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Barriers to Crop Diversification Practices in the European Union: A Narrative Synthesis

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1. Abstract

Crop diversification covers different farm-level practices such as extending crop rotations, intercropping, multicropping, and strip cropping. Irrespective of the well-documented farm-level and societal benefits derived from crop diversification (Kremen and Miles, 2012), European farmers' adoption rates have been low (Kassam *et al.*, 2015; Lahmar, 2010; Magrini *et al.*, 2016; Voisin *et al.*, 2014; Watson *et al.*, 2017). This research explores crop diversification practices that produce a marketable crop, examining their low uptake at the farm-level, upstream and downstream of the farm, and considering the broader agri-food system. This requires a holistic systems approach, like agroecology, which integrates ecological, economic, and social dimensions (Francis *et al.*, 2003; Méndez *et al.*, 2015). More specifically, I synthesis barriers to crop diversification at the farm-level and along the supply chain and explore the relationships between barriers to different crop diversification practices and relationships between barriers and different markets and their respective value chains. To achieve these aims, I conduct two systematic-like reviews: a literature review of peer-reviewed review papers on the adoption of crop diversification practices in Europe and a review of the outputs from six European Union research projects making up the European Crop Diversification Cluster (CDC).

This synthesis supports previous research demonstrating that barriers are context-dependent, interconnected, and occur at multiple levels. Six main findings emerged. First, the results support previous research demonstrating a lock-in to simplified farming systems which focus on major crops and agro-chemicals. Second, the findings suggest that the technical and economic performance in terms of yield and profitability were less significant barriers for farmers than previous reviews indicate. Third, a lack of knowledge and access to support or advice were critical barriers for farmers. Fourth, non-economic factors influenced farmers' decision-making. Fifth, specific markets and value chains impact barriers; the results demonstrate that commodity and alternative markets and their respective value chains have distinctive barriers. Sixth, intercropping has specific barriers, predominantly regarding the separation of mixtures and the need for specialised machinery and infrastructure both on- and off-farm.

2. Summary for a general audience

Since the 1950s, farming has become increasingly specialised, simplified, and intensive. This was made possible through a series of technological developments. Machinery reduced the need for labour and animals on the farm. Synthetic fertilisers provided nutrients to help plants grow and allowed farms and regions to specialise because they were no longer reliant on animals and their manure for fertilisation. Agrochemicals such as pesticides and herbicides protected plants from pests, diseases, and weeds, which were previously controlled by carefully managing crop rotations and selection of locally adapted varieties. Many of these technologies have apparent benefits, but at the same time, it is widely acknowledged that our current agricultural and food systems are not sustainable.

A widely accepted group of practices that are part of the solution is crop diversification. Simply put, crop diversification involves growing a wider variety of crops. Some examples include longer crop rotations, intercropping where two or more crops are grown together, and growing strips of different crops on the same field. Crop diversification counteracts many negative consequences of modern farming and benefits farmers, the environment, and society. For farmers, the benefits include reducing fertiliser and agrochemicals, improving soil health, and spreading financial risk. Some of the benefits to society are reduced greenhouse gas emissions from the production and use of synthetic fertilisers; reduced ground- and surface-water contamination; improved pollination activity; and overall biodiversity. In addition, crop diversification can produce healthy and nutritious food for local consumers; or animal feed to reduce the reliance on imported feed which has additional environmental and societal consequences.

With all the benefits, one might expect that crop diversification would be widely practiced in Europe, but that is not the case. For farmers to adopt crop diversification practices requires multiple developments, many of which are out of their control. Firstly, they need to find which crops fit with their farming system and are adapted to their climate. Secondly, they must search for knowledge on how to grow these new crops or adopt these new practices. Crop diversification might be very different from their current farming. It could represent a fundamental change in production that requires time, energy, and investment in new machinery or equipment. Lastly, they need to find new markets to sell their crop, which do not always exist. If they cannot find a buyer, they may have to find local consumers, which presents a range of new challenges. Beneath all these considerations, farmers are running a business that needs to be profitable and the risk or uncertainty may limit their willingness to

adopt crop diversification practices. It is evident from this short description that adopting crop diversification practices is far more complex than it first appears.

The European Union is funding research into crop diversification with six projects across European countries examining different crop diversification practices. Recognising the complexity of the problem, the projects cover a wide range of topics and include various stakeholders, from breeders, farmers, and advisors to processors and consumers. To bring together this research, I synthesised the projects' research on barriers paying attention to the farm and farmers together with the obstacles that occur beyond the farm. Some of the most relevant outcomes of this research are as follows.

Upstream of the farm, breeders and seed suppliers focus on crops with the largest market in order to make the highest return on investment. Therefore, most research and development is on a few key crops, like wheat. These key crops then have higher yields and other agronomic benefits such as adapted varieties, resistance against pests or diseases, and stress against weather extremes. The same principle applies to agrochemicals to protect the plant. This creates challenges for farmers to find suitable varieties or products to protect their crops.

On the farm and for farmers, there are many different barriers. An interesting finding from this research was that although the profitability of adopting a new practice is essential for farmers, other factors play a crucial role. Having access to knowledge and support from advisors was frequently one of the most important considerations for farmers. Also, the research showed that farmers are motivated by a complex mixture of reasons. For example, environmental stewardship inspired some farmers while others wanted to reduce their dependence on inputs or imported animal feed. Others were just curious!

Most farmers sell their crops to companies who collect, sort, clean, and eventually process the crops into products for humans or animals. Downstream companies are not always willing to accept new crops because of small or unstable markets. New crops might require investments in machinery or infrastructure or need new recipes which need to be tested and marketed. All of which incur additional costs and decrease profitability. Furthermore, many markets are highly competitive. A prominent example is animal feed, which has high competition with inexpensive imports such as soya or industrial by-products. Therefore, new crops are often unattractive for downstream companies, where profit is a crucial consideration.

Local markets can be attractive options for farmers because they receive a higher value which can counter the reduced performance, but this creates other challenges for farmers. Underpinning these local markets and other food markets is consumer demand. For example,

legumes, including beans, lentils, and chickpeas, have relatively small markets due to the low consumption by European consumers.

This short piece gives a glimpse into crop diversification and highlights the interconnected and complex nature of our agricultural and food systems.

3. Introduction

Diversified farming was common in Europe until the 1950s or 1960s, but European agriculture has become increasingly simplified, specialised, and intensive since then. Mechanisation and the development of agro-chemicals made this possible, but a range of factors have driven the trend. The European Union (EU) agricultural policy, mainly through series of changes to the Common Agricultural Policy (CAP), has encouraged regions and farms to specialise (Meynard *et al.*, 2013; Roest, Ferrari and Knickel, 2018). This has been demonstrated with cereal production, which has received more support creating a comparative advantage for European farmers to grow cereals over legumes and other minor crops (Magrini *et al.*, 2016). In addition, European trade policy gave farmers access to inexpensive soya from North America and South America for animal feed which enabled specialisation of regions and farms (Voisin *et al.*, 2014). Furthermore, the low costs of synthetic fertiliser relative to product prices and energy have contributed to this development (Annicchiarico, 2017; Watson *et al.*, 2017).

The negative consequences of modern farming systems are well-documented (e.g., IAASTD, 2009; IPES-Food, 2016). At the farm-level, shorter crop rotations (and to the extreme, monocultures) create more problems with pests, diseases, and weed control (Meynard *et al.*, 2013) and rely on greater use of agrochemicals, which have negative consequences on soil health, ground and surface water contamination, and biodiversity loss (Kremen and Miles, 2012). Moreover, removing crops such as legumes from crop rotations, which fix atmospheric nitrogen, results in a greater reliance on synthetic fertilisers, which have high greenhouse gas emissions from production and transportation (Magrini *et al.*, 2016). At a regional level, there are negative impacts on biodiversity, conflicts with water use, and concentration of animal production in certain regions, which impedes nutrient cycling (Meynard *et al.*, 2013; Meynard *et al.*, 2018; Zander *et al.*, 2016). Internationally, Europe's considerable demand for soya creates imbalances in the cropping systems where the soya is grown (Watson *et al.*, 2017) along with a range of other economic, social, and environmental problems (Leguizamón, 2014).

These challenges and the overarching problems facing contemporary agri-food systems do not have singular or simple solutions but require holistic systems approaches. One such approach is agroecology, integrating ecological, economic, and social dimensions with the aim of making agri-food systems more sustainable (Francis *et al.*, 2003; Méndez *et al.*, 2015). I use an agroecological approach to examine the barriers to adopting and disseminating crop diversification practices in Europe. The approach is agroecological because it considers the farm-level within the broader agri-food system, paying specific attention to downstream of the farm. Furthermore, an agroecological perspective values viewing the problem in a participatory and transdisciplinary manner (Méndez, Bacon and Cohen, 2015). I do so by

including farmers' and other stakeholders' perspectives and knowledge alongside scientific knowledge and confront the problem from different scientific disciplines. Finally, crop diversification is an integral part of agroecology which supports farming practices and systems which mimic natural ecosystems.

In this article, crop diversification refers to farm-level diversification, specifically the process of increasing crop diversity in time and or space by integrating additional crops into the farming system for use as food, feed, or industrial purposes. Crop diversification in time (or temporal crop diversification) includes both integrating new crops on the same field either before or after the main crop within a single growing season (e.g., multicropping or cover crop) or integrating new crops on the same field in separate but successive growing seasons (e.g., crop rotation). Crop diversification in space (or spatial crop diversification) includes growing multiple crops on the same field within the same growing season (e.g., intercropping or strip cropping).

The growing interest in crop diversification practices is due to their wide range of farm-level and societal benefits. In a review comparing conventional farming with diversified farming systems in terms of 12 ecosystem services, Kremen and Miles (2012) concluded that diversified farming systems support biodiversity, improve soil quality, water storage, increase energy efficiency, and resilience to climate change. They further state that diversified farming systems support pollination services and help control pests, weeds, and disease. Some of these benefits provide public goods, while others indirectly or directly benefit farmers. For example, introducing legumes into a cropping system reduces the amount of fertiliser required, or extending the crop rotation can provide a break crop effect which increases subsequent yields and reduces the need to apply agro-chemicals (Watson *et al.*, 2017; Zander *et al.*, 2016). The environmental and agronomic benefits of crop diversification are often seen as a trade-off for the generally lower yields of crop diversification (Kremen and Miles, 2012). However, lower yields are not a given (Ponisio and Ehrlich, 2016) and depend on how the yield is defined. Furthermore, crop diversification, particularly the introduction of legumes, is seen as a strategy to reduce Europe's dependence on imported soya for animal feed and to increase the supply of pulses for direct human consumption, which have numerous health benefits (Voisin *et al.*, 2014; Watson *et al.*, 2017; Zander *et al.*, 2016).

Irrespective of these benefits, crop diversification is not widely practiced in Europe. Conservation agriculture, which includes crop diversification, has experienced slow adoption in Europe in the past, even if there are some signs that it has been increasing in recent years (Kassam *et al.*, 2015; Lahmar, 2010). Similarly, multiple studies have highlighted the low level of legume cultivation in Europe (Magrini *et al.*, 2016; Voisin *et al.*, 2014), for instances, grain legumes have declined in the last five decades to only 1.6% of arable land in Europe as

of 2014 (Watson *et al.*, 2017). The low adoption has prompted researchers to search for causes that explain the decline, examine the barriers or determinants that limit the adoption, and explore the levers or enablers to encourage crop diversification practices.

Many reviews examine the adoption of crop diversification practices as a subcategory of other sustainable agriculture practices (Carlisle, 2016; Knowler and Bradshaw, 2007; Mills *et al.*, 2020; Prager and Posthumus, 2010). However, crop diversification merits a separate examination, especially when incorporating a new marketable or productive crop into the farming system because it creates additional barriers at the farm level and the supply chain. The review articles that only cover crop diversification practices in Europe focus on legumes[1] and there are no reviews on the uptake of other crop diversification practices in Europe (this was also found by Bjarklev *et al.*, 2019).

The existing reviews on legumes primarily examine agronomic and economic barriers at the farm-level but rarely explore other farm-level barriers in detail or include farmers' perspectives. The strength of this literature is the agri-food system approach, understanding the farm as part of a system and influenced by upstream, downstream, and broader economic and political developments. Nevertheless, the barriers downstream of the farm concerning markets, supply chains, and market coordination merit a more detailed analysis. Finally, no article has synthesised the entire range of barriers to crop diversification practices. I address these gaps in the literature by 1) synthesising the barriers to crop diversification practices, 2) exploring the relationships between barriers and different crop diversification practices, and 3) exploring the relationships between barriers and different markets and their accompanying value chains.

To achieve these aims, I first conduct a systematic-like literature review of the review articles on crop diversification practices in Europe. Then I review the outputs from six research projects funded by the European Union, making up the European Crop Diversification Cluster (CDC). Although the six projects are independent, they can be divided into three groups, with each group containing two projects. DIVERSify and ReMIX focus on intercropping mainly at the farm-level, TRUE and LegValue concentrate on legumes but predominantly beyond the farm-level, and Diverfarming and DiverIMPACTS cover a broader range of crop diversification practices with an emphasis on the supply chain (See section 7.1 for more details on the individual projects). The two reviews focus on crop diversification practices that produce a marketable or useable crop instead of practices that only provide an agronomic or ecological service or benefit. However, due to inadequate information on some

[1] Some of these reviews do include sections on intercropping with legumes and there is a recent review on wheat-pea intercropping Mamine and Farès (2020).

crop diversification practices (e.g., strip cropping, multicropping) and to align with the CDC, this paper explores the three partly overlapping categories of crop diversification: intercropping, legumes, and crop diversification in general. To that end, this paper is guided by two research questions: 1) what are the similarities and differences in the barriers to different crop diversification practices? 2) What are the similarities and differences in the barriers to different markets and their respective value chains?

4. Material(s) and methods

The research comprised of four elements: A literature on barriers to agricultural innovation was used to develop a flexible conceptual framework. This conceptual framework guided two literature reviews. A systematic-like literature review on the barriers to crop diversification and a review of the CDC projects' outputs. Finally, to confirm the results and accuracy of my review of the CDC projects, I conducted a workshop with researchers from the CDC.

Although this paper is not a strict systematic review, it has incorporated elements from this research method to improve the credibility of the results and increase the trustworthiness of the research. Several authors have outlined steps to guide qualitative systematic literature reviews (Okoli, 2015; Popay *et al.*, 2006; Xiao and Watson, 2019) and were used to inform my research method.

4.1. Literature search

Peer-reviewed journal articles for the systematic-like literature review were obtained by searching the electronic databases Web of Science and Scopus using keywords in a search string using Boolean operators[2]. Articles were screened for inclusion and exclusion based on predefined criteria. They needed to include at least one type of crop diversification practice, barriers/enablers (or synonyms and similar concepts), and the geographic region was limited to the EU-27, EEA, or the United Kingdom. Only peer-reviewed journal articles were included due to time constraints and because many of the documents from the CDC projects were not subjected to the same peer-review process. This was considered necessary to improve the reliability of the research. In addition, the search was limited to review papers, making the review less comprehensive in its coverage of all the available journal articles on crop diversification. However, as the aim was to identify gaps in the existing literature and to frame the review of the CDC, it remains useful, but a more comprehensive search of the existing peer-reviewed literature would improve the research (see Section 4.5 Limitations). A total of six papers paper fulfilled the screening criteria.

