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Executive Summary

Mixed farming and agroforestry systems (MiFAS) integrate farming activities aiming at creating synergies that provide economic and environmental benefits compared to more specialised farming systems. Yet, evidence on the economic benefits is mostly based on single case-studies at the farm-level. Therefore, several literature gaps arise. First, a systematic overview of the economic implications of MiFAS is missing, particularly considering value-chain partners of farms. Considering value chains is important because promoting the benefits of mixed systems and receiving higher prices is crucial for the success of such systems. Second, systematic quantitative evidence on the socio-economic impacts of switching from specialised to mixed farming and agroforestry is missing. That is, using representative socio-economic farm data from before and after a farm switches and statistically estimating the consequences of such switches compared to farms that remain specialised. Third, quantitative evidence on the resilience of mixed farming and agroforestry systems to shocks particularly those of value chain partners of farms, is lacking.

In this report, we provide threefold evidence to address these knowledge gaps. First, we present a systematic literature review in which we systematise different value chain configurations of MiFAS and synthesise the economic literature on mixed farming and agroforestry systems with a particular focus on value chains. Based on the results of the first part, we secondly quantify the socio-economic consequences of switching from specialised to mixed farming and agroforestry systematically and empirically based on an extensive and representative farm-level economic dataset covering entire Europe. Third, we identify specific consequences for supply chain partners if farms are exposed to extreme weather by zooming into a specific case study of extensive apple production (i.e., agroforestry) and processing in Switzerland.

Findings of sub-chapters suggest that economic benefits of mixed farming are far more moderate than literature suggests. First, past literature on the economics of MiFAS is scarce and highly case study specific. Therefore, earlier studies lack external validity and policy decisions on the support of mixed farming and agroforestry are largely based on the ecological benefits, neglecting the economic implications on farmers and value chain partners. Second, our Europe-wide quantitative assessment of switching to mixed farming and agroforestry shows that farms, which switch from specialised to mixed crop-livestock mostly do so by downsizing livestock production and only slightly increasing crop production. Therefore compared to earlier studies that suggest switching to mixed farming and agroforestry implies adding activities to a specialised farm, the reality looks different. Instead of producing more on the same land with fewer external inputs, farms that become mixed have lower revenues and productivity and must even invest slightly more into labour than during their specialised times before the switch. Third, mixed and agroforestry farms are said to be more resilient to external shocks due to diversified income streams that come from different products. However, it has been neglected so far that downstream value chain partners, which process the products of these farms further, are dependent on a steady supply. Based on a case study, we show that the supply of apples from this agroforestry system is highly volatile and vulnerable to frost damage. Therefore, supply chain partners, which specialise and label their products to show benefits of mixed farming, are exposed to substantial input risk.

Overall we conclude that the socio-economic consequences of mixed farming on productivity, efficiency, and riskiness of the production are lower than literature suggests. While this might be a reason for the so far low uptake of mixed systems in Europe, this suggests potential pathways for policy makers to support the adoption if the ecological benefits outweigh the costs of this support.

Abbreviations

D	Deliverable
EC	European Commission
WP	Work Package
WT	Work Task

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1 Introduction

Mixed farming and agroforestry systems (MiFAS) integrate farming activities aiming at creating synergies that provide economic and environmental benefits compared to more specialised farming systems (e.g., Moraine et al., 2014; Ryschawy et al., 2012; Soussana & Lemaire, 2014). More specifically, maximally integrated MiFAS combine crops, livestock, and forestry on the same piece of land thereby synergizing on nutrient flows (Martin et al., 2016), thereby reducing farmers costs, and increasing the resilience of income against shocks (Bell et al., 2014; Darnhofer, Bellon, et al., 2010; Havet et al., 2014; Kirkegaard et al., 2014; Peyraud et al., 2014; Wilkins, 2008). Yet, evidence on the economic benefits is mostly based on single case-studies at the farm-level (e.g. Ryschawy et al., 2012). Therefore, several literature gaps arise. First, a systematic overview of the economic implications of MiFAS is missing, particularly considering value-chain partners of farms. Considering value chains is important because promoting the benefits of mixed systems and receiving higher prices is crucial for the success of such systems. Second, systematic quantitative evidence on the socio-economic impacts of switching from specialised to mixed farming is missing. That is, using representative socio-economic farm data from before and after a farm switches and statistically estimating the consequences of such switches compared to farms that remain specialised. Third, quantitative evidence on the resilience of mixed farming and agroforestry systems to shocks particularly those of value chain partners of farms, is lacking.

In this report, we provide threefold evidence to address these knowledge gaps. First, we present a systematic literature review in which we systematise different value chain configurations of MiFAS and synthesise the economic literature on mixed farming and agroforestry systems with a particular focus on value chains. Based on the results of the first part, we secondly quantify the socio-economic consequences of switching from specialised to mixed farming and agroforestry systematically and empirically based on an extensive and representative farm-level economic dataset covering entire Europe. Third, we identify specific consequences for supply chain partners if farms are exposed to extreme weather by zooming into a specific case study of extensive apple production (i.e., agroforestry) and processing in Switzerland.

Therefore, this report is structured accordingly into the three main sub-sections, i.e. Section 2 *Mixed farming and agroforestry systems: A systematic review on value chain implications,* Section 3 *The socio-economic consequences of switching from specialised to mixed crop-livestock farming in Europe,* and Section 4 *Resilience of extensive meadow orchards against climatic extremes*. Each of the subsections constitutes a stand-alone scientific article.

Due to the limited potential to retrieve reliable cost information from the MIXED networks, the main farm-level cost analyses (Section 3) are based on FADN data (without agroforestry). The value chain analysis (Section 4) is based on detailed beyond-farm data collected in the MIXED MiFAS network in Switzerland.

2 Mixed farming and agroforestry systems: A systematic review on value chain implications

This section has been published as a stand-alone paper as:

Low, G., Dalhaus, T., & Meuwissen, M. P. M. (2023). Mixed farming and agroforestry systems: A systematic review on value chain implications. *Agricultural Systems*, *206*, 103606.

