/es-09595-220408

Cardinale, B.J., Wright, J.P., Cadotte, M.W., Carroll, I.T., Hector, A., Srivastava, D.S., Loreau, M. & Weis, J.J. (2007). Impacts of plant diversity on biomass production increase through time because of species complementarity. *Proc Natl Acad Sci U S A,* 104(46), 18123-8. https://doi.org/10.1073/pnas.0709069104

Carpenter, S.R. & Bennett, E.M. (2011). Reconsideration of the planetary boundary for phosphorus. *Environmental Research Letters,* 6(1), 014009. https://doi.org/10.1088/1748-9326/6/1/014009

CIDSE (2018). *The principles of agroecology. Towards just, resilient and sustainable food systems*. Brussels. https://www.cidse.org/publications/just-food/food-and-climate/the-principles-of-agroecology.html

Clark, W.C., van Kerkhoff, L., Lebel, L. & Gallopin, G.C. (2016). Crafting usable knowledge for sustainable development. *Proc Natl Acad Sci U S A,* 113(17), 4570-8. https://doi.org/10.1073/pnas.1601266113

Cong, W.F., Hoffland, E., Li, L., Six, J., Sun, J.H., Bao, X.G., Zhang, F.S. & Van Der Werf, W. (2015). Intercropping enhances soil carbon and nitrogen. *Glob Chang Biol,* 21(4), 1715-26. https://doi.org/10.1111/gcb.12738

Davis, A.S., Hill, J.D., Chase, C.A., Johanns, A.M. & Liebman, M. (2012). Increasing Cropping System Diversity Balances Productivity, Profitability and Environmental Health. *Plos One,* 7(10), e47149. https://doi.org/https://10.1371/journal.pone.0047149

De Schutter, O. (2010). *Agroecology and the right to food*. United Nations Human Rights Council. A/HRC/16/49.

DeClerck, F.A.J., Jones, S.K., Attwood, S., Bossio, D., Girvetz, E., Chaplin-Kramer, B., Enfors, E., Fremier, A.K., Gordon, L.J., Kizito, F., Lopez Noriega, I., Matthews, N., McCartney, M., Meacham, M., Noble, A., Quintero, M., Remans, R., Soppe, R., Willemen, L., Wood, S.L.R. & Zhang, W. (2016). Agricultural ecosystems and their services: the vanguard of sustainability? *Current Opinion in Environmental Sustainability,* 23, 92-99. https://doi.org/10.1016/j.cosust.2016.11.016

Denys, C. & Tscharntke, T. (2002). Plant-insect communities and predator-prey ratios in field margin strips, adjacent crop fields, and fallows. *Oecologia,* 130(2), 315-324. https://doi.org/10.1007/s004420100796

Doltra, J. & Olesen, J.E. (2013). The role of catch crops in the ecological intensification of spring cereals in organic farming under Nordic climate.

*European Journal of Agronomy,* 44, 98-108. https://doi.org/10.1016/j.eja.2012.03.006
Duru, M., Therond, O., Martin, G., Martin-Clouaire, R., Magne, M.-A., Justes, E., Journet, E.-P., Aubertot, J.-N., Savary, S., Bergez, J.-E. & Sarthou, J.P. (2015). How to implement biodiversity-based agriculture to enhance ecosystem services: a review. *Agronomy for Sustainable Development,* 35(4), 1259-1281. https://doi.org/10.1007/s13593-015-0306-1
Edwards, A.R. & Orr, D.W. (2005). *The Sustainability Revolution : Portrait of a Paradigm Shift*. Gabriola Island, UNITED STATES: New Society Publishers. http://ebookcentral.proquest.com/lib/slub-ebooks/detail.action?docID=256417
Fahrig, L., Baudry, J., Brotons, L., Burel, F.G., Crist, T.O., Fuller, R.J., Sirami, C., Siriwardena, G.M. & Martin, J.L. (2011). Functional landscape heterogeneity and animal biodiversity in agricultural landscapes. *Ecology Letters,* 14(2), 101-12. https://doi.org/10.1111/j.1461-0248.2010.01559.x
Faith, D.P. (2020). "Biodiversity". In: *The Stanford Encyclopedia of Philosophy (Fall 2019 Edition).* https://plato.stanford.edu/archives/fall2019/entries/biodiversity/ [30 November 2020].
FAO (2017). The Future of Food and Agriculture – Trends and Challenges. Rome: Food and Agriculture Organization of the United Nations.
FAO (2018). *The 10 elements of Agroecology: Guiding the transition to sustainable food and agricultural systems*. Rome. http://www.fao.org/3/i9037en/I9037EN.pdf
Foley, J.A., Defries, R., Asner, G.P., Barford, C., Bonan, G., Carpenter, S.R., Chapin, F.S., Coe, M.T., Daily, G.C., Gibbs, H.K., Helkowski, J.H., Holloway, T., Howard, E.A., Kucharik, C.J., Monfreda, C., Patz, J.A., Prentice, I.C., Ramankutty, N. & Snyder, P.K. (2005). Global consequences of land use. *Science,* 309(5734), 570-4. https://doi.org/10.1126/science.1111772
Foley, J.A., Ramankutty, N., Brauman, K.A., Cassidy, E.S., Gerber, J.S., Johnston, M., Mueller, N.D., O'Connell, C., Ray, D.K., West, P.C., Balzer, C., Bennett, E.M., Carpenter, S.R., Hill, J., Monfreda, C., Polasky, S., Rockstrom, J., Sheehan, J., Siebert, S., Tilman, D. & Zaks, D.P. (2011). Solutions for a cultivated planet. *Nature,* 478(7369), 337-42. https://doi.org/10.1038/nature10452
Folke, C., Hahn, T., Olsson, P. & Norberg, J. (2005). Adaptive Governance of Social-Ecological Systems. *Annual Review of Environment and Resources,* 30(1), 441-473. https://doi.org/10.1146/annurev.energy.30.050504.144511
Francis, C., Lieblein, G., Gliessman, S., Breland, T.A., Creamer, N., Harwood, R., Salomonsson, L., Helenius, J., Rickerl, D., Salvador, R., Wiedenhoeft, M., Simmons, S., Allen, P., Altieri, M., Flora, C. & Poincelot, R. (2003). Agroecology: The Ecology of Food Systems. *Journal of Sustainable Agriculture,* 22(3), 99-118. https://doi.org/10.1300/J064v22n03_10