[2] For complete details of the systematic-like literature review protocol see Appendix A

Documents for the CDC review were obtained from the projects' websites, additional documents (which were not published or confidential at the time) were acquired through direct contact with researchers from the CDC. The documents were also screened for inclusion, but as the projects all covered the geographic region Europe and crop diversification practices, they were only screened for inclusion based on whether they covered barriers or enablers. Unlike the systematic-like literature review, there were no restrictions regarding the document type. Thus, the review of the CDC projects included reports, deliverables, and peer-reviewed journal articles, but the research needed to be conducted by one of CDC projects. A total of 17 documents fulfilled the screening criteria[3].

4.2. Data extraction

The data extraction process applies to both the literature review and the CDC review, but each review was conducted separately. The reviews were performed in two stages, and the data extracted was recorded in spreadsheets using Microsoft Excel. In the first stage, general information about the article was recorded in individual columns, including the citation, date of publication, project, type of document (deliverable, journal article, or report), type of review/method, number of cases, study location (region and country), farming approach, type of crop diversification practice, specific crop(s) covered, and scale.

The second stage was a full-text review to extract the different barriers. Barriers were coded with keywords that described the essence of the barrier and recorded in individual lines of a Microsoft Excel spreadsheet. Similar codes were merged into one another throughout the process and grouped into categories to allow comparisons across different types of crop diversification. In addition to the code, subsequent columns were used to record supplementary information, including any references cited, additional details (e.g., direct quotation), and other comments. Each barrier was labelled according to predefined groups of barriers using a drop-down function. These groups of barriers were identified in the preliminary research on barriers to agricultural innovation and crop diversification and, although broad (e.g., agronomic, supply chain, etc.), were useful to aid the initial sorting and analysis of different barriers.

Due to the diverse range of documents reviewed, both methodologically and epistemologically, different types of barriers were extracted. The two main groups of barriers are those perceived by stakeholders involved in the practice of crop diversification (e.g., farmers, advisors, collectors, processors) and barriers determined by researchers or experts (e.g., economic analysis demonstrating low profitability of legumes). In addition to barriers,

[3] Many of the CDC projects are ongoing so the literature reviewed for this thesis is unlikely to be comprehensive. For a full list of CDC project documents reviewed see Appendix C.

enablers were extracted and used to supplement the barriers and aided the analysis; this was particularly relevant for surveys and workshops where both barriers and enablers were researched. Lastly, some of the documents ranked barriers (predominantly primary research of actors practicing crop diversification). This information was extracted along with the barrier but could not be incorporated systematically due to methodological differences; instead, it was used to strengthen conclusions.

4.3. Data analysis

The data extraction and analysis were part of an iterative process, moving back-and-forth between reviewing the CDC documents and extracting barriers, categorising the barriers, and analysing the results. A preliminary analysis of the CDC results involved tables and concept maps. Two tables were used to organise the documents reviewed and to identify general patterns. The first table contains the methods and particular focus of the document, and the second table displays the main barriers identified in each document. In addition, multiple iterations of concept maps were completed to explore connections between the barriers and the different levels at which the barriers are found (e.g., upstream, farm-level, and downstream).

Similarities and differences between the crop diversification practices were explored using a synthesis table. Early in the research, it was clear that there was not enough data to distinguish between numerous crop diversification practices (e.g., multicropping and strip cropping), which led to the three groups being selected, legumes, intercropping, and generalised crop diversification. This was also done to align with the six projects within the CDC. Moreover, as crop diversification practices were not always helpful to analyse downstream barriers, a second synthesis table was devised to compare barriers based on different value chains and market types.

4.4. External validation

A two-hour workshop with researchers from the different projects ensured that the synthesis accurately portrayed the barriers. This practice is recommended for systematic literature reviews (Popay *et al.*, 2006) but also more broadly in qualitative research (e.g., Ritchie and Lewis, 2003). The workshop was centred on the two synthesis tables (Table 3 & Table 4), which compared the different farm-level and downstream barriers and was guided by eight questions (see Appendix B for details on workshop). The workshop participants received the tables and the questions beforehand. In addition, the workshop provided an opportunity to discuss contradictions between the CDC projects and between the CDC projects and the literature review.

4.5. Limitations

There are two main areas in a systematic or systematic-like review that affect credibility and trustworthiness. The first is the review process (explained above), and the second is the quality of the data included in the review.

There are some key limitations in the review process. First, I worked alone, whereas it is recommended to conduct a systematic review in a team to reduce bias (e.g., Xiao and Watson, 2019). Second, the systematic-like literature review was restricted to peer-reviewed review articles due to time constraints. Including non-review articles and a broader geographic scope would make the review more comprehensive in its coverage. Third, the documents reviewed used diverse methods based on different epistemologies, which resulted in a different focus of the barriers and how the barriers were researched. This was most apparent between the current literature review and CDC review. The literature review mostly determined barriers based on experiments or analysis but rarely included farmers' or other stakeholders' perspectives, which was the case in many of the CDC projects' outputs. Forth, ideally in systematic reviews, researchers conduct a quality assessment of the articles to determine which articles or data should be emphasised. This was not feasible but would produce a more robust synthesis. The limitations in the review process partly contribute to some key limitations in the comprehensiveness and quality of the data used in this review.

A key limitation was the comprehensiveness of barriers between different crop diversification practices, which impeded my ability to explore relationships and make comparisons. This occurred in both reviews. In the literature review, not a single review article covered a crop diversification practice other than legumes (although several articles referred to intercropping with legumes). Similarly, the predominant focus of the CDC review was on legumes and intercropping with less research specifying other practices or crops. This led to creating the category 'generalised crop diversification', which partially overlaps with the other categories. Furthermore, the individual projects within the CDC focused on different levels of the agri-food system, which resulted in barriers not comprehensively cover for the different crop diversification practices at different levels. For example, barriers to intercropping were extensively researched at the farm level by DIVERSify and ReMIX compared to legumes that focused predominantly downstream of the farm.

In addition, there are limitations based on the quality of the data. Research that includes stakeholders often has a degree of participant bias – unless a representative sample is obtained – because the attendees of workshops or the respondents of the survey are likely to have a more positive perception of the topic. This was acknowledged in several of the CDC project documents (Drexler *et al.*, 2018; Pearce *et al.*, 2018; Smadja, Magrini and Muel, forthcoming). Similarly, previous research on the adoption of agricultural innovation has

shown that barriers depend on if farmers have adopted the innovation or not (Carlisle, 2016). Much of the CDC research included farmers who had already adopted a crop diversification practice. Both factors mean that the barriers might not accurately represent the general farming population: limiting the trustworthiness of the findings.

5. Conceptual framework

5.1. Agricultural innovation

The literature on agricultural innovation is diverse, with different epistemologies underlying how innovation is understood and studied. The purpose here is not to cover them extensively but to highlight some key differences. Leeuwis (2004) distinguished between two groups within agricultural research, the persuasive/instrumental and the process orientated/communicative traditions. The persuasive/instrumental tradition typically examines why and how farmers adopt (or do not adopt) innovations with the aim to accelerate adoption and diffusion, which is often perceived as slow. A fundamental assumption is that humans make rational decisions, and with sufficient knowledge of the causes or determinants, human behaviour can be predicted and thus steered in a particular direction. This type of research often views innovations as predefined, following a top-down direction. In other words, the innovations have been developed by scientists for farmers to adopt or implement.

The process management-orientated tradition challenges these underlying assumptions, arguing that there is no objective knowledge but instead multiple realities, and thereby the assumption that human behaviour or actions can be predicted or controlled using rational actor models is misguided. It views innovation and change as a process that cannot be planned, and at very best, guided. Similarly, it moves away from the top-down idea of innovations that are ‘adopted’ or ‘implemented’, arguing that innovations involve multiple actors and often originate at the farm-level. Acknowledging these unknowns and uncertainties, the research seeks to understand the innovation process.

5.2. Barriers to agricultural innovation

With these theoretical foundations established, the following section provides a brief overview of the different types of barriers to agricultural innovation. Beforehand it is necessary to clarify some terminology. In this paper, barriers refer to obstacles or determinants that hinder the adoption of innovative practices, with the terms innovation and practice being used interchangeably. The terminology aligns with the instrumental tradition but views adoption as a more flexible process where farmers experiment with and adapt crops and crop diversification practices to their situation, requirements, and motivations. Second, it is essential to consider different reasons for innovating: Wreford, Ignaciuk and Gruère (2017)

distinguish between public goods and private benefits. In other words, is the innovation aimed to improve the farming system's performance or provide public goods such as ecosystem services (also known as pro-environmental innovation). Innovations sometimes fit neatly into these categories, but often they are a combination of the two, as is the case with crop diversification. Therefore, the literature reviewed here emphasises adopting practices or crops instead of technology, which provides both private benefits and public goods.

At the most basic level, biophysical factors, such as climate and soil type, influence which innovations can be practically implemented (Prager and Posthumus, 2010). Agricultural innovations frequently require a change to the farming system or processes which may introduce agronomic or technical barriers. For example, incorporating cover crops into a crop rotation creates management challenges as they can interfere with cash crops (Carlisle, 2016; Mills *et al.*, 2020); adopting different tillage methods may require new machinery or adapting weed control management (Mills *et al.*, 2020).

Multiple bodies of literature have highlighted that economic factors are important barriers for farmers adopting agricultural innovation (Carlisle, 2016; Mills *et al.*, 2020; Prager and Posthumus, 2010; Wreford, Ignaciuk and Gruère, 2017). For instance, in a review on the adoption of soil conservation practices in Europe over the past 30 years. Prager and Posthumus (2010) state that most studies conclude that economic factors are critical in farmers' decision-making. Although the financial barriers depend on the type of innovation, a narrative review on the adoption of soil health practices in the USA identified three types of barriers that influenced farmers' decisions: opportunity costs, initial investment, and ongoing management costs. However, even when innovations are economically viable, there are often low adoption rates (Carlisle, 2016; Wreford, Ignaciuk and Gruère, 2017), illustrating that non-economic factors influence the decision-making of farmers (Carlisle, 2016; Knowler and Bradshaw, 2007; Mills *et al.*, 2020; Prager and Posthumus, 2010; Wreford, Ignaciuk and Gruère, 2017).

Countless studies have shown that access to information or knowledge contributes to farmers' decision-making. For instance, Carlisle (2016) concluded that access to information was frequently found to be a key barrier for farmers. Other aspects of knowledge include the quality and trustworthiness of the information, which should cover the benefits of the practice, how to implement the practice, while at the same time being adapted to the farmers' context (Carlisle, 2016; Mills *et al.*, 2020; Wreford, Ignaciuk and Gruère, 2017). Furthermore, Wreford, Ignaciuk and Gruère (2017) highlight that farmers are often unaware of agriculture's impact on climate change, implying that education or targeted programs may be required. The access to information often depends on the countries' advisory system (Mills *et al.*, 2020) but also social networks are significant for farmers to exchange knowledge,

ideas, and know-how (Carlisle, 2016; Mills *et al.*, 2017; Mills *et al.*, 2020). Moreover, many other non-economic factors influence farmers' decision-making: motivations, attitudes, beliefs, values, and norms (Mills *et al.*, 2017).

Institutional or regulatory factors can support or hinder the adoption of an innovation both in terms of access to information and support but also financially. Financial support is particularly relevant when the adoption costs are high and, or the private benefits are uncertain or not immediate (Wreford, Ignaciuk and Gruère, 2017). For example, a recent study on the adoption of soil carbon management practices found that the lack of financial incentives or subsidies was a common barrier across different regions in Europe (Mills *et al.*, 2020). For pro-environmental innovations which provide public goods, farmers are regularly encouraged by incentive schemes or programmes such as those included in the second pillar of the Common Agricultural Policy. An alternative to incentivising the adoption of a practice is with restrictions through legislation or regulation. Prager and Posthumus (2010) propose three different adoption pathways for soil conservation practices, adoption based on own initiative, enrolling in an agri-environmental scheme, or complying with legislation. Lastly, in their extensive literature review on climate-friendly practices Wreford, Ignaciuk and Gruère (2017) found that misaligned policies, or policies with other aims, like supporting production or input subsidies, are responsible for some of the existing barriers or encourage climate-incompatible practices.

The paragraphs above focus on the farm-level barriers or barriers directly influencing the farmer and the adoption process. This level of analysis may be adequate for certain practices such as non-harvested cover crops, new tillage practices, or precision agriculture because they are unlikely to influence the type of market that the farmer accesses. However, this article examines crop diversification practice which grow a new marketable crop, so it is necessary to extend the analysis beyond the farm-level to downstream associated with markets, supply chains, and interactions with downstream actors or networks. This was highlighted in some of the general literature on agricultural adoption (Carlisle, 2016; Leeuwis, 2004; Wreford, Ignaciuk and Gruère, 2017) and became apparent through a preliminary investigation of the literature on crop diversification as being significant barriers (Magrini *et al.*, 2016; Meynard *et al.*, 2013; Meynard *et al.*, 2018).

Combined, these ideas – along with key literature on the adoption of crop diversification practices (predominantly Morel *et al.*, 2020) – were used to form a flexible conceptual framework (Table 1) which guided both the systematic-like literature review and the review of the CDC documents and provided a structure to extract the different barriers and organise and analyse the results.

Table 1. Conceptual framework of barriers

Group of Barriers	**Examples of Barriers**
Biophysical/Agronomic	Site specific factors - water availability, climatic issues, and soil type Machinery, available and adapted Seeds, available and adapted Pest, disease, and weed management
Knowledge	Availability of knowledge Advice/support
Socio-cultural	Cultural Farmers' attitude Risk Motivations
Economics (farm-level)	Low profitability or gross margin High production costs – inputs or labour More competitive to grow other crops (opportunity costs) Requires investment
Institutional/Regulatory	Inadequate policy support CAP or agri-environmental schemes EU environmental and sanitary regulations Regulations issues around sanitary, quality and purity
Market & Consumer Demand	Competition with global market Limited, uncertain, or unstable market Consumer demand – willingness to pay more and awareness of benefits of crop diversification
Supply Chain	Logistics – collection, storage, trading, & processing issues High transaction costs dealing Investment and innovation - cleaning, drying, storing, screening, and processing
Market Coordination & Organisation	Contractual issues Standards Market information

6. Literature review on barriers to crop diversification

The poor agronomic performance in terms of yield quantity and stability of legumes compared with other crops were frequently identified as critical barriers to the adoption of legumes. In their review on feed legumes in Italy, Annicchiarico (2017) examined barriers to increased cultivation of legumes in Europe and concluded that the low agronomic performance, particularly yield quantity and yield stability, is the main reason for their low adoption rates. Similarly, Watson *et al.* (2017), in their comprehensive review on grain legume cultivation in Europe, analyse challenges farmers encounter and explore how to change European agricultural systems; they state that the technical performance of legumes needs improvement with investment in plant breeding for mostly yield quantity but also stability. Although the insufficient genetic progress from a lack of breeding is emphasised, the lack of crop management options is highlighted as a barrier contributing to poor agronomic performance of legumes with challenges related to weed, pest, and disease management (Watson *et al.*, 2017; Zander *et al.*, 2016).

The agronomic performance is closely linked with the farm-level profitability of legumes, which was frequently recognised as a central barrier to legume cultivation (Annicchiarico, 2017; Watson *et al.*, 2017; Zander *et al.*, 2016). In their review on the decline and potential recovery of grain legumes in Europe, Zander *et al.* (2016) analyse factors that influence farmers' decisions to grow certain crops. They emphasised economic factors, specifically the net economic value of legumes based on non-market outputs, market outputs, and production or management costs at the farm-level. In addition to the poor agronomic performance, they demonstrated that European grain legumes have low market prices because of inexpensive imports for the feed market and unfavourable policy support, resulting in a gross margin deficit for European grain legumes compared with other crops. Moreover, the non-market outputs of legumes, such as biological nitrogen fixation and break crop effects have a monetary value that is often not included in gross margin calculations. Furthermore, these benefits are not well-known by farmers and advisors, or accounted for by farmers when including legumes into their rotation (Magrini *et al.*, 2018; Zander *et al.*, 2016).