2.1 Introduction

2.1.1 Introduction to mixed farming and agroforestry systems

The global agricultural paradigm is increasingly typified by specialised-intensive farming systems, characterised by their intensity of production, large scale, and specialisation (Lüscher et al., 2014; Moraine et al., 2014). Thanks to the advancement of machinery, agrochemicals, breeding programmes, and globalised supply chains, specialised systems are producing food in unprecedented quantities leading to the gradual diminishing of the threat of global hunger and malnourishment since the Green Revolution of the 1950s (Dalgaard et al., 2003; Evenson & Gollin, 2003). However, a growing scientific consensus charges specialised and intensive systems with the rapid depletion of nutrients in global soils (Borrelli et al., 2017), the excessive use of agrochemicals (Pingali, 2012), and increasing vulnerability to extreme weather (Olesen & Bindi, 2002). Economically, they are increasingly susceptible to price risks (Tothova, 2011) and are associated with longer supply chains with limited resilience capacities to external shocks (McCorriston & Sheldon, 2007; Meuwissen et al., 2019; Paas et al., 2021).

Mixed farming and agroforestry systems (MiFAS) present an opportunity to reduce some of the above symptoms. MiFAS emerged from the principles of agroecology, which aim to increase the sustainability and productivity of agriculture while maintaining the environment (Francis et al., 2003; Kremen & Miles, 2012). These systems seek to do so by incorporating scientific concepts from the disciplines of agronomy, ecology, sociology, and economics (Dalgaard et al., 2003; Gliessman, 2007). A MiFAS can be described as a farming system that integrates different farming and agroforestry enterprises (Figure 1), wherein the multitude of processes and interactions between enterprises “create opportunities for synergistic resource transfers” over space and time dimensions (Martin et al., 2016). MiFAS create synergies such that resources are more effectively utilised fostering more stable profits through diversification (Kirkegaard et al., 2014) and better environmental and ecological stewardship (Moraine et al., 2014; Ryschawy et al., 2012; Soussana & Lemaire, 2014). MiFAS have yielded promising results with respect to socio-economic (Bell et al., 2014; Darnhofer, Bellon, et al., 2010; Havet et al., 2014; Peyraud et al., 2014; Wilkins, 2008) and environmental sustainability indicators (Duru et al., 2015; Hendrickson et al., 2008; Horlings & Marsden, 2011; Kremen & Miles, 2012; Power, 2010; Russelle et al., 2007; Ryschawy et al., 2012).

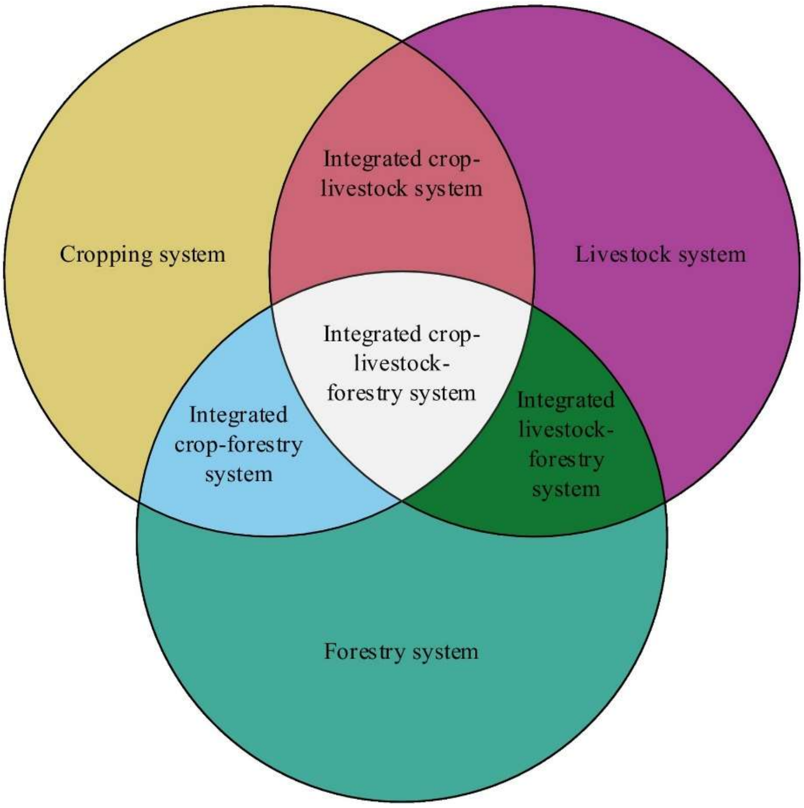

Figure 1. Diagram depicting the different combinations of MiFAS (Taken from Low et al., 2023)

However, research explicitly addressing the value chain implications of employing MiFAS is missing, leading to uncertainty about MiFAS viability in the wider food production environment. This literature gap needs to be addressed to meet the following two issues. The limited value chain research is particularly anecdotal because it is disparate across different socio-economic regions, production systems and ecosystem processes, disciplines, and study designs. In a second issue, existing research has conceptualised MiFAS by fusing biological, agroecological, and – to an extent – economic processes with spatial, temporal, and organisational integration between farming enterprises (Martin et al., 2016; Moraine et al., 2014). While these can be sufficient for the farm-level, MiFAS have not been conceptualised to associate them with upstream and downstream value chains actors. To meet the literature gap, this review therefore has two main objectives: 1) to assess the potential value chain implications of MiFAS; and 2) to operationalise MiFAS configurations in order to facilitate the systematic and quantitative study of MiFAS integration in value chains.

2.1.2 Mixed farming and agroforestry value chains

The value chain is the chain of activities performed by an actor each of which adds value to a product (Porter, 1998). These value-added activities represent the different processes that allow the value chain actor to create more value (whereas the supply chain concerns mainly the movements of products). In a MiFAS for instance, a farm may lower its operating costs by reducing the use of inputs such as agrochemicals and replacing them with lower cost inputs or alternative processes (e.g., no-till, manure-spreading), allowing it to improve profit margins (Garrett et al., 2017; Peyraud et al., 2014). Moreover, a farm could improve the qualities of its outputs by utilising more environmentally friendly practices that could raise the prices of its outputs and differentiate them from competing products. Total value is created along the so-called “long value chain” (totally incorporating the value chains of multiple actors), and products are sold on from actor to actor until the point of consumption (Nagurney, 2006). As products are sold, economic value is internalised by the selling actor (e.g., as profit), in simple terms reflecting market, and supply and demand forces.

Furthermore, some values are not always internalised, and are known as externalities. These can be negative (e.g., pollution) or positive (e.g., carbon capture). Externalities, the cost of producing negative externalities or the benefits of producing positive externalities are not transmitted or valued economically along the value chain. As such, some processes and activities create value that is not in the form of a tangible output for revenue, particularly if they are ecologically or environmentally driven processes (Power, 2010). Being agroecological farming systems, MiFAS create value for the food production chain which can be more, or less, internalised, i.e., valued by the end consumers, other value chain actors, or public institutions. Such values can be environmental, ecological, or societal. For instance, labels are one such way to internalise externalities by appealing to consumers' willingness to pay them (Flinzberger et al., 2020; Röhrig et al., 2020). For our research, similarly to Gaitán-Cremaschi et al. (2015), we place the MiFAS in the long value chain where it creates and transmits tangible value while acknowledging that through ecosystem services produced it also creates additional externalities (Figure 2).