Gaba, S., Bretagnolle, V. & Bridgewater, P. (2020). Social–ecological experiments to foster agroecological transition. *People and Nature,* 2(2), 317-327. https://doi.org/10.1002/pan3.10078

Gaba, S., Lescourret, F., Boudsocq, S., Enjalbert, J., Hinsinger, P., Journet, E.-P., Navas, M.-L., Wery, J., Louarn, G., Malézieux, E., Pelzer, E., Prudent, M. & Ozier-Lafontaine, H. (2014). Multiple cropping systems as drivers for providing multiple ecosystem services: from concepts to design. *Agronomy for Sustainable Development,* 35(2), 607-623. https://doi.org/10.1007/s13593-014-0272-z

Gardner, B. (1996). *European agriculture : policies, production and trade*. Routledge.

Garland, G., Edlinger, A., Banerjee, S., Degrune, F., García-Palacios, P., Pescador, D.S., Herzog, C., Romdhane, S., Saghai, A., Spor, A., Wagg, C., Hallin, S., Maestre, F.T., Philippot, L., Rillig, M.C. & van der Heijden, M.G.A. (2021). Crop cover is more important than rotational diversity for soil multifunctionality and cereal yields in European cropping systems. *Nature Food,* 2(1), 28-37. https://doi.org/10.1038/s43016-020-00210-8

Garnett, T., Appleby, M.C., Balmford, A., Bateman, I.J., Benton, T.G., Bloomer, P., Burlingame, B., Dawkins, M., Dolan, L., Fraser, D., Herrero, M., Hoffmann, I., Smith, P., Thornton, P.K., Toulmin, C., Vermeulen, S.J. & Godfray, H.C. (2013). Agriculture. Sustainable intensification in agriculture: premises and policies. *Science,* 341(6141), 33-4. https://doi.org/10.1126/science.1234485

Gliessman, S. (2013). Agroecology: Growing the Roots of Resistance. *Agroecology and Sustainable Food Systems,* 37(1), 19-31. https://doi.org/10.1080/10440046.2012.736927

Gliessman, S. (2018). Defining Agroecology. *Agroecology and Sustainable Food Systems,* 42(6), 599-600. https://doi.org/10.1080/21683565.2018.1432329

Godfray, H.C., Beddington, J.R., Crute, I.R., Haddad, L., Lawrence, D., Muir, J.F., Pretty, J., Robinson, S., Thomas, S.M. & Toulmin, C. (2010). Food security: the challenge of feeding 9 billion people. *Science,* 327(5967), 812-8. https://doi.org/10.1126/science.1185383

Government Office of Swedish (2018). *EU:s framtida jordbrukspolitik [EU's future agricultural policy]*. Stockholm, Sweden.

Gruber, N. & Galloway, J.N. (2008). An Earth-system perspective of the global nitrogen cycle. *Nature,* 451(7176), 293-6. https://doi.org/10.1038/nature06592

Gunderson, L. & Holling, C.S. (2002). *Panarchy : understanding transformations in human and natural systems*. Washington, DC: Island Press.

Haider, L.J., Hentati-Sundberg, J., Giusti, M., Goodness, J., Hamann, M., Masterson, V.A., Meacham, M., Merrie, A., Ospina, D., Schill, C. & Sinare, H. (2018). The undisciplinary journey: early-career perspectives in sustainability science. *Sustain Sci,* 13(1), 191-204. https://doi.org/10.1007/s11625-017-0445-1

Hauggaard-Nielsen, H., Ambus, P. & Jensen, E.S. (2001). Interspecific competition, N use and interference with weeds in pea–barley intercropping. *Field Crops Research,* 70(2), 101-109. https://doi.org/10.1016/s0378-4290(01)00126-5

Hauggaard-Nielsen, H., Gooding, M., Ambus, P., Corre-Hellou, G., Crozat, Y., Dahlmann, C., Dibet, A., von Fragstein, P., Pristeri, A., Monti, M. & Jensen, E.S. (2009a). Pea–barley intercropping for efficient symbiotic N2-fixation, soil N acquisition and use of other nutrients in European organic cropping systems. *Field Crops Research,* 113(1), 64-71. https://doi.org/10.1016/j.fcr.2009.04.009

Hauggaard-Nielsen, H. & Jensen, E.S. (2001). Evaluating pea and barley cultivars for complementarity in intercropping at different levels of soil N availability. *Field Crops Research,* 72(3), 185-196. https://doi.org/10.1016/s0378-4290(01)00176-9