Magrini *et al.* (2018) and Voisin *et al.* (2014) extend their analysis beyond the farm-level to include barriers both upstream and downstream of the farm. Voisin *et al.* (2014) examine why there is limited forage and grain legume production in France and argue that the low legume production in Europe is the result of a lock-in to specialised and intensified farming systems. This lock-in results in more effort and investment into major crops into breeding and the creation of agronomic references along with the structuring of the sector, networks, organisation, and logistics. This reduces the profitability of legumes compared to major crops and makes it difficult for legumes production systems to compete.

Magrini *et al.* (2018) build on previous work demonstrating the locked-in situation (Magrini *et al.*, 2016; Meynard *et al.*, 2013; Voisin *et al.*, 2014) and use France as a case study to explore the challenges to increase pulses (dry seeds of leguminous plants excluding soya which are not used for oil extraction). They argue that breaking out of the agri-food system lock-in requires multiple and simultaneous innovations at the farm-level but also downstream of the farm in terms of processing and human consumption. They map multiple innovation pathways and highlight a range of different barriers at the farm-level, such as a lack of interest and knowledge, increased complexity, and a lack of support. This is combined with challenges to increase human consumption of pulses and overcome barriers related to food processing.

7. Results

7.1. Background to Crop Diversification Cluster

The Crop Diversification Cluster (CDC) is a group of six research projects – from 2017 until 2021 or 2022 – funded by the European Union from the Horizon 2020 funding stream. A portion of this funding is allocated to address 'societal challenges' with a large part for sustainable agriculture and forestry systems. A key requirement in many project calls is a multi-actor approach (MAA) (EIP-AGRI, NaN). An MAA focuses on the end-users and the real problems or opportunities they encounter. Therefore, the projects must involve a range of actors and include complementary types of knowledge throughout the entire duration of the project.

All six projects within the CDC apply, to various degrees, an MAA in their research on crop diversification, but the focus of these projects has some key differences. The six projects, although independent from one another, can be divided into three groups, with each group containing two projects (Table 2). DIVERSify and ReMIX focus on intercropping and largely at the farm-level. TRUE and LegValue concentrate on legumes but predominantly beyond the farm, encouraging greater use of legumes by supporting markets and supply chains development. DiverIMPACTS and Diverfarming cover a broader range of crop diversification practices, including intercropping, multicropping, and extending rotation, and emphasise supply chains and low input systems. Although there are overlaps between the projects in the crop diversification practices, and the focus of the projects is more elaborate. However, these distinctions apply to the projects generally and correspond with the main barriers extracted for this research.

Table 2. Projects in Crop Diversification Cluster

Project acronym	Full title	Website
DIVERSify	Designing InnoVative plant teams for Ecosystem Resilience and agricultural Sustainability	www.plant-teams.eu
ReMIX	Redesigning European cropping systems based on species MIXtures	www.remix-intercrops.eu
TRUE	TRansition paths to sUstainable legume based systems in Europe	www.true-project.eu
LegValue	Fostering sustainable legume-based farming systems and agri-feed and food chains in the EU	www.legvalue.eu
DiverIMPACTS	Diversification through Rotation, Intercropping, Multiple cropping, Promoted with Actors and value-Chains Towards Sustainability	www.diverimpacts.net
Diverfarming	Crop diversification and low-input farming across Europe: from practitioners engagement and ecosystems services to increased revenues and chain organisation	www.diverfarming.eu

7.2. Overview of results

The results section provides an overview of the barriers obtained from the CDC project documents. The barriers were obtained from seventeen documents: six on intercropping, eight on legumes, and three on crop diversification. Of these documents, four were peer-reviewed journal articles and thirteen were deliverables. The methods used ranged from surveys, workshops, and case studies to literature reviews and reports. The documents focused on different aspects of the agri-food system, with some exclusively covering the farm-level, value chains, or different markets, while others covered multiple levels (see Appendix C for details on the CDC project documents reviewed).

The remainder of results section is divided into two main sections, upstream of the farm and farm-level (7.3) and downstream of the farm (7.4). In addition to a written description of the barriers, two tables provide a visual representation of the barriers and correspond to the two sections. The table which covers farm-level barriers and has three columns, which align with the three crop diversification practices: intercropping, legumes, and generalised crop diversification (Table 3). The table which covers downstream barriers has four columns, which align with the different markets and accompanying value chains: non-specific, commodity (feed), commodity (food), and alternative or niche markets (Table 4).

Table 3. Synthesis table of farm-level barriers to different crop diversification practices

	Barriers/Enablers	Crop Diversification (general)	Intercropping	Legumes
Knowledge	Knowledge	**Technical knowledge & references** **Economic knowledge & references** Farming system & design Awareness of issues concerning specialisation (All from Morel et al. 2020)	**Lack of knowledge** – independent, adapted, suitable format (DIVERSify D1.1[+]) Lack of evidence supporting effectiveness (DIVERSify D1.1) Lack of technical references (Mamine and Farès, 2020)	Lack of knowledge & awareness (LIN workshops; TRUE D7.2)
	Complexity	Increased complexity for management & decision-making (Morel et al. 2020)	Increased on-farm complexity – number/variety of decisions (DIVERSify D1.1) Crop management complexity (ReMIX workshop; DIVERSify D1.1)	
	Advice/Support	Expertise available – enabler (DiverIMPACTS D1.1) **Professional expertise – success factor** (DiverIMPACTS D1.1) Lack of advice (Morel et al. 2020)	**Lack of advice**/support (DIVERSify D1.1) Lack of advice & training (Mamine & Fares) Advisors lack knowledge (ReMIX workshop; DIVERSify D1.1) **Information from advisors as enabler** (ReMIX D1.1)	
Socio-cultural	Farmers' attitudes/ cultural barriers	Cultural barriers & previous generation Limited cooperation between farmers Individualistic mentality (All from Morel et al. 2020)	Perception of agriculture – crop diversification associated with organic agriculture (DIVERSify D1.1) Critical neighbours (ReMIX workshop)	Pulses unattractive, lack prestige, and are too risky for farmers (LIN UK)
Biophysical/Agronomic	Site specific factors	**Climatic issues (e.g., drought)** (DiverIMPACTS D1.1) Soil type – enabler (DiverIMPACTS D1.1	Soil type (ReMIX D1.1)	Yield fluctuations mostly from weather (LIN Germany)
	Suitable varieties	Adapted to local context (Morel et al. 2020)	Varietal selection for two crops (Mamine and Farès, 2020)	Lack of suitable/adapted varieties (TRUE D7.2; D7.3; LIN UK & Germany) Breeding for animal feed not human consumption (LIN UK)
	Availability of inputs	Unavailable/expensive seeds (Morel et al. 2020) **Availability of inputs failure factor** also important success factor (DiverIMPACTS D1.1) Unavailability of inputs (Diverfarming D6.1)	Lack of input suppliers (Mamine and Farès, 2020)	
	Plant Protection	Crop protection & weed management (DiverIMPACTS D1.1) Available/adapted phytosanitary solutions (Morel et al. 2020; Diverfarming D6.1)	**Disease risk** (ReMIX D1.1) Pest/disease complexity (DIVERSify D1.1) Control of sanitary issues (Mamine and Farès, 2020) Control of insects - reason for abandoning mixture (Verret et al. 2020)	Disease & pest control (LIN UK & Germany) Availability of plant protection products (LIN UK & Germany)
	Weed management	Crop protection & weed management – drawback but more often enabler (DiverIMPACTS D1.1)	Weed control complexity (DIVERSify D1.1; ReMIX workshop) Control of sanitary issues (Mamine and Farès, 2020) Control of weeds - reason for abandoning mixtures (Verret et al. 2020)	Not competitive against weeds (LIN Germany)
	Yield quantity	Yield quantity (DiverIMPACTS D1.1)	Quantity & quality (Morel et al. 2020) Unstable or inadequate yield (Mamine and Farès, 2020) Poor yield - reason for abandoning mixtures (Verret et al. 2020)	Protein content of EU legumes variable due to suboptimal storage & post-harvest treatment (LegValue D3.1)
	Yield quality	Yield quality (DiverIMPACTS D1.1)	Quantity & quality (Morel et al. 2020) Quality of final product (ReMIX D1.1)	

	Yield stability	Uncertainties/risks/variability of agronomic performance (Morel et al. 2020)	Unstable or inadequate yield (Mamine and Farès, 2020)	Variable yield (LIN UK & Germany) Legume stability lower than other crops (LegValue D2.1)
	Machinery	Need for innovation (Morel et al. 2020) Technical solutions success and failure factors but more often success factors (DiverIMPACTS D1.1)	**For sowing and harvesting** (ReMIX D1.1)	
	(Post)- harvest		**Harvest complexity** (DIVERSify D1.1) Processing complexity (DIVERSify D1.1) **Grain separation** & simultaneous maturity (ReMIX D1.1) Reason for abandoning mixture (Verret et al. 2020)	
Economics (farm-level)	Profitability	Price of products - drawback but more often an enabler (DiverIMPACTS D1.1) Low or uncertain profitability (Morel et al. 2020) Current situation profitable (Morel et al. 2020)	Stable gross margin – lower yields but lower input costs or high market price (Diversify workshops & Remix workshop)	Limited profitability of legume production (TRUE D7.2) Not profitable at farm-level (TRUE D7.3) Low producer prices (especially faba bean and dried pea) (LegValue D5.1) Limited processing facilities reduces producer price (LegValue D3.1)
	Input costs	Input costs – drawbacks but more often enablers (DiverIMPACTS D1.1) Unavailable/expensive seeds (Morel et al. 2020) Time/skilled labour (Morel et al. 2020)	Expense/cost of implementing plant teams (DIVERSify D1.1) Higher production costs (Mamine and Farès, 2020) Time/skilled labour (DIVERSify D1.1; ReMIX workshop) Lower costs of inputs – pesticides & fertiliser (DIVERSify D1.1; Remix workshop)	Low cost of inorganic fertilisers (TRUE D7.3) Increase in fertiliser prices (LegValue D5.1)
	Investment		Investment for adapted machinery (Morel et al. 2020) Machinery/infrastructure for crop management or post-harvest (DIVERSify D1.1); Remix workshop; Mamine and Farès, 2020)	
Institutional	Policy Support	**Public policy - s**pecifically, Nitrate Directive, CAP Pillar I (Greening measures), and Water Framework Directive were important drawbacks; CAP Pillar I and Nitrate Directive (DiverIMPACTS D1.1) CAP, environmental, & sanitary regulations (Morel et al. 2020)	Lack of policy support (CAP) (DIVERSify D1.1) No support for intercrops under CAP Pillar I & II (Mamine and Farès, 2020) Benefits of crop diversification not valued (DIVERSify D4.5) Government support through subsidies (ReMIX D1.1)	Support for environmentally sustainable approaches (LIN workshops) Financial support (LIN UK) No greening subsidies for legumes when plant protection products applied (LIN UK & Germany) High levels of dissatisfaction of public policy among farmers, collectors, and processors (LegValue D2.1)

Bold text denotes the top 3 barriers or enablers identified in specific document; in some cases it was the most important barrier (Barnes and Ferreira, 2018; Drexler *et al.*, 2018; Smadja, Magrini and Muel, forthcoming) while in other documents it was the most frequently mentioned barriers (Morel *et al.*, 2020; Pearce *et al.*, 2018).

Green text denotes enablers

+ Abbreviations were used regarding CDC project documents for space reasons ('D' denotes 'deliverable')

7.3. Upstream of the farm and farm-level

7.3.1. Agronomic and biophysical barriers

Climate and soil types were both constraints and enablers. In the survey on crop diversification initiatives, climatic issues (e.g., drought) were by far the most relevant agronomic drawback, and soil type was the most important agronomic enabler (Drexler *et al.*, 2018). Soil type was also a barrier for intercropping (Barnes and Ferreira, 2018).

A lack of adapted varieties to the local context was a barrier across all types of crop diversification (Morel *et al.*, 2020). For legumes it was emphasised at multiple scales and by different actors, including the 80 experts who participated in the Delphi[4] (Balázs *et al.*, 2019); various reports on legume markets in the EU (Hamann *et al.*, 2020; Kezeya Sepngang *et al.*, 2020); as a key barrier in the TRUE policy case studies (Kelemen *et al.*, 2019); and raised in the Legume Innovation Network (LIN) workshops in the United Kingdom (UK) and Germany (Hamann *et al.*, 2020). Although, a barrier for intercropping (Mamine and Farès, 2020), more emphasis was placed on other agronomic barriers. In addition, the availability of seeds and other inputs, along with suppliers of inputs, were barriers (Drexler *et al.*, 2018; Mamine and Farès, 2020; Morel *et al.*, 2020).

The significance of plant protection as a barrier varied. In the survey on crop diversification initiatives, crop protection and weed management were important drawbacks, but weed management was also one of the most frequent enablers (Drexler *et al.*, 2018). Moreover, a lack of phytosanitary solutions was only a barrier for a few cases (Morel *et al.*, 2020). At the LIN workshops on legumes, diseases, and pest control were seen as barriers in the UK workshop, while diseases and weed control were raised in the German workshop. For intercropping, "introduces too much disease risk" was the most important barrier for the three different groups of farmers (Barnes and Ferreira, 2018, p. 21). Furthermore, weed management was an obstacle (Henrik Hauggaard-Nielsen *et al.*, 2021) and a reason for farmers abandoning certain mixtures (Verret *et al.*, 2020). Insufficient control of sanitary issues was a barrier for wheat-pea intercrop, with reference to weed control under certain agroclimatic conditions (Mamine and Farès, 2020).

Barriers concerning crop management and harvest complexity were particularly relevant for intercropping. The DIVERSify national workshops identified a wide range of barriers relating to seeding and drilling, crop management, crop-crop competition, yield suppression (Pearce

[4] Delphi is a method used to find a consensus among selected experts on topic or a group of issues and was used by TRUE to examine 10 food policy issues.

et al., 2018). Some are due to a lack of knowledge or guidance, while others are technical in nature. Similarly, harvest complexity has both knowledge and technical components and was the second most important barrier identified in the DIVERSify national workshops (Tippin *et al.*, 2019). Some specific challenges mentioned were simultaneous maturity of crops, combine harvester adjustments, uneven grains, and damage to harvested goods. Moreover, delay in species ripening and imbalance in harvested goods were documented as reasons for farmers to abandon certain mixtures (Verret *et al.*, 2020). Crop mixtures not ripening at the same time was a mid-level barrier in the ReMIX survey, but the lack of machinery for sowing and harvesting was considered the main barrier for farmers (Barnes and Ferreira, 2018). A lack of adapted machinery was also relevant for other crop diversification practices. For instance, technical solutions were more frequently success factors but also failure factors in the survey on crop diversification initiatives (Drexler *et al.*, 2018). A lack of innovations in machinery for field activities was also a barrier for some farmers (Morel *et al.*, 2020), while others adapted their existing machinery (Drexler *et al.*, 2018).

Crop mixtures often require separating, which can present a significant barrier for intercropping. At the DIVERSify workshops, processing complexity was the second most important barrier with concerns related to drying, storing, separating, and contamination (Tippin *et al.*, 2019). Similarly, in the ReMIX survey, grain separation was the third most important barrier and especially significant for the group growing intercrops for food (Barnes and Ferreira, 2018). Furthermore, inadequate separation of crops reduced the quality and was a reason provided by farmers for abandoning certain mixtures as they were rejected by the collector (Verret *et al.*, 2020). In other instances, crop mixtures were accepted by downstream actors, removing the barriers related to on-farm separation (Drexler *et al.*, 2018; Pearce *et al.*, 2018), but in many situations, mixtures are not accepted by downstream actors (Weituschat *et al.*, 2018) (see Section 7.4.2 Supply Chain).