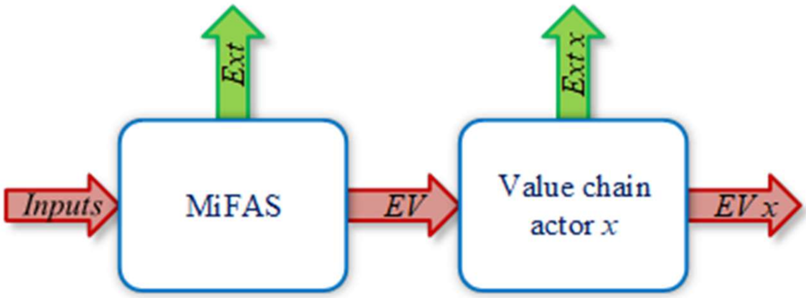

Figure 2. Schematic representation of a MiFAS in the value chain, representing flows of economic value (*EV*) and externalities (*Ext*).

2.2 Methods

2.2.1 Performing the literature search

To select articles that addressed the potential implications of MiFAS on value chains, we followed the PRISMA protocol (http://www.prisma-statement.org/) for performing systematic literature reviews (Moher et al., 2015). We formed a search string using the *Scopus* citation database (https://www.scopus.com) to search for relevant literature studying the value chain impacts of MiFAS. Logically, the search string was split into two sections joined by the AND operator so that articles returned in the search must meet two sets of inclusion criteria.

Keywords and terms in the first set were included to return papers on value or supply chains, farming system design, or which are explicitly review or framework papers. Acknowledging that value chain literature on MiFAS is sparse and our desire to keep a system-wide view (i.e., the whole MiFAS) rather than singular processes we selected broad-reaching keywords for this half of the search. We also specifically chose papers that include the root "compar*" (i.e., to return "comparison", or "comparing") for their breadth of scope.

The second set was comprised of different synonyms and arrangements of MiFAS. These keywords were chosen based on our understanding of the various integrated farming systems encompassing a multiple of farming enterprises; namely arable, livestock, and forestry. We identified these, other synonyms and specific variations of MiFAS from our early scoping of the literature.

Additionally, we specifically chose not to include keywords or terms relating to ecosystem services as much research has already been done about this topic in the service of agroecological farming systems. The valuation of ecosystem services also has its own strand of literature (for example see

Hein et al., 2006; Sagoff, 2011). However, as we have acknowledged earlier (see Section 2.1.2), the nature of MiFAS as an agroecological farming system concerns processes that create societal and environmental value (or negate negative externalities). While not featuring in the search string, we nonetheless allowed in our methods and later thematic analysis (see Section 2.2.2) for the valuation of ecosystem services to emerge in our discussion of the literature, given its importance in the broader discussion of MiFAS value chains. We focused on peer-reviewed papers, namely articles and reviews published in journals indexed in *Scopus* at the time of the publication of this review and written in the English language. *Scopus* is a widely used database for scientific articles and includes articles from a large variety of academic fields and journals.

1st set:

TITLE-ABS-KEY ("supply chain" OR "value chain OR "farm* system design" OR "production chain" OR "upstream" OR "downstream") OR TITLE ("review" OR "framework" OR "compar*") OR KEY ("chain")

2nd set:

TITLE-ABS-KEY ("integrated agriculture" OR "integrated farm*" OR "mixed-farm*" OR "crop-livestock" OR "livestock-crop" OR "dual-purpose" OR "agroforestry" OR "crop-forestry" OR "forestry-crop" OR "livestock-forestry" OR "forestry-livestock" OR "silvopasture" OR "crop-livestock-forestry" OR ("crop" W/2 "forestry" AND "livestock") OR ("crop" W/2 "livestock" AND "forestry") OR ("livestock" W/2 "forestry" AND "crop") OR ("integrat*" W/2 "crop" OR "forestry" OR "livestock"))

First, we performed a screening in order to eliminate duplicate entries and papers indexed on *Scopus* but for which no links to the articles could be found (e.g., .pdf files, journal hyperlinks, etc.) (Figure 3). Following this, all papers were subjected to further screening to scrutinise their content and their relevancy. The three inclusion criteria were: 1) the paper is set in the developed economies of Europe (EU28), Northern America, Australasia, and Eastern Asia (excluding China); 2) the paper has a focus on agricultural and/or food production, or on agricultural supply and/or value chains; and 3) the paper can specify a mixed farming or agroforestry system. These three inclusion criteria were imposed for the retained papers to be topically and contextually relevant to the review. While developing economies present highly relevant and interesting studies on MiFAS (namely Brazil, China, and India), their supply and value chain contexts and the trends facing their agricultural systems offer paradigms too different from those found in the included regions. 80 papers were retained. It was noted during the screening that included papers varied greatly with respect to content, methodology, and relevance to value chain implications.