Hauggaard-Nielsen, H., Mundus, S. & Jensen, E.S. (2009b). Nitrogen dynamics following grain legumes and subsequent catch crops and the effects on succeeding cereal crops. *Nutrient Cycling in Agroecosystems,* 84(3), 281-291. https://doi.org/10.1007/s10705-008-9242-7

Hinrichs, C.C. (2014). Transitions to sustainability: a change in thinking about food systems change? *Agriculture and Human Values,* 31(1), 143-155. https://doi.org/10.1007/s10460-014-9479-5

HLPE (2019). *Agroecological and other innovative approaches for sustainable agriculture and food systems that enhance food security and nutrition*. Rome. http://www.fao.org/3/ca5602en/ca5602en.pdf

Holland, J.M., Bianchi, F.J., Entling, M.H., Moonen, A.C., Smith, B.M. & Jeanneret, P. (2016). Structure, function and management of semi-natural habitats for conservation biological control: a review of European studies. *Pest Manag Sci,* 72(9), 1638-51. https://doi.org/10.1002/ps.4318

Hufnagel, J., Reckling, M. & Ewert, F. (2020). Diverse approaches to crop diversification in agricultural research. A review. *Agronomy for Sustainable Development,* 40(2), 14. https://doi.org/10.1007/s13593-020-00617-4

Hunter, M.C., Schipanski, M.E., Burgess, M.H., LaChance, J.C., Bradley, B.A., Barbercheck, M.E., Kaye, J.P. & Mortensen, D.A. (2019). Cover Crop Mixture Effects on Maize, Soybean, and Wheat Yield in Rotation. *Agricultural & Environmental Letters,* 4(1), 180051. https://doi.org/10.2134/ael2018.10.0051

Iles, A. & Marsh, R. (2012). Nurturing Diversified Farming Systems in Industrialized Countries: How Public Policy Can Contribute. *Ecology and Society,* 17(4). https://doi.org/10.5751/es-05041-170442

IPBES (2019). *Summary for policymakers of the global assessment report on biodiversity and ecosystem services of the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services*. S. Díaz, J. Settele, E. S. Brondízio E.S., H. T. Ngo, M. Guèze, J. Agard, A. Arneth, P. Balvanera, K. A. Brauman, S. H. M. Butchart, K. M. A. Chan, L. A.

Garibaldi, K. Ichii, J. Liu, S. M. Subramanian, G. F. Midgley, P. Miloslavich, Z. Molnár, D. Obura, A. Pfaff, S. Polasky, A. Purvis, J. Razzaque, B. Reyers, R. Roy Chowdhury, Y. J. Shin, I. J. Visseren-Hamakers, K. J. Willis, and C. N. Zayas (eds.). IPBES secretariat, Bonn, Germany. 56 pages.

IPES-Food (2016). *From Uniformity to Diversity: A Paradigm Shift from Industrial Agriculture to Diversified Agroecological Systems*. www.ipes-food.org

Jensen, E.S. (1996). Grain yield, symbiotic N2 fixation and interspecific competition for inorganic N in pea-barley intercrops. *Plant and Soil,* 182(1), 25-38. https://doi.org/10.1007/bf00010992

Jensen, E.S., Bedoussac, L., Carlsson, G., Journet, E.-P., Justes, E. & Hauggaard-Nielsen, H. (2015). Enhancing Yields in Organic Crop Production by Eco-Functional Intensification. *Sustainable Agriculture Research,* 4(3). https://doi.org/10.5539/sar.v4n3p42

Jensen, E.S., Peoples, M.B., Boddey, R.M., Gresshoff, P.M., Hauggaard-Nielsen, H., J.R. Alves, B. & Morrison, M.J. (2011). Legumes for mitigation of climate change and the provision of feedstock for biofuels and biorefineries. A review. *Agronomy for Sustainable Development,* 32(2), 329-364. https://doi.org/10.1007/s13593-011-0056-7

Jerneck, A., Olsson, L., Ness, B., Anderberg, S., Baier, M., Clark, E., Hickler, T., Hornborg, A., Kronsell, A., Lövbrand, E. & Persson, J. (2010). Structuring sustainability science. *Sustainability Science,* 6(1), 69-82. https://doi.org/10.1007/s11625-010-0117-x

Jeuffroy, M.H., Baranger, E., Carrouée, B., de Chezelles, E., Gosme, M., Hénault, C., Schneider, A. & Cellier, P. (2013). Nitrous oxide emissions from crop rotations including wheat, oilseed rape and dry peas. *Biogeosciences,* 10(3), 1787-1797. https://doi.org/10.5194/bg-10-1787-2013

Kates, R.W., Clark, W.C., Corell, R., Hall, J.M., Jaeger, C.C., Lowe, I., McCarthy, J.J., Schellnhuber, H.J., Bolin, B., Dickson, N.M., Faucheux, S., Gallopin, G.C., Grubler, A., Huntley, B., Jager, J., Jodha, N.S., Kasperson, R.E., Mabogunje, A., Matson, P., Mooney, H., Moore, B., 3rd, O'Riordan, T. & Svedlin, U. (2001). Environment and development. Sustainability science. *Science,* 292(5517), 641-2. https://doi.org/10.1126/science.1059386

Kleijn, D., Bommarco, R., Fijen, T.P.M., Garibaldi, L.A., Potts, S.G. & van der Putten, W.H. (2019). Ecological Intensification: Bridging the Gap between Science and Practice. *Trends in Ecology & Evolution,* 34(2), 154-166. https://doi.org/10.1016/j.tree.2018.11.002