Low yield quantity and quality were moderately important barriers. Low yield was the third most important agronomic drawback; at the same time quality of the agricultural product was an important enabler for crop diversification initiatives (Drexler *et al.*, 2018). For intercropping, especially low yield quantity but also the quality was moderately important barriers for the group associated with organic farmers and intercropping (Morel *et al.*, 2020); the low yield was also a barrier to wheat-pea intercropping (Mamine and Farès, 2020); and a reason for farmers abandoning a specific crop mixture (Verret *et al.*, 2020).

Yield instability was identified as a barrier across all types of crop diversification. The variability, risk, or uncertainty of the performance was a barrier relevant across a range of crop diversification strategies (Morel *et al.*, 2020). For legumes, it was mentioned in the Legume Innovation Network (LIN) workshops that variable yield was perceived as a barrier

by farmers in the UK (Howard *et al.*, 2018), and annual yield fluctuations mainly due to weather were a hampering factor in Germany (Maaß *et al.*, 2018). Moreover, in the survey of actors from different legume supply chains, 60% of farmers considered yield stability of legumes lower than other crops (Smadja, Magrini and Muel, forthcoming). Furthermore, in a farm-level survey of Danish organic farmers, yield instability of faba bean was found to limit risk-averse farmers from growing the crop (Hamann *et al.*, 2020). For intercropping, wheat-pea yield instability was also considered as a barrier (Mamine and Farès, 2020) but less frequently raised as a barrier.

7.3.2. Knowledge and farmers' decision-making

Data extracted from the CDC documents showed that a lack of knowledge was a central barrier across different crop diversification practices. "Lack of technical knowledge and references" was the most frequent barrier (21/25 case studies) for a wide range of crop diversification strategies[5] (Morel *et al.*, 2020, p. 9). It was also important for legumes: "lack of knowledge and awareness among producers" was a key barrier identified in the TRUE policy case studies and a challenge raised in all three Legume Innovation Workshops (LIN) (Kelemen *et al.*, 2019, p. 85). Similarly, the 80 experts who participated in the Delphi process looking at policy issues raised knowledge as a key issue (Balázs *et al.*, 2019). For intercropping, a lack of knowledge was the most frequent unsolved or perceived barrier by the participants of the DIVERSify workshops (Pearce *et al.*, 2018).

Although a lack of knowledge was identified across all crop diversification practices, certain knowledge gaps appear more relevant to certain crop diversification practices. Knowledge gaps regarding crop management were predominantly identified for intercropping. Specific aspects mentioned include uncertainties on varieties and mixtures, pest and disease control, and how plant teams fit into rotations (Tippin *et al.*, 2019). Moreover, Mamine and Farès (2020) state that the specific cultivars and agroclimatic parameters influence management options such as sowing and harvesting dates, along with timing for treatments and fertiliser application which make it difficult to establish a universal technical guide on wheat-pea intercropping. They argue that this lack of technical knowledge could lead to abandonment. This was echoed in the DIVERSify workshops; simple solutions and straightforward guidelines adapted to the specific context are required to address these knowledge gaps (Pearce *et al.*, 2018). However, the results from the ReMIX survey contradict these findings: the lack of knowledge to apply intercropping was seen as less important than most other barriers (Barnes and Ferreira, 2018).

[5] Morel *et al.* (2020) examine three types of crop diversification, temporal diversification which includes extending rotation, intercropping, and other forms spatial diversification such as strip cropping and land sharing.

The availability of support or advice regarding crop diversification was an important barrier and enabler to crop diversification in general. In a survey of different types of crop diversification initiatives in Europe conducted by DiverIMPACTS "expertise available on diversification" (p.24) was one of the most important agronomic enablers; moreover, professional expertise was considered the most important success factor (Drexler *et al.*, 2018). This was also true for intercropping; a lack of support was identified as a key barrier in the national workshops, with 9/11 workshops classifying it as an unsolved practical barrier (Tippin *et al.*, 2019); and transmission of information from advisors was one of the top three enablers in the Remix survey (Barnes and Ferreira, 2018). A lack of knowledge among agronomists and advisors was also mentioned (Henrik Hauggaard-Nielsen *et al.*, 2021; Pearce *et al.*, 2018).

Moving from a simplified farming system to a diversified one increases complexity. These changes occur at the farm-level in terms of agronomic management and consist of changes beyond the farm-level, such as accessing new markets, and frequently multiple innovations must occur simultaneously. Although not covered extensively by any of the projects, it was mentioned in multiple documents and across the different types of diversification. For example, Morel *et al.* (2020) identified two barriers, one dealing with the increased complexity and uncertainty concerning decision making and the other requiring a change in thinking or cognitive frame. Similarly, for intercropping, the complexity and increase in the total number of decisions required regarding crop management can discourage farmers (Pearce *et al.*, 2018).

Other factors appear to influence farmers' perception of crop diversification. At the DIVERSify workshops, some farmers associated intercropping with organic farming, which has a negative perception among integrated and conventional farmers, thereby dissuading its adoption; similar sentiments were expressed at the TRUE LIN workshops (Tippin *et al.*, 2019). Furthermore, Weituschat *et al.* (2018) showed that different perceptions of agriculture influence farmers' perspectives on crop diversification practices. They claimed that farmers within a conventional paradigm see farming as an input-out system which contrasts with an agroecological paradigm where farmers view the farm as a complex system. The adoption of crop diversification for farmers within the conventional paradigm requires a more holistic rethinking, whereas farmers within the agroecological paradigm view crop diversification practice as part of incremental innovation. The more a practice is perceived as a holistic innovation, the riskier it becomes for farmers.

7.3.3. Farm-level economic barriers

Profitability at the farm-level was a barrier to all crop diversification practices but with varied results. The profitability of legumes at the farm-level was a key barrier according to the TRUE policy case studies (Kelemen *et al.*, 2019) and by the experts who participated in the

Delphi process (Balázs *et al.*, 2019). This contrasts with results from Morel *et al.* (2020), where low or uncertain profitability was not a barrier for farmers adopting a temporal crop diversification strategy, which included extending their crop rotation with legumes or other minor crops. Other results also demonstrate that profitability was not a barrier. In the survey on crop diversification initiatives, the product price was more frequently seen as enablers than drawbacks, with some respondents stating that the high market value offset the low yields (Drexler *et al.*, 2018). Similarly, in the DIVERSify workshops, participants stated that low yields for intercropping were offset by reduced input costs (fertiliser and pesticides), resulting in a stable gross margin (Tippin *et al.*, 2019); comparable statements were mentioned in the REMIX workshop (Henrik Hauggaard-Nielsen *et al.*, 2021).

Increased production costs more frequently arose as a barrier for intercropping than for other practices. In the survey of crop diversification initiatives, production costs were more frequently identified as enablers than drawbacks (Drexler *et al.*, 2018). In contrast, the expense of implementing plant teams was the third most frequently mentioned barrier at DIVERSify workshops (Tippin *et al.*, 2019).

Different reasons were provided for increased production costs, mostly more expensive inputs, including seeds (Morel *et al.*, 2020), seeds mixes (Pearce *et al.*, 2018), and phytosanitary products and fertilizer (Mamine and Farès, 2020). Nevertheless, other attendees highlighted that intercropping reduces the need for inputs, particularly fertiliser and pesticides (Remix Workshop; (Pearce *et al.*, 2018), which was identified as an important reason for intercropping (Barnes and Ferreira, 2018). Intercropping can also increase crop management costs, such as doubling sowing, drying, and separating costs (Mamine and Farès, 2020; Pearce *et al.*, 2018). Moreover, increased time and skilled personnel (which is not always available) required for crop diversification may act as an additional financial barrier (Henrik Hauggaard-Nielsen *et al.*, 2021; Morel *et al.*, 2020; Pearce *et al.*, 2018).

Investment in adapted machinery was a key barrier for intercropping. It was demonstrated to be the important farm-level barrier for farmers practicing intercropping (Morel *et al.*, 2020). Likewise, it was raised in the DIVERSify workshops that some plant teams require expensive specialised equipment or infrastructure for crop management and post-harvest operations, which due to the unreliable benefits of plant teams is a high-risk investment (Pearce *et al.*, 2018); similar barriers were present for wheat-pea intercropping (Mamine and Farès, 2020). The ReMIX survey also identified a lack of machinery as a barrier, but it is unclear if the barrier was due to availability or high investment costs (Barnes and Ferreira, 2018).

7.3.4. Institutional and regulatory barriers

Policy support was an essential barrier. In the survey of crop diversification initiatives, public policy was the third most important drawback with specific policies including the Nitrate

Directive, CAP Pillar I (Greening measures), and Water Framework Directive ranking as barriers, at the same time CAP Pillar I and Nitrate Directive were also ranked as enablers to less degree (Drexler *et al.*, 2018). At the DIVERSify national workshops, lack of policy support (with specific reference to CAP) was raised as an issue in several workshops regardless of not being included in the topics for discussion (Pearce *et al.*, 2018). Likewise, the ReMIX survey on intercropping found that more government support through subsidies was a key enabler (Barnes and Ferreira, 2018). The lack of policy support for intercropping under CAP is supported by the review of wheat-pea intercropping; coupled support under CAP Pillar 1 is only available for pure crops with no provisions for intercropping. Similarly, for the CAP Pillar 2, no environmental premiums are offered for intercropping (Mamine and Farès, 2020). Furthermore, policy support for diversified cropping systems and environmentally sustainable approaches was deemed necessary by some participants of the Diversity and TRUE workshops (Tippin *et al.*, 2019).

7.4. Downstream of the farm

7.4.1. Markets

Finding suitable markets for minor crops was a further constraint. The lack of pre-existing, or very small, markets was a significant barrier for the group 'changing from within'[6], which includes farmers adopting temporal crop diversification and engaging in commodity value chains (Morel *et al.*, 2020, p. 9). In addition, a lack of established markets and supply chains were barriers for farmers adopting intercropping (Pearce *et al.*, 2018); similarly, according to TRUE Atlantic and LIN workshops, market constraints and a lack of demand increased reluctance to grow legumes (Tippin *et al.*, 2019).

Related to the availability of markets is the demand uncertainty, which was relevant for a wide range of actors. In the LegValue survey, demand uncertainty was the most important barrier for the three groups of actors (farmers, collectors, and processors) across different legume value chains; however, they also found that increasing demand was the main lever (Smadja, Magrini and Muel, forthcoming). Similarly, uncertain or unstable markets was an important barrier and associated with the group changing from outside, which includes intercropping, and smaller local or national markets (Morel *et al.*, 2020). Finally, in the survey on crop diversification initiatives, the main failure factor was market conditions (Drexler *et al.*, 2018).

[6] Morel *et al.* (2020) analyse barriers based on three innovation settings, 'changing from within' is associated with temporal crop diversification, commodity markets, and mostly conventional farmers; 'building outside' is associated with intercropping, local markets, and only organic farmers; and 'playing horizontal' is associated with spatial crop diversification and arrangements with other farmers

Table 4. Synthesis table of downstream barriers to different crop diversification practices

	Barriers/ Enablers	**Non-specific**	**Commodity (Feed)**	**Commodity (Food)**	**Alternative or Niche Markets**
Markets	Market demand	EU legumes not enough to meet demand (TRUE D4.3[+]; LegValue D2.1) Market constraints (LIN Atlantic) **Growing demand for legumes - for producers, collectors & processors** (LegValue D2.1) Lack of markets/supply chains aligned with monocultures (DIVERSify D1.1) Existence of market (Verret et al. 2020) Small market for mixed products [director & miller] (ReMIX workshop)	No or limited market (Morel et al. 2020) Increasing demand for GMO-free feed (LegValue D3.1) Growth in livestock and fish sector in EU (LegValue D5.1)		Distance from urban market (Diverfarming D6.1)
	Market stability	**Market conditions – failure factor** (DiverIMPACTS D1.1) **Demand uncertainty for producers, collectors & processors** (LegValue D2.1)			Uncertain/unstable markets (Morel et al. 2020)
	Competition	Competition with imports (LIN Mediterranean) Competition with mainstream producers – more frequently an enabler than a drawback (DiverIMPACTS D1.1)	Feed markets – high competition with soya imports (LegValue D3.1; TRUE D4.3; Diverfarming D6.1) Increasing prices of soya (LegValue D5.1)	Increasing demand for chickpeas and lentils but high competition with imports (LegValue D3.1)	Competition with imports regarding local and/or organic markets for intercropping (Morel et al. 2020)
Supply Chain	Logistics	Low volumes increase collection costs (Mamine and Farès, 2020) Low volumes & geographically dispersed (Diverfarming D6.1) Downstream actors not accepting mixtures (DiverIMPACTS D1.1; Diverfarming D6.1 DIVERSify D1.1; Verret et al. 2020)	**Collection constraints due to low volumes** (Morel et al. 2020) No dedicated transport hubs for EU non-soya legumes (TRUE D4.3)	Processing & trade infrastructure at smaller scale (TRUE D4.1)	
	Profitability	Higher costs of raw material from species mixtures [ingredients]* (ReMIX workshop)	Grain legumes complicate feed formulas resulting in increased costs – transaction costs from peas add 12% to price (TRUE D4.3)		Higher costs associated with crop diversification products (Morel et al. 2020)
	Investment	Investment for cleaning, drying, and storing equipment (Morel et al. 2020; Diverfarming D6.1; LegValue 5.1) Investment in processing equipment (Morel et al. 2020) Investment in machinery to separate mixtures (Morel et al. 2020) Sorting crop mixtures requires additional silos (Mamine and Farès, 2020; Diverfarming D6.1)	Low investment in infrastructure for processing and storage due to low volumes of non-soya legumes (TRUE D4.3)		
	Technical /innovation	Lack information on technologies [farmers and collectors] LegValue D7.3) Technical challenges depend on plant team (DIVERSify workshop; (Mamine and Farès, 2020) Processing is more complex & time consuming (ReMIX workshop) Allergen issues (ReMIX workshop)			Innovation for processing, cleaning, & drying Innovation for storing Innovation for separation (All from Morel et al. 2020)

Market Coordination	Contracts	Flexible contracts – production, risks, & control costs (Morel et al. 2020) Unequal distributions of costs/benefits between actors (Diverfarming D6.1) No fair sharing of added value (LIN Athens)	Duration of contract (Morel et al. 2020) Power imbalance between farmers & traders (Morel et al. 2020) Value added for legumes not always reflected in producer price (LegValue D3.1)		**Fair sharing of value between actors** No guaranteed or limited volumes and quality to establish contracts Communication between value chain actors (All from Morel et al. 2020)
	Market information	Market information (LegValue D2.1) Information on economic partners & technologies (LegValue D2.1) Knowledge of markets or standards not always known (Diverfarming D6.1) Better market transparency (Legvalue D2.1)	Non-soya legumes prices not internationally available (TRUE D4.3)		
	Standards	Absolute focus on commodity standards is a barrier to crop diversification (Diverfarming D6.1) Non-soya legumes lack defined standards (TRUE D4.3) Standards incompatible with plant teams (DIVERSify workshops) Limit varieties of wheat that can be used (Mamine and Farès, 2020) Purity standards & lack of quality standards (Remix workshop) **Acceptance of plant teams in supply chain (quality standards)** (ReMIX D1.1)	Less well-known/no standards limit minor crops use in feed (Diverfarming D6.1) Low acceptance of EU legumes in compound feed (LegValue D3.1) Feed safety regulations limit inter- and intra-farm use (Mamine and Farès, 2020)		Shorter, more local supply chains have different standards – taste, nutrition, production type (Diverfarming D6.1) Regulation – sanitary, quality and purity aspects (Morel et al. 2020)
Consumer Demand	Demand	Low demand (LegValue D5.1; TRUE D7.2; TRUE D7.3) Increasing demand for vegetarian eating habits (TRUE D4.1; LegValue D3.1) Increasing demand for organic consumption (TRUE D4.1)	Increasing demand for organic and non-GMO animal products (TRUE D4.3; LegValue D3.1)		Demand for organic and quality produce is high (DiverIMPACTS D1.1)
	Willingness to pay	Doubts about willingness to pay more for more diversified products (Morel et al. 2020)		Legume based products are more expensive than basic meat products (LegValue D5.1)	
	Awareness of benefits	Lack of knowledge and awareness among consumers about health and environmental benefits of legumes (LIN workshops; TRUE D7.3; LegValue D5.1) **Raise consumers' awareness of diversification benefits** (Morel et al. 2020)			

Bold text denotes the top 3 barriers or enablers identified in specific document; in some cases it was the most important barrier (Barnes and Ferreira, 2018; Drexler *et al.*, 2018; Smadja, Magrini and Muel, forthcoming) while in other documents it was the most frequently mentioned barriers (Morel *et al.*, 2020; Pearce *et al.*, 2018).