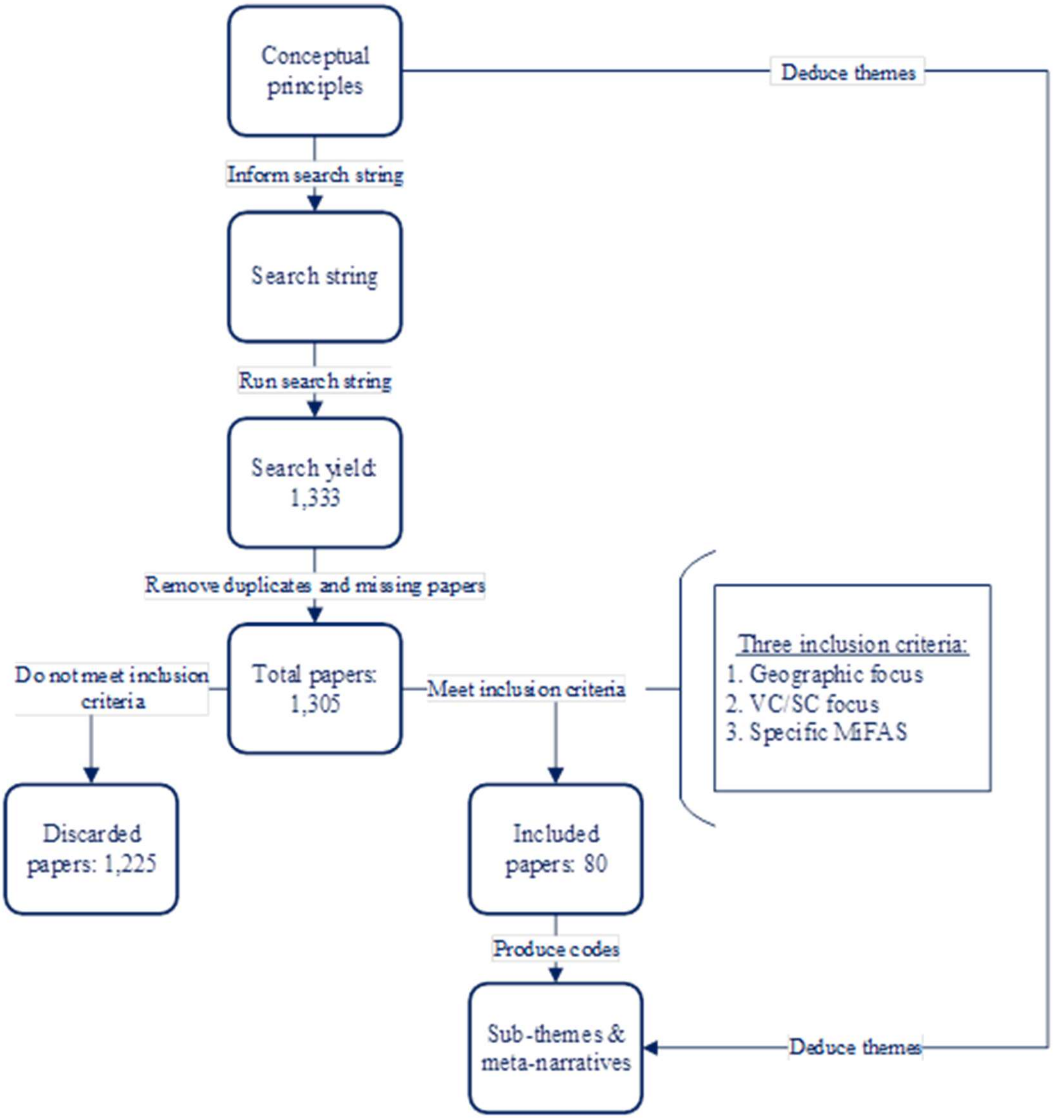

Figure 3. Schematic overview of the method used to perform the literature review, following the PRISMA guidelines.

2.2.2 Methodology for analysing the literature

Thematic analysis is a method for identifying, analysing, and reporting patterns within qualitative data (Snyder, 2019; Ward et al., 2009). Specific approaches and methods for performing a systematic thematic analysis are established in Braun and Clarke (2006) and Thomas and Harden (2008), wherein qualitative codes (describing basic features of data) are generated from text and are then clustered into themes – the units for analysis. According to Braun and Clarke (2006), themes can be identified in two primary ways: through induction (bottom-up) or deduction (top-town). Our review used the deductive approach for the themes, mainly as we are concerned with exploring pre-determined themes. We identified four main themes centred around the creation and transmission of value in MiFAS chains.

The first principal theme was *MiFAS value creation*, centred upon value being created specifically within the farm-level boundary and considering the processes for value creation strictly performed within the MiFAS. Chiefly, these would be the values that are produced because of the integration of the various farming and agroforestry enterprises. The second theme was *Impacts of the farming environment on value creation*. This theme addressed the influencing factors that could influence value creation in the MiFAS, where the farming system must respond to the pressures outside of its control or boundary and which can affect how value is subsequently created by the MiFAS. Thirdly was *Ecosystem services valuation:* this theme addressed the value that is not always immediately internalised through the sale of products from a MiFAS, where the value created and transmitted is often non-tangible, but which could be appraised either economically or socially and/or ecologically. Fourthly and lastly, the theme *Integration in the long value chain* concerned the integration of the MiFAS in the long value chain, where the value created by the farm-level is directly linked with the interactions that the farming system has with both upstream (e.g., for farming inputs) and downstream actors (e.g., buyers of farming outputs).

However, during our reading we identified in three of the four themes (*MiFAS value creation*, *Impacts of the farming environment on value creation*, and *Ecosystem services valuation*) that additional sub-themes are required to allow us to discuss complex sub-issues within themes (Braun & Clarke, 2006). In theme 1, *MiFAS value creation*, we identified the two sub-themes *1a. Farm-level value chain* and *1b. Coordination management*. In theme 2, *Impacts of the farming environment on value creation* we identified three sub-themes: *2a. Biophysical environment*, *2b. Political & institutional environment*, and *2c. Economic environment*. In theme 3, *Ecosystem services valuation*, we identified two sub-themes: *3a. Economic valuation* and *3b. Ecological valuation*. Lastly, theme 4, *Supply & value chain integration* is standalone.

With the themes and sub-themes having been established the qualitative codes could then be produced from the literature. In each paper we noted whether it addressed a specific code. When a code was identified it was marked in an Excel spreadsheet (see online supplementary data), and each code was marked only once regardless of how prominent it was in a specific paper. The codes were categorised under the sub-themes to extract the meta-narratives (see section 2.3.2). The extraction of meta-narratives brings together the storylines within each theme. As MiFAS literature is diverse and specific research on value chains is limited, we produced meta-narratives in order to qualitatively review thematically relevant literature (Snyder, 2019). Meta-narratives are used to tell a compelling and coherent story from the literature while providing concrete evidence and examples from the data to “capture the essence of the point you [*sic*] are demonstrating, without unnecessary complexity” (Braun & Clarke, 2006). Meta-narratives are comparable with meta-analyses, where the latter is typically applied to summarise quantitative empirical literature (DerSimonian & Laird, 1986; Wong et al., 2013).

2.2.3 Conceptualising MiFAS configurations

While analysing the literature, we observed that a common understanding of how MiFAS value chain actors interact with each other is lacking. Therefore, we conceptualised MiFAS value chain configurations informed by what we had observed in the papers being included in our thematic analysis. We were suitably placed to identify how different configurations of MiFAS take shape and believed that an overview of these could help to identify and refer to MiFAS configurations in future research on value chains.