Klein, J.T. (1990). *Interdisciplinarity : history, theory, and practice*. Wayne State Univ. Press. http://ludwig.lub.lu.se/login?url=https://search.ebscohost.com/login.aspx?direct=true&db=cat07147a&AN=lub.1444232&site=eds-live&scope=site

Kloppenburg, J. (2010). Social Theory and the De/Reconstruction of Agricultural Science: Local Knowledge for an Alternative Agriculture1. *Rural*

*Sociology,* 56(4), 519-548. https://doi.org/10.1111/j.1549-0831.1991.tb00445.x

Kremen, C., Iles, A. & Bacon, C. (2012). Diversified Farming Systems: An Agroecological, Systems-based Alternative to Modern Industrial Agriculture. *Ecology and Society,* 17(4). https://doi.org/10.5751/es-05103-170444

Kremen, C. & Miles, A. (2012). Ecosystem Services in Biologically Diversified versus Conventional Farming Systems: Benefits, Externalities, and Trade-Offs. *Ecology and Society,* 17(4). https://doi.org/10.5751/es-05035-170440

Kuemmerle, T., Levers, C., Erb, K., Estel, S., Jepsen, M.R., Müller, D., Plutzar, C., Stürck, J., Verkerk, P.J., Verburg, P.H. & Reenberg, A. (2016). Hotspots of land use change in Europe. *Environmental Research Letters,* 11(6). https://doi.org/10.1088/1748-9326/11/6/064020

Lang, D.J., Wiek, A., Bergmann, M., Stauffacher, M., Martens, P., Moll, P., Swilling, M. & Thomas, C.J. (2012). Transdisciplinary research in sustainability science: practice, principles, and challenges. *Sustainability Science,* 7(S1), 25-43. https://doi.org/10.1007/s11625-011-0149-x

Leslie, H.M., Basurto, X., Nenadovic, M., Sievanen, L., Cavanaugh, K.C., Cota-Nieto, J.J., Erisman, B.E., Finkbeiner, E., Hinojosa-Arango, G., Moreno-Baez, M., Nagavarapu, S., Reddy, S.M., Sanchez-Rodriguez, A., Siegel, K., Ulibarria-Valenzuela, J.J., Weaver, A.H. & Aburto-Oropeza, O. (2015). Operationalizing the social-ecological systems framework to assess sustainability. *Proc Natl Acad Sci U S A,* 112(19), 5979-84. https://doi.org/10.1073/pnas.1414640112

Letourneau, D.K., Armbrecht, I., Rivera, B.S., Lerma, J.M., Carmona, E.J., Daza, M.C., Escobar, S., Galindo, V., Gutierrez, C., Lopez, S.D., Mejia, J.L., Rangel, A.M., Rangel, J.H., Rivera, L., Saavedra, C.A., Torres, A.M. & Trujillo, A.R. (2011). Does plant diversity benefit agroecosystems? A synthetic review. *Ecological Applications,* 21(1), 9-21. https://doi.org/10.1890/09-2026.1

Levin, S.A. & Clark, W. (2010). Toward a Science of Sustainability: Report from Toward a Science of Sustainability Conference. Center for International Development at Harvard University.

Liebman, M. & Dyck, E. (1993). Crop Rotation and Intercropping Strategies for Weed Management. *Ecological Applications,* 3(1), 92-122. https://doi.org/10.2307/1941795

Marini, L., St-Martin, A., Vico, G., Baldoni, G., Berti, A., Blecharczyk, A., Malecka-Jankowiak, I., Morari, F., Sawinska, Z. & Bommarco, R. (2020). Crop rotations sustain cereal yields under a changing climate. *Environmental Research Letters,* 15(12), 124011. https://doi.org/10.1088/1748-9326/abc651

Marshall, E.J.P. & Moonen, A.C. (2002). Field margins in northern Europe: their functions and interactions with agriculture. *Agriculture, Ecosystems &*

*Environment,* 89(1-2), 5-21. https://doi.org/10.1016/s0167-8809(01)00315-2

Martin, G., Moraine, M., Ryschawy, J., Magne, M.-A., Asai, M., Sarthou, J.-P., Duru, M. & Therond, O. (2016). Crop–livestock integration beyond the farm level: a review. *Agronomy for Sustainable Development,* 36(3), 53. https://doi.org/10.1007/s13593-016-0390-x

Matson, P.A., Parton, W.J., Power, A.G. & Swift, M.J. (1997). Agricultural intensification and ecosystem properties. *Science,* 277(5325), 504-9. https://doi.org/10.1126/science.277.5325.504

Maxwell, J.A. (2012). *What Is Realism, and Why Should Qualitative Researchers Care? A realist stance for qualitative research.* London: SAGE Publications, Inc.