Green text denotes enablers.

* Square brackets ([]) denotes that the barrier was identified by a specific stakeholder which was explicitly mentioned in the deliverable

+ Abbreviations were used regarding CDC project documents for space reasons ('D' denotes 'deliverable')

The lack of markets and uncertain demand is closely connected with the competitiveness of minor crops with imports or other major crops that have similar market outlets. The competition was particularly relevant for commodity markets where the price is the main coordination mechanism (e.g., animal feed markets) and was frequently highlighted in reports (Hamann *et al.*, 2020; Kezeya Sepngang *et al.*, 2020; Weituschat *et al.*, 2018). Competition of domestic legumes and pulses with imports was also mentioned as a barrier at the TRUE Mediterranean and LIN workshops (Tippin *et al.*, 2019). Interestingly, Morel *et al.* (2020) showed that local organic markets also must compete with imports. In contrast, the survey on crop diversification initiatives found that competition with mainstream producers was more frequently an enabler than a drawback (Drexler *et al.*, 2018).

7.4.2. Supply chain

The small volumes of minor crops and/or when they are geographically dispersed create collection constraints. "Volumes are too limited in a given area to be profitably or easily collected" was a crucial barrier for farmers engaging in commodity markets but not farmers engaging in smaller alternative markets (Morel *et al.*, 2020, 9). The extensive literature on review on crop diversification value chains identified geographical dispersion as a key factor influencing barriers to adoption (Weituschat *et al.*, 2018). Likewise, for wheat-pea intercrops, high collection costs associated with dispersed or small volumes were identified as a barrier (Mamine and Farès, 2020).

For downstream actors, dealing with minor crops requires investment in machinery and infrastructure, and as with collection, small volumes do not encourage investment (Hamann *et al.*, 2020). Investment for cleaning, drying, and storing was a central barrier for multiple innovation settings (Morel *et al.*, 2020). In addition, investment to ensure adequate storage cells or silos was raised in multiple deliverables (Hamann *et al.*, 2020; Mamine and Farès, 2020; Weituschat *et al.*, 2018). Without adequate storage, crops with smaller volumes are either sold closer to harvest, reducing the price received (Mamine and Farès, 2020), or bundled by trading companies to reduce transaction costs (Kezeya Sepngang *et al.*, 2020). For intercropping, further investments are required in machinery to separate mixtures (Morel *et al.*, 2020), along with possible investments in infrastructure and storage (e.g., extra silos for sorting) (Mamine and Farès, 2020).

While collection and storage are only constrained by small volumes and profitability, there are downstream technical barriers related to crop mixtures. Morel *et al.* (2020) identified three barriers related to downstream innovation: cleaning, drying, or storage; separation; and processing. All three barriers were associated with the group changing from outside, which includes organic farmers adopting intercropping but also the downstream actors who require innovation adapted to smaller scales to reflect the small volumes.

Further down the value chain, processing imposes additional barriers. As with the other downstream actors, small volumes are a crucial constraint to achieve economies of scale (Hamann *et al.*, 2020; Weituschat *et al.*, 2018). TRUE stakeholder consultations highlighted that including grain legumes (peas and faba beans) in feed formulas adds costs, to build additional silos, devise new recipes, and along the value chain; in total, the transaction costs for pea can add 12% to feed price (Hamann *et al.*, 2020). Similarly, in the Remix workshop on plant teams, actors believed that profitability could be reduced because of the higher cost of processing complex raw materials from species mixtures (Henrik Hauggaard-Nielsen *et al.*, 2021). The small volumes of minor crops further limit processors' willingness to invest in infrastructure (Hamann *et al.*, 2020) and processing equipment (Morel *et al.*, 2020). Finally, on a macro-scale, the limited number of processing facilities limits the value added to the crops and hence producer price (Kezeya Sepngang *et al.*, 2020) along with the total number of innovative legume-based products (Balázs *et al.*, 2019).

7.4.3. Market coordination

7.4.3.1. Contracts

The lack of suitable contracts may impede the adoption and dissemination of crop diversification. Fair sharing of risk and added value between farmers and other actors in the value chain was equally the second most cited barrier and relevant for farmers intercropping and engaging in smaller alternative markets (Morel *et al.*, 2020). It was also raised in the LIN Athens workshop regarding legumes (Yiannis Panagiotakis *et al.*, 2018) and supported in other reports. For instance, the value-added for legumes (especially dry pea and faba beans) depends on their final use (feed or food) but is not always reflected in the producer price (Kezeya Sepngang *et al.*, 2020).

Other contractual issues were highlighted. Morel *et al.* (2020) found that especially small volumes but also variable quality were barriers to establishing contracts for intercropping and/or smaller value chain actors. Similarly, value chain actors are reluctant to enter long-term contracts due to the variable quantity and quality of intercropping (Mamine and Farès, 2020). This is compounded by less well-known, or lack of, standards for minor crops. Furthermore, longer contracts can benefit both farmers and downstream actors by ensuring a stable supply and demand needed to make investments, take risks, or plan crop rotations. The ideal group involved in longer, more globalised value chains found the short duration of contracts a barrier (Morel *et al.*, 2020). However, this contrasts with other results; some stated that European farmers and downstream actors generally prefer short-term contracts because they are more flexible to react to market prices or changes in policy (Kezeya Sepngang *et al.*, 2020; Weituschat *et al.*, 2018).

A lack of market information regarding prices, standards, and available markets creates additional barriers. The LegValue survey showed that a lack of information was considered a

barrier for all actors, but with some differences; for farmers, it was the most important, they lack information regarding markets, technologies, and economic partners, whereas collectors lacked information on technologies, and processors on market information (Smadja, Magrini and Muel, forthcoming). In addition, the knowledge of different markets and their specific standards are not always known by farmers (Weituschat *et al.*, 2018 citing Bachev, 2012). The example of soya and non-soya legumes demonstrates the lack of market transparency. Soya prices are internationally available from multiple sources, while non-soya legumes are not always available or sometimes only on a regional basis (Hamann *et al.*, 2020).

7.4.3.2. Standards

To operate in the European food supply chain, actors must comply with EU regulations on food safety and marketing standards. Although mentioned sparingly, they were considered barriers by some actors or in certain situations. Regulations regarding sanitary, quality, and purity were identified as a barrier for some by Morel *et al.* (2020); similarly, stringent purity standards were raised in the Remix workshop (Henrik Hauggaard-Nielsen *et al.*, 2021). Finally, feed safety regulations disadvantage inter- and intra- farm use of intercrops as farmers may need to comply with health standards (regarding mycotoxins and microorganisms) which increase costs and reduce the economic advantage of using intercrops directly for feed (Mamine and Farès, 2020).

Food processors and retailers operate with standards based on product quality such as product form, size, and protein content which farmers need to maintain to sell their crops and/or receive premiums. For example, the higher protein content in barley determines if the quality is suitable for alcohol production or feed, with the higher protein corresponding with a superior price. Product quality standards were raised as a barrier in the DIVERSify and TRUE LIN workshops; the attendees perceived that quality and supermarket standards are incompatible with plant teams (Tippin *et al.*, 2019). However, it should be noted that intercropping with legumes has the potential to increase the protein content of the cereals helping farmers comply with quality standards. Alternatively, shorter or more local chains have different quality standards such as taste and nutritional value (Weituschat *et al.*, 2018 citing Meynard *et al.*, 2017); or defined production criteria such as organic farming, which may dissuade some farmers from entering these markets (Weituschat *et al.*, 2018).

Moreover, minor crops do not always have defined standards which create barriers for processing and trade (Weituschat *et al.*, 2018). This was displayed by Hamann *et al.* (2020) in their analysis of feed markets, they showed that imported soya has an advantage because it is traded based on a defined standard, protein content, which contrasts with the lack of standards for EU fodder legumes and non-soya grain legumes. The same applies for processors formulating new recipes, unknown or less well-known feed-related properties increase complexity for processors to adapt to feed formulas while maintaining a low price.

7.4.4. Consumer demand

The low consumption of legumes by EU citizens – on average 1.6% of protein from pulses (Kootstra, Schoorlemmer and de Visser, 2017) – is a well-known but important barrier directly connected to market demand. Multiple reasons for their low consumption were given by the 80 experts who participated in the Delphi: weak marketing, resulting in an outdated image of legumes; cultural factors, legumes are seen as 'poor man's food'; shortage of appealing recipes and products; long cooking time; and knowledge on cooking legumes (Balázs *et al.*, 2019). The latter barrier was supported by Toma *et al.* (2020), who conducted a choice experiment with UK consumers; the regular meat consumers mentioned not knowing how to cook pulses as the main barrier. Other potential barriers include the higher cost of legume-based products compared with basic meat products (Kezeya Sepngang *et al.*, 2020) and doubts that consumers are willing to pay more for products from diversified farming systems (Morel *et al.*, 2020).

There is a belief that consumers are unaware of the environmental and health benefits of crop diversification. The "need to raise consumers' awareness or bad visibility of diversification benefits" was a prominent barrier for 17/25 innovation cases (Morel *et al.*, 2020, 9). This aligns with the three LIN workshops, where a key challenge was the lack of knowledge and awareness among consumers about the environmental and health benefits of legumes (Kelemen *et al.*, 2019); likewise, it was identified in the Delphi process (Balázs *et al.*, 2019). However, in the choice experiment, 75% of the regular meat consumers group revealed that they eat pulses because they are a good source of protein, implying that UK consumers have some awareness of the health benefits of pulses (Toma *et al.*, 2020).

8. Discussion

The results of reviewing documents from the Crop Diversification Cluster (CDC) research projects reveal significant variation in the barriers even within specific crop diversification practices. This indicates that many factors influence the presence or absence of barriers: the plant team or specific crop, type of cropping system, geographic region, institutional environment, and the farmers. Therefore, there is a need to address barriers in a case-by-case manner and considering the specific context of the farms and value chains. Previous research has made similar conclusions, emphasising the lack of universal barriers or determinants to explain the adoption of agricultural innovation or practices (Carlisle, 2016; Knowler and Bradshaw, 2007; Prager and Posthumus, 2010). A second overarching finding of the present review is the complex and interconnected nature of barriers that occur at multiple levels, upstream of the farm, on the farm, and downstream of the farm. This implies that barriers need to be addressed in a simultaneous and coordinated manner, as suggested by Magrini *et al.* (2018), Meynard *et al.* (2017), and Voisin *et al.* (2014).

8.1. Upstream of the farm

Upstream of the farm there are common barriers regarding inputs, specifically how available and adapted seeds and plant protection products are for crop diversification, both of which limit farmers' ability to obtain adequate and stable yields. The CDC results show that the lack of adapted varieties was a barrier across different crop diversification practices, including intercropping (Mamine and Farès, 2020), legumes (Balázs *et al.*, 2019; Kelemen *et al.*, 2019), and crop diversification (Morel *et al.*, 2020). This is supported by the present review of peer-reviewed literature, which underscores the limited genetic progress of legume yields compared to cereals in Europe (Annicchiarico, 2017; Watson *et al.*, 2017; Zander *et al.*, 2016) and for intercropping (Voisin *et al.*, 2014).

Combined, these barriers represent a lock-in at the agri-food system level (based on ideas from Geels, 2002; Geels and Schot, 2007), where research and development focus on major crops due to their larger markets and higher return on investment, thereby reducing breeding and research into plant protection products and herbicides for minor crops. This lock-in within Europe towards major crops is well-acknowledged (Magrini *et al.*, 2016; Meynard *et al.*, 2018; Voisin *et al.*, 2014). For example, Magrini *et al.* (2016) compare the number of publicly registered legume varieties with wheat in Europe; in 2015, there were 2,500 wheat varieties compared with 400 for pea and less than 150 for beans. A similar comparison has been made for other minor crops (Meynard *et al.*, 2013; Meynard *et al.*, 2018). Most of the CDC documents refer indirectly to this lock-in through other barriers, but some refer to it directly (Kelemen *et al.*, 2019; Weituschat *et al.*, 2018).

The same lock-in effect applies to the limited development, licensing, and distribution of plant protection products and herbicides for minor crops. Although mechanical control combined with row spacing can be effective for some grain legumes (e.g., chickpea and faba bean), in other situations (e.g., field pea) chemical controls are required. However, due to the small production area, there has been limited development of suitable herbicides (Watson *et al.*, 2017). Although intercropping helps controls weeds, when chemical weed control is needed, then finding an herbicide suitable for both crops in the plant team is challenging (Mamine and Farès, 2020; Watson *et al.*, 2017).

The CDC results align with the current literature review, with some farmers expressing direct concerns about the lack of plant protection products or suitable herbicides (Howard *et al.*, 2018; Maaß *et al.*, 2018; Morel *et al.*, 2020; Pearce *et al.*, 2018). The majority, however, did not refer directly to the lack of chemical products but to general challenges with plant protection and weed management, which were undeniably very important across all crop diversification practices (Drexler *et al.*, 2018). Nonetheless, the CDC results indicate that it

may be of more significant concern for intercropping due to the total number of barriers and the ranking of those barriers within the documents (Drexler *et al.*, 2018; Pearce *et al.*, 2018).

8.2. Farm-level

8.2.1. Yield quantity and stability

The yield quantity and stability are determined by a combination of factors, namely adapted inputs, machinery, knowledge, and biophysical constraints, making it difficult to separate their relative contribution to yield stability or quantity. Regardless, the CDC results reveal that yield quantity was often a mid-level barrier across different crop diversification practices (Drexler *et al.*, 2018; Morel *et al.*, 2020). At the same time, barriers concerning poor yield were also absent in many project documents. The CDC results, therefore, contrast with the literature review on legumes where poor yields were frequently considered the main reason for low adoption rates of legumes in Europe (Annicchiarico, 2017; Watson *et al.*, 2017).

The CDC results indicate that yield stability was possibly a more important consideration for farmers than yield quantity (Mamine and Farès, 2020; Morel *et al.*, 2020; Smadja, Magrini and Muel, forthcoming). This aligns with the current literature review, where in one of the few surveys including farmers' perspectives, a perceived high yield variability (along with the associated revenues) discouraged risk-averse farmers from adopting legumes (Richthofen *et al.*, 2006 cited by Watson *et al.*, 2017 and Zander *et al.*, 2016). Nonetheless, the literature devotes less time to exploring how yield stability impacts the adoption by farmers and more time quantifying the stability of European legume yields (see Watson *et al.*, 2017; Zander *et al.*, 2016 for comprehensive overviews).