2.3 Results

2.3.1 Descriptive overview of the literature review

Our search yielded 1,333 results (Figure 3). The first screening led to the exclusion of 28 duplicate or missing papers and 80 papers were retained for the thematic analysis. We noted during the screening that the retained papers varied greatly in content, MiFAS types, methodology, and relevance to value chain implications. 62 papers, representing over 77% of the total, were published since 2012 (last 10 years). 50 papers were indexed in *Scopus* as “Article” and 30 as “Review”.

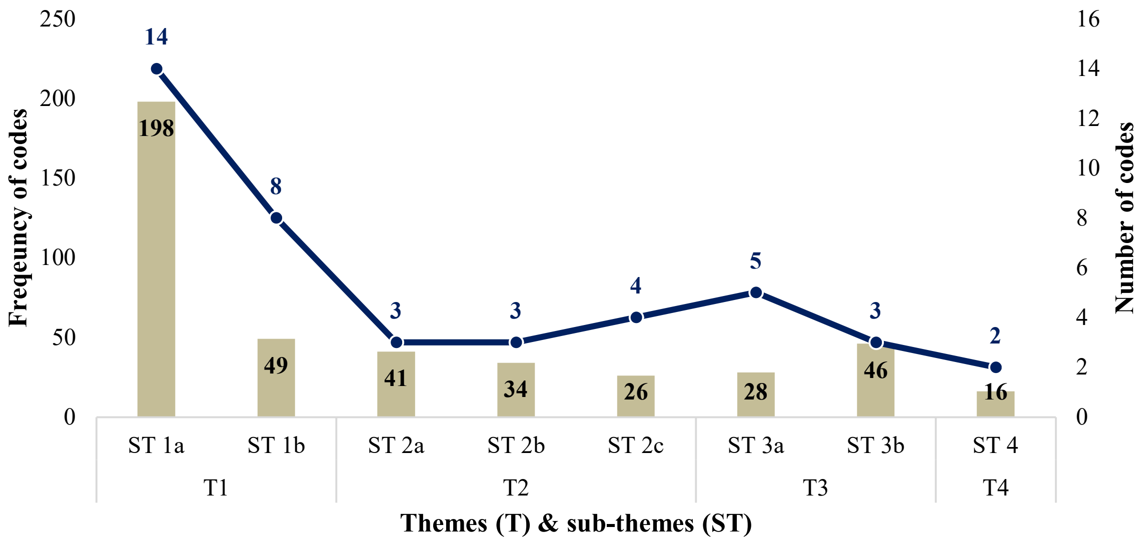

Figure 4. Summary of the results: frequency (represented by columns and the left y axis) and number (represented by the line and the right y axis) of codes by theme (T) and sub-theme (ST). T1 = *MiFAS value creation*, ST 1a = *Farm-level value chain*, ST 1b = *Coordination management*; T2 = *Impacts of the farming environment on value creation*, ST 2a = *Biophysical environment*, ST 2b = *Political & institutional environment*, ST 2c = *Economic environment*; T3 = *Ecosystem services valuation*, ST 3a = *Economic valuation*, ST 3b = *Ecological valuation*; T4 & ST 4 = *Supply & value chain integration*.

We identified 42 distinct codes which we categorised under the four themes (see online supplementary table A1 for the code list). Codes in sub-theme *1a*. *Farm-level value chain* are the most frequently occurring (198 times), while also being the most numerous amongst all sub-themes (14 codes) (Figure 4). On the other hand, theme 4. *Supply & value chain integration* has both the fewest code occurrences and number of codes, at 16 and 2 respectively. In total, the plurality of papers discussed *MiFAS value creation* above all other themes. Codes in sub-theme *3b.* were on average the most frequently cited, meanwhile sub-theme *3a.* had the fewest mean code citations. Even within sub-themes, some codes were particularly prominent, such as code 5: *Ecosystem services in MiFAS decrease variable input usage and costs* (sub-theme *1a*.) and code 39: *Socio-economic value-added motivates MiFAS* (sub-theme *3a*.), suggesting that some research is niched along specific discussion points. It is evident that some sub-themes represent significant research fields, while others are less explored – namely concerning farm business economics and the value chain. We can also see (in online supplementary data) that some papers address specific sub-themes. For example, the paper by Flinzberger et al. (2020) is particularly concerned with product labelling in agroforestry landscapes and makes significant contributions to the meta-narrative of sub-theme *3a*. Other papers, particularly reviews, often transect (sub-)themes. Therefore, it is important to consider the impact that individual papers had on the meta-narratives.

2.3.2 Themes & meta-narratives

2.3.2.1 MiFAS value creation

Sub-theme 1a. Farm-level value chain

Sub-theme *1a. Farm-level value chain* emerged as a distinct sub-theme as its primary focus was on the processes performed strictly through the integration and interconnectedness of farming enterprises within the so-called “farming boundary”; i.e., farming activities. This entails value being produced through the integration of production of the various farming and agroforestry enterprises over time and space dimensions.

It was found that integrating farming enterprises tends to improve yields and land-use efficiency and can reduce variable costs. Namely, most of these benefits are tied directly to the provision of ecosystem services, which decrease the need for synthetic inputs such as fertilisers and pesticides (being replaced instead by biological processes) and therefore can reduce variable costs, and can improve yields particularly by allowing for synergistic and continuous production cycles that allow land to be used more optimally and mobilise greater biological activity. Several papers suggest that the land equivalent ratios of MiFAS are the same or exceed those of specialised systems. Graves et al. (2007) modelled land equivalent ratios in European integrated crop-forestry systems, and found them to be between 1 – 1.4, indicating that, under typical management, integrating crops and trees on the same land is more productive. Furthermore, the functions of ecosystem services are reinforced by time and a greater diversity of biological processes in the farming system up to and including pest and weed suppression (Malézieux et al., 2009) and enhanced soil fertility (Tsonkova et al., 2012). Therefore, as ecosystem services are continually provisioned within the farming system the greater the purported production benefits. As such, the benefits should be evaluated in the middle or long term as systems and processes require time to mature.