McGinnis, M.D. & Ostrom, E. (2014). Social-ecological system framework: initial changes and continuing challenges. *Ecology and Society,* 19(2). https://doi.org/10.5751/es-06387-190230

Méndez, V.E., Bacon, C.M. & Cohen, R. (2013). Agroecology as a transdisciplinary, participatory, and action-oriented approach. *Agroecology and Sustainable Food Systems,* 37(1), 3-18. https://doi.org/10.1080/10440046.2012.736926

Meynard, J.-M., Charrier, F., Fares, M.h., Le Bail, M., Magrini, M.-B., Charlier, A. & Messéan, A. (2018). Socio-technical lock-in hinders crop diversification in France. *Agronomy for Sustainable Development,* 38(5), 54. https://doi.org/10.1007/s13593-018-0535-1

Millennium Ecosystem Assessment (2005). *Ecosystems and human well-being: synthesis*. Washington, DC: Island Press. https://www.millenniumassessment.org/documents/document.356.aspx.pdf

Miller, T.R., Wiek, A., Sarewitz, D., Robinson, J., Olsson, L., Kriebel, D. & Loorbach, D. (2013). The future of sustainability science: a solutions-oriented research agenda. *Sustainability Science,* 9(2), 239-246. https://doi.org/10.1007/s11625-013-0224-6

Mitchell, D.C., Castellano, M.J., Sawyer, J.E. & Pantoja, J. (2013). Cover Crop Effects on Nitrous Oxide Emissions: Role of Mineralizable Carbon. *Soil Science Society of America Journal,* 77(5), 1765-1773. https://doi.org/10.2136/sssaj2013.02.0074

Mitchell, M. (2009). *Complexity a guided tour*. Oxford: Oxford University Press.

Moonen, A.-C. & Bàrberi, P. (2008). Functional biodiversity: An agroecosystem approach. *Agriculture, Ecosystems & Environment,* 127(1-2), 7-21. https://doi.org/10.1016/j.agee.2008.02.013

Morel, K., Revoyron, E., San Cristobal, M. & Baret, P.V. (2020). Innovating within or outside dominant food systems? Different challenges for contrasting crop diversification strategies in Europe. *PLOS ONE,* 15(3), e0229910. https://doi.org/10.1371/journal.pone.0229910

Nastar, M., Boda, C.S. & Olsson, L. (2018). A critical realist inquiry in conducting interdisciplinary research: an analysis of LUCID examples. *Ecology and Society,* 23(3). https://doi.org/10.5751/es-10218-230341

Nicholls, C.I., Altieri, M.A. & Vasquez, L. (2016). Agroecology: Principles for the Conversion and Redesign of Farming Systems. *Journal of Ecosystem & Ecography,* 01(s5). https://doi.org/10.4172/2157-7625.S5-010

Ofori, F. & Stern, W.R. (1987). Cereal-Legume Intercropping Systems. *Advances in Agronomy.* 41-90.

Ollivier, G., Magda, D., Mazé, A., Plumecocq, G. & Lamine, C. (2018). Agroecological transitions: What can sustainability transition frameworks teach us? An ontological and empirical analysis. *Ecology and Society,* 23(2). https://doi.org/10.5751/es-09952-230205

Ostrom, E. (2009). A general framework for analyzing sustainability of social-ecological systems. *Science,* 325(5939), 419-22. https://doi.org/10.1126/science.1172133

Pe'er, G., Dicks, L.V., Visconti, P., Arlettaz, R., Baldi, A., Benton, T.G., Collins, S., Dieterich, M., Gregory, R.D., Hartig, F., Henle, K., Hobson, P.R., Kleijn, D., Neumann, R.K., Robijns, T., Schmidt, J., Shwartz, A., Sutherland, W.J., Turbe, A., Wulf, F. & Scott, A.V. (2014). Agriculture policy. EU agricultural reform fails on biodiversity. *Science,* 344(6188), 1090-2. https://doi.org/10.1126/science.1253425

Petrosillo, I., Aretano, R. & Zurlini, G. (2015). Socioecological Systems. In: Fath, B. (ed.) *Encyclopedia of Ecology*. Oxford: Elsevier. 419-425. https://doi.org/10.1016/b978-0-12-409548-9.09518-x

Piikki, K. & Söderström, M. (2019). Digital soil mapping of arable land in Sweden – Validation of performance at multiple scales. *Geoderma,* 352, 342-350. https://doi.org/10.1016/j.geoderma.2017.10.049

Poeplau, C. & Don, A. (2015). Carbon sequestration in agricultural soils via cultivation of cover crops – A meta-analysis. *Agriculture, Ecosystems & Environment,* 200, 33-41. https://doi.org/10.1016/j.agee.2014.10.024

Pretty, J. (2008). Agricultural sustainability: concepts, principles and evidence. *Philos Trans R Soc Lond B Biol Sci,* 363(1491), 447-65. https://doi.org/10.1098/rstb.2007.2163

Purvis, B., Mao, Y. & Robinson, D. (2018). Three pillars of sustainability: in search of conceptual origins. *Sustainability Science,* 14(3), 681-695. https://doi.org/10.1007/s11625-018-0627-5

Ramankutty, N., Evan, A.T., Monfreda, C. & Foley, J.A. (2008). Farming the planet: 1. Geographic distribution of global agricultural lands in the year 2000. *Global Biogeochemical Cycles,* 22(1), n/a-n/a. https://doi.org/10.1029/2007gb002952

Redlich, S., Martin, E.A., Steffan-Dewenter, I. & Willis, S. (2018a). Landscape-level crop diversity benefits biological pest control. *Journal of Applied Ecology,* 55(5), 2419-2428. https://doi.org/10.1111/1365-2664.13126

Redlich, S., Martin, E.A., Wende, B. & Steffan-Dewenter, I. (2018b). Landscape heterogeneity rather than crop diversity mediates bird diversity in agricultural landscapes. *PLOS ONE,* 13(8), e0200438. https://doi.org/10.1371/journal.pone.0200438

Renard, D. & Tilman, D. (2019). National food production stabilized by crop diversity. *Nature,* 571(7764), 257-260. https://doi.org/10.1038/s41586-019-1316-y