In general, grain legume yields are more variable. However, some evidence suggests that yield instability is often overestimated because legumes are grown on less favourable land and due to methods of unsuitable analysis, such as not comparing similar soils or management techniques and conducting short-term experiments (Watson *et al.*, 2017; Zander *et al.*, 2016). For intercropping of legumes with cereals, Watson *et al.* (2017) demonstrate that in many situations, intercropping improves yield quantity and/or stability of either the mixture, the legume, or the cereal, but in some cases not, with the benefits most pronounced in low-input systems.

The mixed results in the current review of peer-review literature help explain why yield quantity and stability were sometimes barriers, but not always, and often less important than other barriers. It further suggests that other barriers were potentially more decisive in the adoption process or farmers' decision-making. In addition, a better understanding of farmers' motivations for crop diversification may explain some of the differences in the CDC results: Barnes and Ferreira (2018) show that obtaining a higher yield is not always the main

perceived benefit or consideration for farmers intercropping. This aligns with Wreford, Ignaciuk and Gruère's (2017) distinction between producing public goods and private benefits. Even if the farmer is primarily concerned with producing a private benefit, they may not aim for higher yields but to reduce inputs, improve soil quality, or for a range of other reasons.

8.2.2. Knowledge and farmers' decision-making

The CDC results reveal that regardless of the crop diversification practice, farmers lack knowledge. It was the most frequently mentioned barrier in two project documents (Morel *et al.*, 2020; Pearce *et al.*, 2018) and identified in all three LIN workshops and the TRUE policy case studies (Kelemen *et al.*, 2019). Although the current review or peer-reviewed literature mentions that technical references for minor crops are needed (Voisin *et al.*, 2014) and that there is a lack of knowledge on legume cultivation (Annicchiarico, 2017), they do not emphasise the importance of knowledge for farmers adopting crop diversification. In contrast, the CDC results highlight that there are different aspects to knowledge, including awareness of issues regarding specialisation, access to independent knowledge, and the format of knowledge. For example, formal and informal networks, such as demonstration events or workshops, were shown to be a valuable form of knowledge exchange between farmers. Knowledge is closely aligned with access to support or advice, and the CDC results show that it is vital for farmers but often lacking (Barnes and Ferreira, 2018; Drexler *et al.*, 2018; Pearce *et al.*, 2018). Similarly, the CDC results are supported by the current literature review (Magrini *et al.*, 2018; Voisin *et al.*, 2014), but less emphasised.

The CDC results on knowledge align with the adoption of agricultural innovation literature, where knowledge and different facets of knowledge are central in theories (Leeuwis, 2004; Prager and Posthumus, 2010) and frequently recognised as integral in encouraging the adoption of innovative practices (Carlisle, 2016; Mills *et al.*, 2020; Prager and Posthumus, 2010). Moreover, other literature not covered in the current literature review supports the CDC results: Zimmer *et al.* (2016), in a survey on Luxembourgish farmers, concluded that "the lack of information and knowledge about grain legume cultivation are the main barriers in grain legume production" (p.9).

The significance of knowledge as a barrier underscores that crop diversification practices are knowledge-intensive and inherently more complex than simplified cropping systems, which rely heavily on agro-chemicals (Magrini *et al.*, 2018; Mills *et al.*, 2020). The increased complexity was rarely directly referred to in the CDC projects, with some exceptions (Morel *et al.*, 2020; Weituschat *et al.*, 2018). Furthermore, the CDC results suggest that intercropping introduces more complexity than other crop diversification practices because it requires additional decisions regarding selecting varieties and ratios of crops within plant

teams, along with sowing, harvesting, and processing multiple crops (Barnes and Ferreira, 2018; Mamine and Farès, 2020; Pearce *et al.*, 2018; Verret *et al.*, 2020).

The greater emphasis on knowledge, support, and increased complexity in the CDC results compared with the current literature review can partly be explained by the focus, which was agronomic and economic orientated, but also because they rarely included research that incorporated farmers' perspectives. In that sense, it indirectly assumes that farmers always make decisions rationally, which, as highlighted by much of the adoption literature, is not the case (Carlisle, 2016; Mills *et al.*, 2017; Mills *et al.*, 2020; Prager and Posthumus, 2010).

The results from the CDC support that farmers' decision-making is not based on economic factors alone. For instance, farmers' motivations to adopt crop diversification practices are diverse. They frequently include a mixture of agronomic, economic, and environmental motivations (Barnes and Ferreira, 2018; Pearce *et al.*, 2018; Smadja, Magrini and Muel, forthcoming) and within these broad categories included a range of specific aims such as conserving on-farm resources, producing on-farm fodder, reducing inputs, enhancing biodiversity, and curiosity. The array of motivations and reasons for crop diversification influenced the significance of barriers for farmers (Barnes and Ferreira, 2018); however, motivations were infrequently examined, making it difficult to determine their degree of influence. This again highlights a wide range of private benefits and public goods which may motivate farmers to adopt crop diversification (Wreford, Ignaciuk and Gruère, 2017). Moreover, other non-economic factors emerged in the CDC results: farmers' perception of agriculture and the associated risk of adoption, farmers' perception of crop diversification, concerns regarding neighbours, cultural barriers, and issues with farm succession. All of which suggest that future research on crop diversification should pay more attention to farmers' decision-making and incorporate lessons from the adoption of agricultural innovation literature.

8.2.3. Farm-level profitability

The low profitability of legumes was raised as a barrier in multiple CDC project deliverables (TRUE D7.3; TRUE D7.2) and was firmly supported by the current literature review (Annicchiarico, 2017; Watson *et al.*, 2017; Zander *et al.*, 2016). In France, the average gross margin was 2-6 times smaller for grain legumes than for non-legume major crops (Magrini *et al.*, 2016), and for Europe, grain legumes gross margin range from 70 up to several hundred euros per hectare less than for other crops (Zander *et al.*, 2016). Although there is frequent reference to the low profitability in the current literature review, there are few references on how this influences farmers' decision-making. The one exception comes from Voisin *et al.* (2014); they refer to a study which states that conventional farmers are reluctant to grow legumes because of the small gross margin, specifically mentioning poor yield and low market price, compared with cereals and oilseed rape (Carrouée *et al.*, 2012).

Other results from the CDC suggest that crop diversification can be profitable or at least does not represent a barrier to its adoption. For instance, the survey on crop diversification initiatives showed that profitability was more frequently an enabler (Drexler *et al.*, 2018); likewise, it was not a barrier for farmers adopting temporal crop diversification (Morel *et al.*, 2020), and low yields could be offset by higher market prices or reduced costs for intercropping (Barnes and Ferreira, 2018; Pearce *et al.*, 2018). Furthermore, growing legumes as an intercrop can improve profitability because the gross margin is more stable and higher for mixtures than when the crops are grown separately (Annicchiarico, 2017; Watson *et al.*, 2017). Still, the CDC results are not robust enough to state if farmers perceive this benefit or not.

Several factors may influence the mixed results regarding profitability. There are many economic benefits of crop diversification for farmers not captured in gross margin calculations. Research using modified gross margin calculation – which include nitrogen savings due to legumes' ability to fix nitrogen, savings from pest control due to break crop effects, and yield enhancement on subsequent crop – demonstrate that there are more situations where legumes are more competitive (Magrini *et al.*, 2018; Voisin *et al.*, 2014; Zander *et al.*, 2016). Some of the CDC results show that these benefits motivate farmers to adopt crop diversification (Barnes and Ferreira, 2018; Sears *et al.*, 2021). Therefore they are likely to influence farmers' decision-making or evaluation of which crops to grow. Nevertheless, even with a modified gross margin analysis, Watson *et al.* (2017) contend that legumes are still not economically competitive in most situations due to inadequate technical performance; Annicchiarico (2017) made a similar conclusion. This demonstrates that downstream markets and the price farmers receive play an essential role in determining profitability. Moreover, the current literature review only covered legumes, potentially other minor crops covered in the CDC results have higher market values which countered the low yields. A final factor influencing farmers' perception of profitability is non-economic motivations for diversifying, as discussed above.

The results suggest that intercropping has higher ongoing management costs and initial on-farm investment. The ongoing costs include seeds and plant protection products, more time and or labour for crop management, and post-harvest operations (Mamine and Farès, 2020; Pearce *et al.*, 2018). However, this may have arisen because the CDC results covered intercropping more at the farm level than the other crop diversification practices. A more pronounced difference for intercropping was the initial investment in machinery, equipment, or infrastructure. It was the most frequent farm-level barrier for the farmers adopting intercropping (Morel *et al.*, 2020). The lack of machinery was the highest-ranked barrier in the ReMIX survey (Barnes and Ferreira, 2018) and mentioned in other outputs (Henrik Hauggaard-Nielsen *et al.*, 2021; Mamine and Farès, 2020; Pearce *et al.*, 2018). This relates to

crop management, mostly harvesting, grain separation, and processing, which were correspondingly significant barriers only for intercropping (Barnes and Ferreira, 2018; Pearce *et al.*, 2018; Tippin *et al.*, 2019). Although the required investment was an anticipated finding and supported by previous research on intercropping (e.g., Lithourgidis *et al.*, 2011), the significance of these barriers is notable and shows that financial support or forms of collective ownership are required to encourage the adoption of intercropping.

The CDC results show that policy support across crop diversification practices was important for farmers and can represent a significant barrier to adoption (Barnes and Ferreira, 2018; Drexler *et al.*, 2018; Kelemen *et al.*, 2019; Mamine and Farès, 2020). Specifically, not high enough subsidies was cited as a barrier in both the CDC results (Howard *et al.*, 2018; Maaß *et al.*, 2018; Pearce *et al.*, 2018) and the current literature review (Annicchiarico, 2017; Magrini *et al.*, 2018) implying that private benefits from crop diversification are not enough to encourage adoption (Wreford, Ignaciuk and Gruère, 2017). Alternatively, farmers may not be aware of, or take into account, the agronomic benefits of crop diversification, as suggested by Magrini *et al.* (2018). Therefore any financial support should be combined with education or awareness campaigns, which may promote more permanent adoption than if farmers only enrol in agri-environmental schemes for financial reasons (Prager and Posthumus, 2010). However, currently coupled support and environmental premiums are only available for pure crops with currently no provision for intercropping within CAP Pillar 1 and 2 (Mamine and Farès, 2020), which may partly explain the inadequate policy support experienced by farmers adopting intercropping.

8.3. Downstream of the farm

The CDC results on barriers downstream of the farm were obtained from a wider range of sources with more reports and fewer surveys or workshops directly, including the relevant stakeholders' perspectives. This is partly due to the variation of downstream value chains and markets and the broader range of actors involved. Moreover, a large amount of the CDC's research on downstream barriers deals with legumes. As the current literature review on peer-reviewed literature only covered legumes, there is a bias in the discussion towards legumes.

The CDC and the current literature review underscore the significance of creating markets for minor crops. The CDC results highlight that low market stability and the lack of existing or small markets were frequently key barriers across different crop diversification practices, value chains, and for different actors along the chain (Drexler *et al.*, 2018; Morel *et al.*, 2020; Pearce *et al.*, 2018; Smadja, Magrini and Muel, forthcoming; Verret *et al.*, 2020). The is support by the current literature review where low consumer demand for legumes and market demand for feed derived from minor crops were frequently stressed as main reasons for low legume cultivation in Europe (Magrini *et al.*, 2018; Voisin *et al.*, 2014; Watson *et al.*, 2017; Zander *et al.*, 2016). Simultaneously, however, there are promising trends for crop

diversification markets in Europe due to vegetarian eating habits, demand for organic products, demand for organic and non-GMO animal products, and rising prices of soya and fertiliser (Drexler *et al.*, 2018; Hamann *et al.*, 2019; Hamann *et al.*, 2020; Kezeya Sepngang *et al.*, 2020; Kootstra, Schoorlemmer and de Visser, 2017). These trends can further be supported by educating and informing consumers on the health and environmental benefits of legumes and crop diversification which was frequently considered a barrier (Kelemen *et al.*, 2019; Morel *et al.*, 2020). Therefore, although the results highlight that there are significant opportunities to expand crop diversification in Europe, suitable and attractive markets and value chains are required to encourage wider adoption and dissemination.

The CDC results and the current literature review demonstrate that legumes and other minor crops cannot compete directly with mainstream production and markets, but only in niche markets. This aligns with two strands of inquiry I observed in the current review of peer-reviewed literature. First, how to improve legumes' economic and technical performance to compete directly with the mainstream (Annicchiarico, 2017; Watson *et al.*, 2017; Zander *et al.*, 2016). Second, how can market outlets which are currently niches, be developed and expanded to challenge or influence the dominant regime[7] (Magrini *et al.*, 2018; Voisin *et al.*, 2014). The same two strands are found in the CDC results; Weituschat *et al.* (2018) extend this analysis showing that longer, more globalised value chains that focus on commodities create more barriers to adopting and disseminating crop diversification. They conclude that localised and relational-based value chains provide more flexibility and a better opportunity for adoption, even though they encounter a range of additional barriers.

A more nuanced understanding of the barriers associated with various markets and value chains may help devise more appropriate and tailored support. Therefore, the following section highlights some of the main barriers associated with two broad categories: commodity and alternative markets. These categories are used for an analytical purpose and do not capture a range of markets and value chains. Instead, they can be seen as two ends of a spectrum. However, as most of the CDC results did not distinguish between value chains and markets (particularly farm-level research), more categories are not possible. The limited coverage by the CDC also means that the analysis relies heavily on two documents: Morel *et al.* (2020) and Weituschat *et al.* (2018).

The results indicate that commodity markets and their accompanying value chains have distinct barriers. Commodity markets are typically made up of longer value chains with more actors or steps and may include export. The dominant strategy for the actors involved in these

[7] Regime, or socio-tecnical regime, is based on multi-level perspective theory by Geels (2003) and in this case refers to the dominant agri-food systems in Europe based on simplified and specialised farming systems.

value chains is economies of scale, corresponding with specialisation. Therefore, it follows that the first and foremost barrier is competition. As outlined in the discussion above on upstream and farm-level barriers, major crops and their accompanying production systems have had significant support and research and development in Europe since the 1950s. This makes it difficult for minor crops and their accompanying production systems to compete based on simple metrics like yield, gross margin, and standards (Magrini *et al.*, 2018; Meynard *et al.*, 2018; Watson *et al.*, 2017; Zander *et al.*, 2016).

Low market values compound the challenge to compete due to inexpensive imports and supply chain deficiencies in Europe and for minor crops. As actors within these value chains attempt to achieve economies of scale, the small volumes of minor crops are unattractive, resulting in limited investment in the necessary infrastructure and equipment for cleaning, drying, storing, and processing, along with the development of new and innovative products (Hamann *et al.*, 2020; Kootstra, Schoorlemmer and de Visser, 2017; Morel *et al.*, 2020; Weituschat *et al.*, 2018). This reinforces the preference for imported protein or use of other major crops and leads to barriers at the farm level with collection because producers are dispersed, and volumes are small (Mamine and Farès, 2020; Morel *et al.*, 2020; Weituschat *et al.*, 2018). In addition, farmers within commodity value chains must comply with quality standards to receive premiums and stringent purity standards to have crops accepted (Henrik Hauggaard-Nielsen *et al.*, 2021; Morel *et al.*, 2020; Pearce *et al.*, 2018). Moreover, standards for minor crops and non-soya legumes do not always exist or are not always well-known, which reduces their use by processors for both feed and food (Hamann *et al.*, 2020; Weituschat *et al.*, 2018). There are differences between feed and food commodity markets, but the CDC results do not permit a more nuanced comparison between different commodity markets (Table 4).