However, increases in yields and efficiency can be withheld by constraints. Firstly, land may be used more effectively, but only up to the point where it is not being used competitively amongst farming activities. For ecosystem services to materialise into production benefits, diversification should lead to synergies. In such cases, poor management of MiFAS can undo benefits. For example, tree shade in agroforestry is an important management consideration when integrating them with crops (Tsonkova et al., 2012) and livestock (Anderson & Batini, 1984). Additionally, animal droppings may not be evenly distributed across pastures in crop-livestock rotations overloading some areas while leaving others deficient (Sekaran et al., 2021). Secondly, while variable costs can be reduced, MiFAS also seem to face significant challenges with respect to fixed costs, such as of capital investments, and of labour. Diversified holdings tend to require more farming infrastructure and machinery and of labour (likely exceeding what can be available on a family farm, for instance); as such MiFAS may also be harder to upscale due to these cost constraints. Correspondingly, the high opportunity costs associated with MiFAS can also be a drawback for farms seeking to become more integrated as limited knowledge and the time to establish profitable MiFAS can deter adoption. Marton et al. (2016) suggest that specialised crop farms have higher yields than mixed crop-livestock farms leading to higher phosphorous use efficiency (while crop-livestock farms were more nitrogen and potassium efficient), and that this could be attributed to better crop management practices: a crop-livestock farmer needs to be a generalist with knowledge about cropping and livestock, while a specialised farmer needs to only focus on one activity.

While the effects of integration on costs seem mixed, MiFAS present a greater degree of flexibility against production risks and can perform better than specialised systems under adversity, such as by providing income stability as diversification can spread revenue streams (Garrett et al., 2017). Ecosystem functions also seem to play a reinforcing role in increasing resilience capacities and the longer a farm remains integrated and diversified, the more such a farm can manage its resilience to adverse conditions (Peterson et al., 2020; Thiessen Martens et al., 2015).

In essence, sources of value creation within a MiFAS stem from its ability to reduce variable costs as well as maintain if not raise outputs, primarily by improving the efficiency that resources such as nutrients and land are utilised. However, value creation in a MiFAS is stymied by the high cost to work an integrated system in terms of working and human capital. Although MiFAS requires a great investment, the specific advantages of MiFAS versus specialised or less integrated/diversified farming systems may manifest in their ability to be more resilient under adverse conditions and over longer periods of time. Rather than assessing the added value of MiFAS in the short term, the benefits of MiFAS may need a more nuanced, longer-term perspective and assessment.

Sub-theme 1b. Coordination management

Distinctly from *Farm-level value chain*, this sub-theme emerged to address the importance of a third dimension of integration: coordination management (recalling that integration also takes place over space and time dimensions, see Section 2.2.1). Particularly, the management of integrative processes was identified as a key driver for their intensity and scale; where the management capabilities, capacities, and desires of farmers may affect the degree to which the farming system is integrative. Additionally, this allowed us to interpret a MiFAS farming boundary as one that can also enclose multiple interconnected farm businesses, including functionally specialised farms.

It was found that increased coordination between farmers is highly desirable, as it implicitly allows for greater integration between the enterprises themselves. In so doing, coordination between farm managers enables the provision of more ecosystem services (Martin et al., 2016; Moraine et al., 2017), which as mentioned earlier has a positive knock-on effect on production synergy, while additionally enabling internal markets and supply chains to form allowing farms to improve value creation and retention (Röhrig et al., 2020) potentially increasing the farming system's ability to negotiate with downstream actors. Internal markets themselves can also be partly facilitated through the standardisation of production (Moraine et al., 2014; Ryschawy et al., 2019). With closer integration, value may also be added into the MiFAS boundary by reducing costs of labour and opportunity costs of knowledge through the pooling of resources (Moraine et al., 2014; Peyraud et al., 2014), while simultaneously permitting greater risk sharing and flexibility against adversity.

However, increased coordination and integration between farms has been found to be difficult, as synergising processes and operations over time and space requires extensive management from involved parties (Alary et al., 2019; Hilimire, 2011; Martin et al., 2016; Ryschawy et al., 2019); differences in management styles, planning, risk attitudes, conflicting interests, and reduced individual ownership of processes only become more exacerbated as the prerequisites (such as trust) and costs for closer integration increase. For example, (Moraine et al., 2016) describe how, by engaging with each other through cooperative structures, farmers may lose control over the management and governance of their activities.

By expanding the definition for what a MiFAS boundary may encompass, i.e., multiple farm businesses, we could identify that coordination between farms has the potential to multiply the benefits of integration at the farm-level, such as by increasing the provision of ecosystem services and reducing operating costs. Furthermore, it may also enable farms with different specialisations to engage with one another and make use of comparative advantages, such as in knowledge and capital. Internal markets and supply chains facilitate trade and exchange of by-products and resources such as land. Significantly, this may also enable farms to increase the territory upon which integrative operations take place for instance, expanding the useable area for farming rotations. However, the high management cost of coordination hinders the adoption of more integrative practices between farming enterprises; interpersonal challenges may not necessarily be overcome by economic arguments alone. It may suffice that integrating practices may be kept to an acceptable maximum while the source of value-added comes from the system's interactions with downstream value chain actors.

2.3.2.2 Impacts of the farming environment on value creation

Sub-theme 2a. Biophysical environment

Darnhofer et al. (2010) indicated that the behaviour of farming systems is nested within three main domains: the ecological (for our sake named biophysical); policies and social norms (political and institutional); and economic. We purposed these domains as broadly concerned with factors that can influence value creation in a MiFAS, where the farming system must respond to pressures outside of its control or boundary and which can affect how value is subsequently created by the MiFAS.

Sub-theme *2a. Biophysical environment* identified three codes. Agroclimatic conditions such as weather and geography may constrain the kinds of ecosystem services produced and forms of integration. In the high rainfall zone of southern Australia, (Nie et al., 2016) describe that in drought events crop-pasture intercropping (rotating cropping and livestock) may exacerbate grain yield penalties as a result of competition for above- and below-ground resources, while stubble grazing by livestock may reduce soil cover essential for moisture retention and organic matter recycling. It should be noted that in Nie et al. (2016), yields can be improved under normal growing conditions. On the other extreme, Alary et al. (2019) describe that if climatic and growing conditions are ideal for specific agricultural productions, lower-value productions are pushed towards more marginal and less productive lands enforcing agricultural specialisation in regions. For example, in southern France, areas suitable for high-value permacultures (such as vineyards and orchards) tend to exclude livestock (Alary et al., 2019). As such, growing conditions may cause the dislocation and disassociation of farming enterprises and limit integration.

On the upside, MiFAS may nonetheless take better advantage of marginal agricultural lands, where the provision of ecosystem services may enhance the suitability and profitability of farming enterprises. In New Zealand, the integration of trees (including for timber) in pasturelands on North Island alleviates issues of soil erosion arising from difficult topography, high rainfall and highly erodible soils, enabling farmers to maintain productive systems in lands sometimes even too steep for livestock systems alone (Cubbage et al., 2012). The adoption of silvopasture and silvoarable systems in areas exhibiting high temperature and humidity conditions such as in the southern United States can both improve the productivity and wellbeing of livestock and reduce the severity of crop-losses due to drought and flooding, respectively (Cubbage et al., 2012). By extension, as climate and weather risks become more frequent and severe due to the onset of climate change, some MiFAS have also been shown to be more resilient. Integrated livestock-forestry systems such as the *montado* or *dehesa* in Iberia are less prone to the risk of wildfires as a result of managed grazing of combustible materials while also providing shade to animals (Aguilera et al., 2020; Ortega et al., 2012). Increased dryland soil salinity in Australia forced on by land-use change and land and water degradation could be offset by productive agroforestry (George et al., 2012).