Rockstrom, J., Steffen, W., Noone, K., Persson, A., Chapin, F.S., 3rd, Lambin, E.F., Lenton, T.M., Scheffer, M., Folke, C., Schellnhuber, H.J., Nykvist, B., de Wit, C.A., Hughes, T., van der Leeuw, S., Rodhe, H., Sorlin, S., Snyder, P.K., Costanza, R., Svedin, U., Falkenmark, M., Karlberg, L., Corell, R.W., Fabry, V.J., Hansen, J., Walker, B., Liverman, D., Richardson, K., Crutzen, P. & Foley, J.A. (2009). A safe operating space for humanity. *Nature,* 461(7263), 472-5. https://doi.org/10.1038/461472a

Rockstrom, J., Williams, J., Daily, G., Noble, A., Matthews, N., Gordon, L., Wetterstrand, H., DeClerck, F., Shah, M., Steduto, P., de Fraiture, C., Hatibu, N., Unver, O., Bird, J., Sibanda, L. & Smith, J. (2017). Sustainable intensification of agriculture for human prosperity and global sustainability. *Ambio,* 46(1), 4-17. https://doi.org/10.1007/s13280-016-0793-6

Rosa-Schleich, J., Loos, J., Mußhoff, O. & Tscharntke, T. (2019). Ecological-economic trade-offs of Diversified Farming Systems – A review. *Ecological Economics,* 160, 251-263. https://doi.org/10.1016/j.ecolecon.2019.03.002

Sadok, W., Angevin, F., Bergez, J.-É., Bockstaller, C., Colomb, B., Guichard, L., Reau, R. & Doré, T. (2008). Ex ante assessment of the sustainability of alternative cropping systems: implications for using multi-criteria decision-aid methods. A review. *Agronomy for Sustainable Development,* 28(1), 163-174. https://doi.org/10.1051/agro:2007043

Schipanski, M.E., Barbercheck, M., Douglas, M.R., Finney, D.M., Haider, K., Kaye, J.P., Kemanian, A.R., Mortensen, D.A., Ryan, M.R., Tooker, J. & White, C. (2014). A framework for evaluating ecosystem services provided by cover crops in agroecosystems. *Agricultural Systems,* 125, 12-22. https://doi.org/10.1016/j.agsy.2013.11.004

Schipanski, M.E., MacDonald, G.K., Rosenzweig, S., Chappell, M.J., Bennett, E.M., Kerr, R.B., Blesh, J., Crews, T., Drinkwater, L., Lundgren, J.G. & Schnarr, C. (2016). Realizing Resilient Food Systems. *Bioscience,* 66(7), 600-610. https://doi.org/10.1093/biosci/biw052

Sen, A. (2013). The Ends and Means of Sustainability. *Journal of Human Development and Capabilities,* 14(1), 6-20. https://doi.org/10.1080/19452829.2012.747492

Shucksmith, M., Thomson, K.J. & Roberts, D. (2005). *The CAP and the regions: the territorial impact of the Common Agricultural Policy*. Wallingford: CABI Publishing. https://doi.org/10.1079/9780851990552.0000

Sirami, C., Gross, N., Baillod, A.B., Bertrand, C., Carrie, R., Hass, A., Henckel, L., Miguet, P., Vuillot, C., Alignier, A., Girard, J., Batary, P., Clough, Y., Violle, C., Giralt, D., Bota, G., Badenhausser, I., Lefebvre, G., Gauffre, B., Vialatte, A., Calatayud, F., Gil-Tena, A., Tischendorf, L., Mitchell, S., Lindsay, K., Georges, R., Hilaire, S., Recasens, J., Sole-Senan, X.O., Robleno, I., Bosch, J., Barrientos, J.A., Ricarte, A., Marcos-Garcia, M.A., Minano, J., Mathevet, R., Gibon, A., Baudry, J., Balent, G., Poulin, B., Burel, F., Tscharntke, T., Bretagnolle, V., Siriwardena, G., Ouin, A., Brotons, L., Martin, J.L. & Fahrig, L. (2019). Increasing crop heterogeneity enhances multitrophic diversity across agricultural regions. *Proc Natl Acad Sci U S A,* 116(33), 16442-16447. https://doi.org/10.1073/pnas.1906419116

Smith, C.S. & McDonald, G.T. (1998). Assessing the sustainability of agriculture at the planning stage. *Journal of Environmental Management,* 52(1), 15-37. https://doi.org/10.1006/jema.1997.0162

Soinne, H., Keskinen, R., Räty, M., Kanerva, S., Turtola, E., Kaseva, J., Nuutinen, V., Simojoki, A. & Salo, T. (2020). Soil organic carbon and clay content as deciding factors for net nitrogen mineralization and cereal yields in boreal mineral soils. *European Journal of Soil Science*(n/a). https://doi.org/10.1111/ejss.13003

Statistics Sweden (2020a). *Ekologisk växtodling 2019. Serie JO – Jordbruk, skogsbruk och fiske [Organic crop production 2019. Series JO – Agriculture, forestry and fish]*. https://djur.jordbruksverket.se/webdav/files/SJV/Amnesomraden/Statistik,%20fakta/Arealer/JO13/JO13SM2001/JO13SM2001_omstatistiken.htm