Conversely, alternative markets with short or local supply chains have a range of different barriers. They are characterised by fewer intermediary actors, or none in the case of direct marketing, geographically closer to consumers or markets, and target higher value niche markets. Therefore the technical performance, specifically yield, is less important because of higher market values (Drexler *et al.*, 2018; Pearce *et al.*, 2018). This can result in better competition with mainstream producers (Drexler *et al.*, 2018). However, competition with imports can also be a barrier for farmers engaging in local organic markets, as shown by Morel *et al.* (2020).

In terms of the supply chain for alternative markets, Morel *et al.* (2020) found that when intermediary processing steps are required, then collection is not a constraint, but costs associated with diversified products and investment in cleaning, drying, and storing equipment are still substantial barriers to smaller value chain actors, along with a need for

innovation at smaller scales. Even though this is a similar barrier to commodity value chains due to a different scale of operation, different support may be required. Although there is not a focus on commodity standards, these markets must comply with other standards such as taste, nutrition, and production type (Meynard *et al.*, 2017 cited by Weituschat *et al.*, 2018). The latter can discourage conventional farmers who believe that consumers interested in local markets will also choose organic production methods (Morel *et al.*, 2020). Only barriers from the CDC results have been discussed, but there are likely specific barriers associated with short or local supply chains which deserve consideration, for instance, distance from urban markets (Weituschat *et al.*, 2018).

Although the above distinction regarding different markets and value chains also applies to intercropping, some additional downstream barriers are only relevant for intercropping. The main and most cited barrier in the CDC results was separation. On-farm separation is frequently necessary and a potential barrier for farmers because downstream actors are often unwilling to accept crop mixtures because it requires investment in equipment and infrastructure for sorting and storage (Magrini *et al.*, 2018; Voisin *et al.*, 2014; Weituschat *et al.*, 2018). Need for investment also depends on the technical difficulties with separation. These depend on the plant team (i.e., separation is more difficult when the grain size or colour are similar) and the degree of separation depends on the end market. Feed markets generally have fewer downstream barriers as the mixture does not always require separation when used as silage or if the grains are to be fed directly to animals. Even when it requires separation, then purity standards are lower for feed markets. Thus, contamination from broken or damaged grains not being adequately sorted is less likely to affect the product's marketability. In contrast, requirements for food markets are higher and low levels of contamination can result in rejection by a collection agency and abandoning of crop mixtures by farmers (Verret *et al.*, 2020), thus creating a more significant barrier for farmers growing intercrops for food (Barnes and Ferreira, 2018). The results show that these barriers can be significant for farmers and downstream actors but depend on many factors in addition to the different markets and value chains.

9. Conclusion

This synthesis reveals that barriers to crop diversification are complex, interconnected, and occur at multiple levels. Thus, the findings support previous research suggesting that barriers need to be addressed simultaneously and in a coordinated manner (Magrini *et al.*, 2018; Meynard *et al.*, 2017; Voisin *et al.*, 2014). It further shows that overcoming barriers, and more generally the problems facing contemporary agri-food systems, often do not have singular or straightforward solutions. This highlights the need for more research like agroecology, which applies holistic and systems approaches to understand connections between barriers and different levels of the agri-food system.

At the same time, the synthesis supports the need for more participatory and transdisciplinary research. In the current literature review of review articles on crop diversification, stakeholders' perspectives were often absent. Their limited inclusion implies (potentially unknowingly) that farmers only make rational decisions. This aligns with agricultural research from persuasive or instrumental tradition (Leeuwis, 2004). The assumption is that by improving crop diversification systems' technical or economic performance, adoption should follow. As shown by the adoption of agricultural innovation literature, farmers' decision-making is less predictable (Carlisle, 2016; Mills *et al.*, 2020; Prager and Posthumus, 2010). The review of Crop Diversification Cluster (CDC) documents, which often included stakeholders' (primarily farmers') perspectives, supports the adoption of agricultural innovation literature. The CDC results reveal not only different barriers but also differences in the significance of other barriers. However, due to the limitations of this study, validation of these differences requires further research.

Furthermore, this research explores relationships between barriers and different crop diversification practices and between barriers and different markets and their respective value chains. However, my ability to do is limited by the points mentioned above and the variation in the barriers within specific crop diversification practices. This supports previous research and highlights that addressing barriers requires a case-by-case approach and consideration of the specific context (Carlisle, 2016; Knowler and Bradshaw, 2007; Prager and Posthumus, 2010). Even though this limits my ability to analyse the relationship and make robust conclusions, my findings can be summed up by the following six conclusions.

First, the results support research demonstrating a lock-in to simplified farming systems which focus on major crops and agro-chemicals. This lock-in reduces crop diversification and minor crops' ability to compete in terms of technical and economic performance at the farm-level and downstream of the farm. This aligns with the second conclusion. The review of CDC documents suggests that performance, in terms of yield and profitability, is vital for farmers but less significant than indicated in the current review of the peer-reviewed literature. As highlighted in the discussion, many factors may affect these results, but it shows that other factors influence farmers' decision-making.

Third, a lack of knowledge and access to support or advice were key barriers for farmers adopting different crop diversification practices. The CDC results align with the adoption of agricultural innovation literature in showing that knowledge is more than just technical references but also includes a range of other aspects such as quality and trustworthiness of information and the format in which the information is presented.

Fourth, non-economic factors influence farmers' decision-making and supports previous literature on the adoption of agricultural innovation (Carlisle, 2016; Mills *et al.*, 2017; Mills *et al.*, 2020; Prager and Posthumus, 2010). The CDC results highlighted that a farmer's motivation to adopt crop diversification influences their decision-making, with some evidence indicating that it influences barriers (Barnes and Ferreira, 2018). Still, other non-economic factors, such as perception of agriculture, social networks, and cultural barriers, were scattered through CDC results indicating that other non-economic barriers also contribute to farmers' decision-making. Nonetheless, they were not covered extensively by any of the CDC projects, and further research to understand their influence on decision-making is needed.

Fifth, the CDC results show that commodity markets and alternative markets along with their respective value chains have different barriers. Even though a more detailed analysis with additional categories was not possible, the CDC results showed substantial differences. These differences should be considered explicitly in future research and in devising political support for developing markets and value chains. Furthermore, Morel et al.'s (2020) research suggest that farmers (and potentially other downstream actors) engaging in specific value chains have some differences and correspondingly encounter distinct barriers. For example, farmers adopting temporal crop diversification and engaging in commodity markets were less convinced or aware of crop diversification's benefits, less willing to cooperate with other farmers. Moreover, they had more challenges obtaining independent advice because of their connection with conventional actors (e.g., input providers) who do not benefit from promoting crop diversification. This links with the previous conclusion about understanding farmers' decision-making.

Sixth, the results support previous literature showing that intercropping has specific barriers different from other crop diversification practices. Predominantly regarding the separation of mixtures and the need for specialised machinery and infrastructure both on- and off-farm. Tailored support is required to overcome these barriers and encourage adoption and dissemination in Europe.

The present synthesis of barriers sits between and draws from two bodies of literature with different approaches to understanding the low adoption rates of crop diversification in Europe. The agricultural innovation literature covers crop diversification as a subcategory of other sustainable agricultural practices. It provides a subtle understanding of barriers, specifically at the farm-level and concerning farmers' decision-making. However, there is often limited analysis of downstream barriers and the broader agri-food system. In contrast, the review articles on crop diversification practices in Europe examine adoption with an agri-food system approach, viewing the farm as part of a system and influenced by upstream, downstream, and broader economic and political developments. At the same time, the

weakness is the limited analysis of actors. Both bodies of literature provide valuable insights into the low adoption of crop diversification in Europe, future research could continue to bridge the gap between them.

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Appendix: A Research protocol for literature review

1. Research question and conceptual framework

1.1 Aim

To synthesise the barriers that limit the adoption dissemination of crop diversification practices in Europe.

1.2 Primary question

What barriers limit the adoption and dissemination of crop diversification practices in Europe?

1.3 Question component

Table 1. Question component (PICo)

PICo	Component	Objective
Problem	Dissemination of crop diversification	Dissemination includes the adoption of crop diversification practices by farmers, the involvement of actors in the supply chain both downstream and upstream of the farm, and consumption of the products Crop diversification practices include introducing minor crops, legumes, intercropping, multiple cropping, lengthening crop rotation, and cover crops
Interest	Barriers	To identify the different barriers limiting adoption and dissemination
Context	Europe	European agricultural land

1.4 Theory of change

An initial reading of the literature on adopting agricultural innovation along with key literature on the adoption of crop diversification practices (predominantly Morel et al., 2020) was used to form a flexible conceptual framework (Table 2) which guided both the rapid review and the review of the European Crop Diversification Cluster project documents. This provided a structure to extract the different barriers and organise and analyse the results.

Table 2. Theory of change

Group of Barriers	**Examples of Barriers**
Knowledge	Availability of knowledge Advice/support
Socio-cultural	Culture barriers Farmers' attitude Risk
Biophysical/Agronomic	Site-specific factors - water availability, climatic issues, and soil type Machinery, available and adapted Seeds, available and adapted Pest, disease, and weed management
Economics (farm-level)	Low profitability or gross margin High production costs – inputs or labour More competitive to grow other crops/opportunity costs Requires investment
Institutional/Regulatory	Inadequate policy support Barriers related to CAP or agri-environmental schemes EU environmental and sanitary regulations Regulations issues around sanitary, quality, and purity aspects
Market & Consumer Demand	Competition with global market Limited, uncertain, or unstable market Consumer demand – willingness to pay more and awareness of benefits of crop diversification
Supply Chain	Logistics – collection, storage, trading, & processing issues High transaction costs dealing Investment and innovation - cleaning, drying, storing, screening, and processing
Market Coordination & Organisation	Contractual issues Market Information Standards

2. Databases and search string

2.1 Databases

The following databases are used:

Web of Science Core Collection

Scopus

2.2 Search string

The search string is divided into the following components, resulting in

- 103 results in the Web of Science Core Collection database, and
- 267 results in the Scopus database

Table 3. Search string

Article type	
1	(review OR "meta analysis" OR meta-analysis OR "rapid evidence assessment" OR "systematic map*")
Agriculture keywords	
2	(farm* OR agri* OR agro* OR "food system")
Crop diversification practice keywords	
3	(diversity OR diversification OR "minor crop" OR *rotation* OR "crop rotation" OR pulse* OR grain-legume* OR legume* OR intercrop OR "companion crop*" OR "companion plant*" OR "cover crop" OR "catch crop" OR multicrop* OR "multiple crop*" OR "strip crop*" OR "alley crop*" OR "mixed crop*" OR "spatial diversification" OR "temporal diversification" OR "underutili?sed crop*" OR "major crop")
Synonyms for barriers and levers	
4	(barrier* OR obstacle* OR constraint* OR hind* OR challenge* OR "lever*" OR driver * OR enabl* OR opportunit* OR lock-in*)
Different types of barriers and levers	
5	(adopt* OR uptake OR implement* OR transition* OR "supply chain*" OR market*)
Geographic qualifier keywords	
6	(europ* OR austria OR austrian OR Belgium OR Bulgaria OR Croatia* OR Cyprus OR Czech OR Dannish OR Denmark OR Scadinavia* OR Estonia* OR Finnish OR Finland OR French OR France OR German* OR Greek OR Greece OR Hungar* OR Iberia* OR Iceland* OR Irish OR Ireland OR Ital* OR Latvia* OR Liechtenstein* OR Lithuania* OR Luxembourg* OR Malt*OR Dutch OR Holland OR Netherlands OR Norwegian OR Norway OR Polish OR Poland OR Portug* OR Romania* OR Slovak* OR Slovenia* O R Spanish OR Spain OR Swed* OR Swiss OR Switzerland OR British OR Britain OR E nglish OR England OR Scottish OR Scotland OR Welsh OR Wales OR "United Kingdo m" OR UK)
Animal qualifier keywords	

7	(mammal OR marine OR aquaculture)
Final combination of search groups in search string	
#1 AND #2 AND #3 AND #4 AND #5 AND #6 NOT #7	

2.3 Evaluating the comprehensiveness of Search

A list of articles was identified prior to establishing the final search string as being key papers within the field of crop diversification.

List of key articles:

- Mamine, F., 2020. Barriers and levers to developing wheat–pea intercropping in Europe: A review. Sustainability, 12(17), p.6962. doi:10.3390/su12176962
- Magrini M-B, Anton M, Cholez C, Corre-Hellou G, Duc G, Jeuffroy M-H, et al. Why are grain legumes rarely present in cropping systems despite their environmental and nutritional benefits? Analyzing lockin in the French agrifood system. Ecological Economics. 1 juin 2016; 126(Supplement C):152–62.
- Meynard JM, Messean A, Charlier A, Charrier F, Farès M, Le Bail M, et al. Crop Diversification: obstacles and levers, study of farms and supply chains. Synopsis of the study report, INRA. 2013.
- Morel K, Revoyron E, San Cristobal M, Baret PV (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
- Voisin A-S, Gue'guen J, Huyghe C, Jeuffroy M-H, Magrini M-B, Meynard J-M, et al. Legumes for feed, food, biomaterials and bioenergy in Europe: a review. Agron Sustain Dev. 1 avr 2014; 34(2):361–80.
- Zander P, Amjath-Babu TS, Preissel S, Reckling M, Bues A, Schläfke N, et al. Grain legume decline and potential recovery in European agriculture: a review. Agronomy for sustainable development. 2016; 36(2):26.

3. Screening Procedure

3.1 Screening Procedure

The screening determines which articles are included in the review and is based on the inclusion and exclusion criteria (Section 3.2). The screening consists of two-stage, abstract screening and full-text review.

3.1.1 Abstract Screening

Abstract screening is the coarse sieve to remove papers that are not relevant based on the inclusion and exclusion criteria. The benefit of the doubt is always given if the reviewer is unsure.

3.1.2 Full-text Screening

If the reviewer is uncertain about the relevance, then sections or the entire text are reviewed based on the inclusion and exclusion criteria.

3.2 Inclusion criteria

3.2.1 Geographic region

Research must be conducted or concerning at least one country within EU-27, EEA, or the United Kingdom.

3.2.2 Type of study

Only peer-reviewed articles in review format will be considered for inclusion:

- Literature review
- Quick scoping review
- Rapid Evidence Assessment
- Meta-analysis
- Systematic review
- Review of reviews
- Systematic mapping

3.2.3 Practices reviewed

Only articles covering at least one crop diversification practice from the following list will be considered for inclusion:

- Catch crops
- Companion crops
- Cover crops
- Crop rotation (lengthening crop rotation with additional crops)
- Including minor crops
- Intercropping
- Introducing legumes (grain or forage)
- Multiple cropping
- Mixed cropping

3.2.4 Focus – barriers and drivers

Only articles concerning barriers or drivers (and synonyms) to the dissemination of crop diversification will be considered for inclusion. The barriers/drivers are not restricted to the farm level but included the supply chain, institutions, and consumption.

3.3 Exclusion criteria

Exclusion criteria are used to determine which articles should be excluded from the review (Table 4).