We found that the biophysical environment plays a particularly important role in determining the kinds and amount of ecosystem services produced by a MiFAS. While it is found that some integrations or MiFAS are not necessarily optimal under specific environmental conditions, or when such a situation arises where the value of ecosystem services are not greater (in terms perhaps of economic returns) than employing specialised systems, MiFAS may nonetheless be better suited to utilise marginal lands where high-value production is limited. In cases where the provision of ecosystem services through integration improves the productivity and resilience of farming systems over specialised systems, a MiFAS may be able to create more value-added, particularly over longer periods of time where changes to weather patterns are concerned. This could open the possibility for repurposing land that has otherwise been abandoned due to environmental and geophysical challenges with relatively higher value-added productions.

Sub-theme 2b. Political & institutional environment

Under sub-theme *2b. Political & institutional environment*, we identified that significant barriers exist for the adoption or practice of MiFAS. We find that policy has a tendency towards disincentivising MiFAS. In California, for example, the *Leafy Green Marketing Agreement* regulation requires the passing of one year between the application of raw manure and the planting of leafy greens, effectively forcing farmers to separate crops from livestock in order to comply. While meeting the regulation is voluntary, downstream buyers may identify produce coming from integrated crop-livestock systems as hazardous due to potential food contamination (Hilimire, 2011). In another case, Reeg, (2011) describes that farmers in Germany may be uncertain about future policy changes that affect long-term land usage such as the planting of trees. Barriers can emerge from a lack of subsidies, support or awareness of the ecological and societal value that MiFAS may have; in the EU, for example, there is a distinct lack of subsidies or support schemes integrated in the Common Agricultural Policy for MiFAS, affecting economic profitability, causing land-use polarisation, and harming the integrity of existing integrated systems (Flinzberger et al., 2020; Havet et al., 2014). All the while, agricultural policies in developed regions (such as in Europe) have historically focused on increasing productivity, increasing health safety and standardising agricultural production. In recent years awareness for the impacts that agriculture has on the environment has led to a gradual shift in policy objectives (Graves et al., 2007). Farmers increasingly need to comply with environmental regulations or are incentivised to take agro-environmental measures to address the negative impacts of agriculture (such as in the EU's Common Agricultural Policy), though they largely remain beholden to regional and international markets for economic viability (Duru & Therond, 2015). As a result of weak policy, few farmers are incentivised to either transition to or maintain MiFAS, and this has the knock-on effect of reinforcing the specialisation of farming systems, leading to an institutional lock-in effect of both management skill specialisation and supply chain specialisation (Duru & Therond, 2015; Garrett et al., 2017).

Sub-theme 2c. Economic environment

In this sub-theme, the most significant issue identified centred around the high cost of labour, which more significantly affects farming systems that perform labour intensive activities such as those involved in integrated farming. Labour requirements to perform integrated farming tend to increase or become more intense, offsetting cost reductions. Exacerbating this issue is the lack of social capital in farming regions in the form of rural abandonment (Martin et al., 2016) and the lack of generational succession (Ryschawy et al., 2014), leading to labour shortages that could severely affect MiFAS. For instance, an evaluation of crop-livestock systems in the United States suggested that labour requirements increased by 59% and 232% when alfalfa and livestock are introduced to farming systems, respectively, while at the same time an aging and diminishing rural population makes labour intensive work less sustainable (Hendrickson, 2020), forcing systems to specialise (requiring less labour and capital). In other regions, such as in the Mediterranean, high costs and low profitability of extensive livestock systems have further led to rural abandonment and intensification, at the expense of extensive crop-livestock and agroforestry systems that require both ecological diversity and knowledge capital (Aguilera et al., 2020). However, in being more diversified, MiFAS can nonetheless be more resilient against market and price risks such as price volatility for inputs and outputs; the former due to being less dependent on external inputs, and the latter due to diversification (Malézieux et al., 2009; Monge et al., 2016).

It emerged that specialised farming systems tended to be both more affordable and straightforward than MiFAS, being less dependent on increasingly limited socio-economic capital of agricultural regions. While market and price risks may be reduced in MiFAS, a significant limiting factor surrounding the viability of MiFAS seemed to concern how well they can be integrated in farming regions where broader socio-economic trends are pushing towards specialisation. Interestingly, the literature has suggested that social vulnerability, for instance in rural job security, could proxy a farming system's ability to cope socio-economically to adverse conditions (Sneessens et al., 2019); while labour demands may increase in MiFAS, such farming systems that require more fulfilling and permanent employment could alleviate trends in depopulating rural areas.

2.3.2.3 Ecosystem services valuation

Sub-theme 3a. Economic valuation

Sub-theme *3a. Economic valuation* emerged as the first of two sub-themes on ecosystem services valuation. We recognised that value is not always immediately internalised through the sale of MiFAS products where value created and transmitted is sometimes intangible, but which could be appraised in the value chain. In this regard, the literature has highlighted labelling as a positive recourse towards capturing more value within the MiFAS boundary, as labelling outputs that are produced using ecosystem services increases consumers' perceived value. For instance, labelling and certification schemes permit quality assurance to consumers (Röhrig et al., 2020). Additionally, labelling outputs from regions traditionally employing MiFAS, such as with geographic indicators, may also support their conservation by increasing value-added and alleviating issues of land abandonment and intensification (Flinzberger et al., 2020). Labels may also support the establishment of internal markets that can strengthen the cohesion and social interactions of integrated farmers (Moraine et al., 2014). Important social implications may positively value MiFAS, such as enhanced landscape beauty and wildlife diversity that can foster tourism, recreation and hunting activities (Le Houérou, 1993); arising cultural functions and employment opportunities add further value to the system (Lovell et al., 2010).