Statistics Sweden (2020b). *Jordbruksstatistisk sammanställning 2020 med data om livsmedel – tabeller*
*[Agricultural statistics 2020 including food statistics – tables]*. https://jordbruksverket.se/download/18.78dd5d7d173e2fbbcda98893/1597390150166/JS_2020.pdf

Steffen, W., Richardson, K., Rockstrom, J., Cornell, S.E., Fetzer, I., Bennett, E.M., Biggs, R., Carpenter, S.R., de Vries, W., de Wit, C.A., Folke, C., Gerten, D., Heinke, J., Mace, G.M., Persson, L.M., Ramanathan, V., Reyers, B. & Sorlin, S. (2015). Sustainability. Planetary boundaries: guiding human development on a changing planet. *Science,* 347(6223), 1259855. https://doi.org/10.1126/science.1259855

Swedish Land Survey (2018). *Scania County. SWEREF 99 TM. GSD-Map of Sweden 1:1 million, vector format [Map]. https://www.lantmateriet.se/sv/Kartor-och-geografisk-information/geodataprodukter/produktlista/sverigekartor/ (accessed 05 December 2018).*

Tamburini, G., Bommarco, R., Wanger, T.C., Kremen, C., van der Heijden, M.G.A., Liebman, M. & Hallin, S. (2020). Agricultural diversification promotes multiple ecosystem services without compromising yield. *Sci Adv,* 6(45), eaba1715. https://doi.org/10.1126/sciadv.aba1715

The Royal society (2009). *Reaping the benefits: Science and the Sustainable Intensification of Global Agriculture*. (RS policy document 11/09). The Royal Society, London. https://royalsociety.org/topics-policy/publications/2009/reaping-benefits/

Tilman, D., Balzer, C., Hill, J. & Befort, B.L. (2011). Global food demand and the sustainable intensification of agriculture. *Proc Natl Acad Sci U S A,* 108(50), 20260-4. https://doi.org/10.1073/pnas.1116437108

Tilman, D., Cassman, K.G., Matson, P.A., Naylor, R. & Polasky, S. (2002). Agricultural sustainability and intensive production practices. *Nature,* 418(6898), 671-7. https://doi.org/10.1038/nature01014

Tilman, D., Fargione, J., Wolff, B., D'Antonio, C., Dobson, A., Howarth, R., Schindler, D., Schlesinger, W.H., Simberloff, D. & Swackhamer, D. (2001). Forecasting agriculturally driven global environmental change. *Science,* 292(5515), 281-4. https://doi.org/10.1126/science.1057544

Tonitto, C., David, M.B. & Drinkwater, L.E. (2006). Replacing bare fallows with cover crops in fertilizer-intensive cropping systems: A meta-analysis of crop yield and N dynamics. *Agriculture, Ecosystems & Environment,* 112(1), 58-72. https://doi.org/10.1016/j.agee.2005.07.003

Trenbath, B.R. (1993). Intercropping for the management of pests and diseases. *Field Crops Research,* 34(3-4), 381-405. https://doi.org/10.1016/0378-4290(93)90123-5

Tribouillois, H., Cohan, J.-P. & Justes, E. (2015). Cover crop mixtures including legume produce ecosystem services of nitrate capture and green manuring: assessment combining experimentation and modelling. *Plant and Soil,* 401(1-2), 347-364. https://doi.org/10.1007/s11104-015-2734-8

Tscharntke, T., Klein, A.M., Kruess, A., Steffan-Dewenter, I. & Thies, C. (2005). Landscape perspectives on agricultural intensification and biodiversity â“ ecosystem service management. *Ecology Letters,* 8(8), 857-874. https://doi.org/10.1111/j.1461-0248.2005.00782.x

Valkama, E., Lemola, R., Känkänen, H. & Turtola, E. (2015). Meta-analysis of the effects of undersown catch crops on nitrogen leaching loss and grain yields in the Nordic countries. *Agriculture, Ecosystems & Environment,* 203, 93-101. https://doi.org/10.1016/j.agee.2015.01.023

Vandermeer, J. (1989). *The ecology of intercropping*. New York, USA: Cambridge University Press.

Vandermeer, J., Aga, A., Allgeier, J., Badgley, C., Baucom, R., Blesh, J., Shapiro, L.F., Jones, A.D., Hoey, L., Jain, M., Perfecto, I. & Wilson, M.L. (2018). Feeding Prometheus: An Interdisciplinary Approach for Solving the Global Food Crisis. *Frontiers in Sustainable Food Systems,* 2(39). https://doi.org/10.3389/fsufs.2018.00039

Vandermeer, J.H. (2011). *The ecology of agroecosystems*. Sudbury, Mass: Jones and Bartlett Publishers.

Veres, A., Petit, S., Conord, C. & Lavigne, C. (2013). Does landscape composition affect pest abundance and their control by natural enemies? A review. *Agriculture, Ecosystems & Environment,* 166, 110-117. https://doi.org/10.1016/j.agee.2011.05.027

Vermeulen, S.J., Campbell, B.M. & Ingram, J.S.I. (2012). Climate Change and Food Systems. *Annual Review of Environment and Resources,* 37(1), 195-222. https://doi.org/10.1146/annurev-environ-020411-130608

Walker, B., Holling, C.S., Carpenter, S.R. & Kinzig, A.P. (2004). Resilience, Adaptability and Transformability in Social-ecological Systems. *Ecology and Society,* 9(2). https://doi.org/10.5751/es-00650-090205