Table 4. Exclusion criteria

Exclusion Labels	Description
Wrong study design	If the article is not peer-reviewed or does not have a review incorporated (e.g., a field experiment), then it should not be included.
Wrong location	If the article is not focused on European farming systems, it should be excluded, i.e., no articles focusing solely on North American or tropical farming systems should be included.
Wrong practice	If the article does not cover a minimum of one crop diversification practice (Section 3.2.3) then it should not be included.
Wrong focus	If the article does not cover barriers or drivers to crop diversification, then it should not be included.
Wrong language	If the language is not in English, then it should not be included.

4. Data coding strategy

The data coding strategy is conducted in two stages. All data extracted will be recorded in a spreadsheet using Excel.

4.1 Stage 1 – general information

In the first stage, general information about the article is extracted. This can be conducted without reading the entire text. The following information will be extracted:

- Paper citation
- DOI
- Type of review
- Number of studies reviewed in the article
- Location of study – region and country
- Farming approach
- Type of crop diversification practice
- Specific crop(s) covered
- Scale

4.2 Stage 2 – qualitative assessment

The second stage is a full-text review to identify more detailed information about the different barriers. The following information will be extracted:

- Group of barriers (see first column Table 2) – e.g., agronomic, farm-level economic, supply chain, etc.
- Specific barrier (see second column Table 2) – e.g., seeds or phytosanitary solutions
- Source
- Additional details – e.g., a direct quotation
- cited (in the text review)

- Page number
- Comment

The information extracted from each article will be filled out in a separate row of the spreadsheet. It is highly probable that each article will evaluate multiple crop diversification practices and/or list multiple barriers; each practice or barrier should be filled out in a separate row resulting in each article having multiple rows.

To complete the qualitative assessment, the entire text should be read and not only sections relevant to barriers. Barriers identified are classified according to the different groups of barriers (Table 2), which can be found in a drop-down box in the Excel spreadsheet. The precise barrier and (when applicable) the cause/result/impact of the barrier should be recorded in the spreadsheet. For example, the barrier low gross margin for legumes based on low yields and low producer price would be classified in the group 'economic (farm-level)', the precise barrier is 'low profitability', and the cause is 'low yields and market prices'. In addition, any sources cited in the text, the page number, and additional details (i.e., direct quotations) should be recorded into the spreadsheet.

5. Study appraisal

No study appraisal is conducted for this rapid review

Appendix: B Workshop with Crop Diversification Cluster researchers

All the participants received a similar copy of this appendix along with the results tables found in the thesis (Table 3 & Table 4), and a draft of thesis before the workshop.

Aims of meeting

1. To discuss the similarities and differences in the barriers identified across the CDC projects.
2. To validate the synthesis and see if it accurately captures the findings from across the CDC and/or does not miss any important aspects.

Rough agenda

- 10-minute presentation of thesis and plan for the meeting
- 45 minutes to discuss farm-level barriers
- 5-minute break
- 30 minutes to discuss downstream barriers
- 15 minutes to discuss additional factors influencing the presence/absence of barriers
- 10 minutes for final comments

Questions to guide farm-level barriers discussion

Note to reader – the discussion for the farm-level barriers used the table found in the thesis (Table 3) as a visual aid.

1. The peer-reviewed literature along with some results from the CDC highlight the lock-in regarding **research and development of inputs for minor crops**, namely seeds and plant protection products. The CDC results suggest that the availability of inputs are barriers to farmers but less significant than the peer-reviewed literature.
    a. Based on your research how important are the lack of appropriate inputs for farmers in the adoption of crop diversification? Are there differences between crop diversification practices?
2. The results suggest that the **lack of knowledge** is one of the most important barriers across different types of crop diversification. Naturally, every new practice, innovation, or crop will have specific knowledge requirements, but the results suggest that crop diversification is more knowledge-intensive and complex than simplified farming systems.
    a. Do you think that lack of knowledge is one of the most important barriers for farmers adopting crop diversification?
    b. Extra: Based on your research do you agree that farmers see crop diversification as more complex, and if yes, is the increased complexity of crop diversification a barrier to its adoption?

3. **Yield quantity and stability** are emphasised in the peer-reviewed literature as being important reasons for the low adoption of legumes in Europe. The CDC results suggest that quantity and stability are barriers but perhaps less significant for farmers.
    a. Based on your research, do you agree with this statement? Are there differences between crop diversification practices?
4. The CDC results and the peer-reviewed literature are mixed regarding the **profitability of crop diversification** at the farm-level with some suggesting that intercropping with legumes is more profitable than growing legumes in monocrop while other results highlight that the higher production costs (inputs and management) and investment for intercropping is a barrier to its adoption.
    a. Based on your experience, do you feel that we are able to draw robust conclusions on the profitability (or not) of crop diversification practices and any differences between practices?
    b. Extra: How important was maximising profit for the farmers that you worked with? Are other motivations (such as spreading risk, producing on-farm feed, reducing inputs) as important in the decision-making of farmers?

Questions to guide downstream barriers discussion

Note to reader – the discussion for the downstream barriers used the table found in the thesis (Table 4) as a visual aid.

1. **Market demand and market stability** were highlighted as crucial barriers in several deliverables across crop diversification practices and for different value chains. However, Morel et al.'s (2020) research found differences between innovation settings. For the group 'changing from within' which is associated with temporal crop diversification, commodity markets, and mostly conventional farmers the barrier limited, or no markets was important, while for the group 'building outside' which is associated with intercropping, local markets, and only organic farmers the barrier uncertain or unstable markets was more important.
    a. Did your research find differences in market demand and market stability for different types of markets (food vs feed or commodity vs local), crop diversification practices, specific crops, or plant teams?
2. There are several common **barriers along the supply chain regarding low volumes, profitability, and the need for investment and innovation**. Based on their extensive literature review on crop diversification value chains, Weituschat et al. (2018) assert that farmers engaging in longer commodity value chains encounter more challenges than farmers engaging in local or niche markets.
    a. Does your research within the CDC support this statement?
3. **Market coordination** emerged as an important factor with barriers covering **contracts**, **market information**, and **standards**. Although there was limited and unequal coverage across the different deliverables and projects there appears to be some similarities and differences depending on the type of market. Some similarities include the need for contracts that ensure fair sharing of risk and value along the

supply chain, inadequate market information, the lack of standards for minor crops. For certain markets/value chains some of the differences appear to be specific barriers to establish contracts and the types of standards (i.e., purity or taste).

a. Based on your experience, do you view market coordination as an important factor? Are there differences between markets/value chains or crop diversification practices?

Other factors that influence the presence/absence of barriers

1. In addition to analysing the influence of crop diversification practices and type of value chain on the presence and absence of barriers several other factors emerged during my research as being relevant. These include **geographical region** (DiverIMPACTS D1.1), **adoption vs non-adoption** (ReMIX D1.1; DIVERSify D1.1/D4.5); **perception of crop diversification/farming style**; **and farming system**.
    a. Are there other factors you found that influence the presence/absences of barriers that we have not discussed or are now highlighted in the table?

Appendix: C Documents reviewed from Crop Diversification Cluster

Citation	Title	Project	Diversification	Focus	Aim/Objective	Method
(Pearce *et al.*, 2018)	Synthesis report on national stakeholder meetings	DIVERSify	Intercropping	Farm-level	"Identify tacit knowledge, bottom-up innovations, strategies and current farmer best practice in diverse cropping systems." (p.4)	15 participatory stakeholder workshops in 11 countries
(Tippin *et al.*, 2019)	Report on practical restrictions imposed by plant teams	DIVERSify	Intercropping	Farm-level	To understand "how barriers are viewed differently between countries and the how other factors (such as farming system and type) can affect whether barriers are unsolved, perceived or solved." (p.6)	Builds on results from stakeholder workshops, includes experiences from Participatory Farmers, and makes comparisons from TRUE and DiverIMPACTS
(Barnes and Ferreira, 2018)	Identification of the regional context to increase the use of species mixtures	ReMIX	Intercropping	Farm-level	"[T]o explore the current activities towards intercropping and the motivations, reasons and barriers for encouraging more intercropping within European arable systems." (p.4)	Survey of European farmers with (n=166)
(Henrik Hauggaard-Nielsen *et al.*, 2020)	Translating the multiactor approach to research into practice: the case of species mixtures in the ReMIX project	ReMIX	Intercropping	Multi-level	"While crop mixtures was the theme the aim was to learn about multi-actor approaches and how to bring different improve communication between different disciplines." (p.7)	3-day workshop with 63 participants; mostly ReMIX researchers and 8 distinct value chain actors
(Verret *et al.*, 2020)	Tracking on-farm innovative practices to support crop mixture design: The case of annual mixtures including a legume crop	ReMIX	Intercropping	Farm-level	"[I]dentify and analyze the crop mixtures grown by these farmers, with a view to creating cognitive resources to help other farmers to adopt and adapt this practice to their own context. (p.1)	Farm survey and semi-structured interviews 10-90 minutes (n=47)

(Mamine and Farès, 2020)	Barriers and Levers to Developing Wheat–Pea Intercropping in Europe: A Review	DiverIMPACTS	Intercropping	Multi-level	Analyse barriers and levers to the adoption and diffusion of wheat-pea intercropping.	Literature review
(Drexler *et al.*, 2018)	Typology of diversification experiences with description of driving factors to support crop diversification	DiverIMPACTS	General crop diversification	Multi-level	"[T]o identify and analyse factors of success and failure associated with a variety of crop diversification experiences (CDEs)." (p.3)	Well-structured survey (n=129); one response was per initiative and included a wide range of actors
(Weituschat *et al.*, 2018)	Systematic overview of agri-food value chains in the EU as connected to crop diversification	DIVERFARMING	General crop diversification	Farm/ Value chain	"[T]o identify factors related to value chains limiting or promoting adoption" (p.4)	Extensive literature review on the adoption of crop diversification; number of papers reviewed were 47
(Morel *et al.*, 2020)	Innovating within or outside dominant food systems? Different challenges for contrasting crop diversification strategies in Europe	DiverIMPACTS	General crop diversification	Multi-level	"[E]xplores the extent to which barriers to crop diversification can be related to the proximity of innovation settings with dominant food systems. (p.1)	Multi-step approach, 46 barriers to crop diversification identified through multiple workshops; the barriers were linked to 25 innovation settings (cases studies) using multi correspondence analysis.
(Smadja, Magrini and Muel, forthcoming)	Report on legume-based value/supply chains sector diagnosis	LEGVALUE	Legumes	Value Chain	To identify and analysis the main characteristics of diverse legume-based value chains in the EU	Survey 127 stakeholder from 29 case studies; made up of 44 farmers, 26 processors, and 17 collectors
(Kootstra, Schoorlemmer and de Visser, 2017)	Macro-developments that can influence European legume value chains	LEGVALUE	Legumes	Value Chain	Examines how the macro developments influence the legume value chains in the EU	DESTEP analysis used to examine different macro-developments, demographic, environmental, social, technological, economic, and political

(Kezeya Sepngang *et al.*, 2020)	Report on legume markets in the EU	LEGVALUE	Legumes	Markets	Analysis of legume markets in the EU	Mixed methods: databases were explored for a quantitative description of EU legume market; expert interviews (n=30) supplemented this analysis; 5 country specific case studies were completed prior to the report
(Hamann *et al.*, 2019)	A map of value chains for legumes used as food	TRUE	Legumes	Value Chain (Food)	"[T]o provide an overview of the infrastructure for trade and processing of fresh produce and dried legume-grains (mainly pulses) in the EU food market." (p.8)	Explorative and qualitative approach including desk-based research and multiple primary data collection methods, such as stakeholder consultations and attending workshops.
(Hamann *et al.*, 2020)	Facilitating the EU market demand for legume-grain and -fodder as feeds	TRUE	Legumes	Value Chain (Feed)	"[T]o provide a qualitative assessment of the competitiveness of European-grown fodder- and grain-legumes for the feed sector in contrast to imported soya bean feed." (p.8)	Desk-based research comprised of qualitative and quantitative data; primary data collection included, case studies, interviews with farmers, research experiments, stakeholder consultations, and attending workshops.
(Toma *et al.*, 2020)	Behavioural analysis of farmers' uptake and consumers' choice	TRUE	Legumes	Farm-level & Consumer	"This report presents the impact of key factors influencing decision making of farmers and consumers to uptake legume cultivation and, respectively, the choice to include legumes into diets." (p.2)	1)Structural equation model to test three hypotheses regarding behavioural determinants to legume uptake and intention to legume uptake(n=176) 2)National web-based choice experiment for UK consumers on purchase of different types of lasagna according to five attributes, meat/meat substitute, production, content of fat, origin, convenience, and price (n=1880)

(Kelemen *et al.*, 2019)	Co-production of the Policy assessment	TRUE	Legumes	Policy	"[T]o provide a 'critical analysis of existing policies and governance solutions for legume-supported systems', which help identify limiting and enabling factors as well as leverage points for further policy interventions." (p.7)	Policy analysis based literature review, document analysis, key stakeholder interviews, and 8 in-depth policy analysis on cases studies
(Balázs *et al.*, 2019)	Application of Delphi for governance contexts which favour legume supported value chains	TRUE	Legumes	Policy	"To present governance solutions that deliver to the expectations of different actors to guide further desirable development of pathways for legume-dependent food- and feed-systems." (p.7)	Dephi is method used to reach a consensus among 80 policy experts on 10 food policy areas previously identified by the TRUE project

Appendix: D Reflection on learning process

An initial comment. For me, it is challenging to reflect on my thesis while it is ongoing. I often need some time and distance from a project to make a balanced reflection. Therefore, I see this reflection as a starting point. At the same time, as I highlighted in my learner document – from the first semester of my Master's in Agroecology at the Norwegian University of Life Science (NMBU) – structured reflection is a skill that I struggle with; therefore, the requirement is no doubt beneficial for me and my learning process.

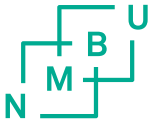
Starting with the topic, which is large and complicated. In hindsight, I think it was too broad for a master thesis and my competencies. By this, I mean that it was ambitious for a student unfamiliar with the research area and who has not conducted research on the topic before to research the topic alone. Well, at least it was for me. I now have more appreciation for why this type of research should be conducted in a team with different disciplinary backgrounds; something which I mention in my thesis. It also means that I do not feel that I covered all the aspects in sufficient detail. In other words, I do not know if I managed to capture the 'whole' or the entire system. I found it particularly challenging to capture the system while at the same time focusing in on specific aspects of interest. Therefore, I see my thesis as a starting point that would need to be worked on by a team to capture the complexity and wholeness of the system.

The breadth of the topic also meant that I spent a long time grappling with reviewing the documents and making sense of the information, which resulted in me not have enough time to develop strong theoretical arguments. At the same time, because I was covering so many topics, it meant that other theoretical approaches could, and perhaps should have, been explored. This brings me back to agroecology. An agroecological approach could have played a more prominent role in the analysis, but due to time constraints, it was lacking.

A final reflection on my learning from this thesis is the inherent challenges of conducting participatory and transdisciplinary research. The two reviews that I conducted for my thesis display this contrast. The literature review of review articles on crop diversification used conventional scientific knowledge, with limited inclusions of stakeholders' perspectives and other forms of knowledge. In contrast, the CDC results used an array of participatory approaches and incorporated different forms of knowledge. This created obvious methodological challenges with making direct comparisons between the reviews. Also, it introduced additional complexity, which was difficult for me to analyse as I did not always have the knowledge, tools, or methodological framework to make sense of this added information. For example, in the workshop with the CDC researchers, we discussed if farmers lacked knowledge (which came up as one of the most important barriers) or if they actually lacked confidence with the practice. Confidence and other concepts emerged during the research, which I did not know to incorporate or analyse. This brings me back to my

previous point of needing to work on this type of research in a team with different disciplinary backgrounds.

Regardless of these challenges, my thesis was a rewarding learning process.



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