Wezel, A., Herren, B.G., Kerr, R.B., Barrios, E., Gonçalves, A.L.R. & Sinclair, F. (2020). Agroecological principles and elements and their implications for transitioning to sustainable food systems. A review. *Agronomy for Sustainable Development,* 40(6), 40. https://doi.org/10.1007/s13593-020-00646-z

Wezel, A., Soboksa, G., McClelland, S., Delespesse, F. & Boissau, A. (2015). The blurred boundaries of ecological, sustainable, and agroecological intensification: a review. *Agronomy for Sustainable Development,* 35(4), 1283-1295. https://doi.org/10.1007/s13593-015-0333-y

Wiek, A. & Lang, D.J. (2016). Transformational Sustainability Research Methodology. In: *Sustainability Science*. 31-41. https://doi.org/10.1007/978-94-017-7242-6_3

Wood, D. & Lenné, J.M. (1999). *Agrobiodiversity : characterization, utilization and management*. Wallingford: CABI.

Wood, S.A., Karp, D.S., DeClerck, F., Kremen, C., Naeem, S. & Palm, C.A. (2015). Functional traits in agriculture: agrobiodiversity and ecosystem services. *Trends in Ecology & Evolution,* 30(9), 531-9. https://doi.org/10.1016/j.tree.2015.06.013

World Commission on Environment and Development (1987). Our common future, report. Oxford: Oxford University Press.

# Popular science summary

Modern agriculture is based mainly on large-scale and industrialized farming systems that include only a few crops that depend on large external inputs of fertilizers, pesticides and fuel for machinery. Increasing the crop diversity is suggested as a key strategy to improve agriculture's sustainability, since it can have positive effects on biodiversity both within and outside the agricultural fields, reduce the need for external inputs and reduce the environmentally harmful losses of nutrients. The crop diversity can be increased via different practices, for example: diversified crop rotations, meaning that an increased number of different crops are grown in rotation with each other; intercropping or species mixtures, where a mixture of two or more crops is grown in the same field at the same time; and cover crops that are grown in periods between two cash crops.. In this thesis, different methods were used to evaluate the sustainability of diversified cropping systems where either one or several crop diversification practices were applied. We carried out literature review, field experiments, farmer interviews and socio-economic and environmental evaluation of cropping systems. Finally, we mapped the distribution of crop diversity in the Scania region and tested if crop diversity correlated with crop yields. The results from this thesis have shown promising results from enhancing overall sustainability when increasing crop diversity within the farm and expressed in the landscape. Crop diversity by using intercropping, cover crops, larger variety of crops in the crop rotation, or applying other diversification practices in the fields or farm can, for example, improve the nutrient use management, increase soil carbon, and improve soil quality without compromising productivity.

Moreover, implementing these practices may help the farming system cope better under adverse climate conditions. However, there are still many challenges farmers face for increasing crop diversity in their farms. Many factors influence crop choices, such as markets, prices, regulations. There is a need for further socio-economic support to increase the opportunities to implement more crop diversity at the local and national levels.

# Populärvetenskaplig sammanfattning

Det moderna jordbruket, baserat på storskalig industriell produktion av ett fåtal grödor och stora insatser av gödsel, pesticider och energi, orsakar negativ miljöpåverkan. Att öka gröddiversiteten, d.v.s. mångfalden av odlade grödor, föreslås som en viktig strategi för att stärka jordbrukets hållbarhet, genom positiva effekter på biologisk mångfald, minskat beroende av externa insatsmedel och minskade växtnäringsförluster från odlad mark. Gröddiversiteten kan ökas genom olika metoder, till exempel: diversifierade växtföljder, där flera olika grödor odlas omväxlande efter varandra; samodling, där en blandning av två eller fler olika grödor odlas samtidigt på samma fält; och mellangrödor som odlas för att minska perioderna av obevuxen mark mellan skörd och etablering av nästa huvudgröda. I denna avhandling kombineras olika studier för att utvärdera hållbarheten hos odlingssystem där en eller flera metoder för gröddiversifiering tillämpas. Studierna inkluderar sammanställning av publicerade forskningsresultat, fältförsök, intervjuer med lantbrukare, socio-ekonomiska och miljömässiga utvärderingar av odlingssystemens hållbarhet, samt analys av samband mellan gröddiversitet och skördenivåer på landskapsnivå.

Resultaten visar att gröddiversitet har positiva effekter på odlingssystemets övergripande hållbarhet. Samodling, mellangrödor och diversifierade växtföljder kan bidra till mer effektiv resursanvändning, minska risken för växtnäringsförluster, öka mängden mark-kol och förbättra markens bördighet med bibehållna skördenivåer av de odlade grödorna. Dessutom kan ökad gröddiversitet stärka jordbrukets förmåga att klara av ogynnsamma väder-förhållanden. Men lantbrukare står inför många utmaningar för att kunna öka gröddiversiteten i sina odlingssystem. Efterfrågan, lönsamhet och regelverk har stark påverkan på lantbrukarnas val av grödor, och det behövs mer ekonomiskt och politiskt stöd för att stimulera en ökad gröddiversitet i jordbrukets odlingssystem.

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Increasing crop diversity may be a key strategy to promote multiple benefits and enhance the sustainable development of agroecosystems. In this thesis, I combined theoretical approaches and scientific methods along several scales to assess the sustainability of diversified cropping systems and increase the knowledge of complex cropping systems. The findings of this thesis support that increased crop diversity across spatial and temporal scales can contribute to resource-efficient production and enhance the delivery of ecosystem services, thus contributing to more sustainable cropping systems.

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