Barriers against labelling exist, however. Firstly, labelling and certification standards are simply lacking. This can be due in part to the costs of producing, implementing, and marketing a label being too expensive, all the while market infrastructure and consumer awareness of the value-added of MiFAS products are negligible. Implicit in the labelling process requires a substantial degree of coordination and compliance between MiFAS, in order to both market outputs and reduce costs. Cooperative structures and collectively processing primary outputs into added-value secondary products allow farmers to take greater ownership of their value chain and capture more value. It was suggested in Röhrig et al. (2020) that small scale, direct marketing of MiFAS products could both overcome marketing and labelling costs by appealing to consumers' beliefs of nutritional and physical characteristics of products, taste, origin, animal welfare and environmental stewardship.

Sub-theme 3b. Ecological valuation

Ecosystem services may alternatively create ecological value that is not appraised in the value chain and instead produce externalities that are nonetheless consumed in some fashion. Valuing the ecological externalities produced from ecosystem services should have for an objective to make producing positive externalities more equitable. Conservationism seems to be motivator for implementing and supporting MiFAS, as such systems are dependent and interlinked with the local socio-ecologies that they are situated in (Pavlidis & Tsihrintzis, 2018), such as the *montado* system that has played an important historic role in the Portuguese agricultural landscape (Flinzberger et al., 2020). Beneficiaries of the impacts of the ecosystem services produced by MiFAS (such as in reducing negative externalities and creating positive externalities) tend to be both the farmer and the public domain. The farmer may benefit from ecosystem services by increasing their resilience and reducing natural and ecological risks (such as against weather shocks, fire incidence or disease outbreaks). The public domain broadly benefits from better agricultural practices that may limit environmental and ecological degradation, for example (Alary et al., 2019; Campos et al., 2020). However, the need to form mechanisms to support the provision of these ecosystem services must come through better evaluating the true cost of producing them. Subsidies or environmental credit schemes may help to promote MiFAS, as would appraising the intermediate processes that produce inputs to be consumed during the production process of primary outputs; for instance, inputs that would otherwise be considered without value such as by-products or waste (e.g., rotten fruit or overgrowth that can be eaten by livestock) (Campos et al., 2020).

2.3.2.4 Supply & value chain integration

This standalone theme concerns the integration of MiFAS in the long value chain, where the value created by the farm-level is directly linked with the interactions the farming system has with both upstream actors (e.g., for farming inputs) and downstream actors (e.g., buyers of farming outputs). It was found that weak supply and production chain integration and influence reduces that amount of value captured by MiFAS. For example, farms participating in long supply chains in globalised markets need to concentrate and specialise production in order to be competitive (Moraine et al., 2014). Farms that are diversified and reduce their use of external inputs also participate less in their procurement from the market (taking less advantage of economy of scale, though in return potentially making up for it in economy of scope) (Havet et al., 2014). Even integration at a territorial level may present additional challenges in the form of additional transportation and logistical costs and need for increased management and organisation (Garrett et al., 2017; Moraine et al., 2014) where physical infrastructure and distance may impede some territorial MiFAS. Shortening the supply chain and long value chain in order to reach sellers of inputs and buyer of outputs may help to alleviate some stresses. The local procurement of inputs can reduce logistical costs, where closer integration between farmers may lead to Coasean agreements that extend value captured within MiFAS boundaries (Havet et al., 2014; Röhrig et al., 2020). Likewise, direct marketing, voluntary price signalling, and on-site processing may increase the perceived value of products and place farmers in MiFAS closer to the final consumers of their products, reducing how much value is passed to intermediary value chain actors and enabling farmers to capture more value-added (Alam et al., 2014; Röhrig et al., 2020). For instance, once farmers are able to communicate directly with consumers or through local sales channels about their products and product qualities, consumers are more receptive to ecosystem services in product value (Lovell et al., 2010; Röhrig et al., 2020).

2.3.3 Mixed farming and agroforestry system configurations

While the meta-narratives were being produced, we understood that there was a lack of a framework available for the study of MiFAS, particularly with respect to how value is created. All the while, the literature tended to focus on the merits of specific interspecies interactions or processes, and rarely with the viewpoint of value creation by the farming system. In the process of producing the meta-narratives, we became increasingly informed of the means by which value is created within the MiFAS boundary (i.e., *MiFAS value creation*); how different external factors can influence value creation in the MiFAS (i.e., *Impacts of the farming environment on value creation*); how the externalities created by a MiFAS are or could potentially be appraised in the long value chain (i.e., *Ecosystem services valuation*), and; how MiFAS are integrated in wider supply and value chains (i.e., *Supply & value chain integration*).

As a result, we propose the following Figures 5A-5E. as baseline MiFAS configurations. We hypothesise that each configuration creates, captures and transmits value differently. Each configuration is designed such that a researcher may more concretely describe the following: the value-added processes performed within the MiFAS boundary; and the placement of and connections between value chain actors both within the boundary and without. The configurations themselves are universal, not focusing on the individual arrangements of species or processes but instead on the characteristics and standards of the systems they represent. Integration between farming enterprises is referred to in these configurations as “interconnectedness” in order to encapsulate synergies as well as drawbacks.

Each configuration is represented by a MiFAS boundary that encloses the sum of all the operations that take place by the actors directly involved and managing the interconnectivity of farming enterprises. These actors are principally the farmers and the beneficiaries of the MiFAS. The economic value created within the MiFAS boundary is the sum of the value of outputs leaving the boundary (revenue) less the sum of the value of inputs entering the boundary (costs). From Porter (1998), this difference encapsulates the primary activities performed by the boundary: inbound logistics, operations, outbound logistics, marketing and sales, and service; and the secondary activities: firm infrastructure, human resource management, technology development, and procurement. As such, value created and captured in the MiFAS boundary is tangible, possessing economic value. In our configurations we also allow for cash subsidies to also factor within the MiFAS boundary. Additionally, the configurations account for value flows of ecosystem services that are internalised including internally consumed ecosystem services, though not externalities (which are not consumed).

In Figure 5A the above is simply represented as a MiFAS boundary that encloses a farming business, a single farm holding. Within this single business the processes of integrating farming enterprises takes place. The value created by the MiFAS is retained within the boundary and – because there is one actor in this boundary – captured by the farm business. Figure 5B includes the addition of another value-added enterprise that is performed by the farm business but which itself is not a farming activity. Such an enterprise can be processing dairy into cheese or fruit into jam, *et cetera* to create refined outputs for later sale. This could also include providing services that create value, such as touristic services. In Figure 5B we denote the implicit connection between the interconnectedness of the farming enterprises and the off-farm enterprises as being vertically integrated, where performing additional non-farming related activities (though directly depending on them) extends the value captured by the system boundary.

In Figure 5C the boundary now encloses two or more specialised farming businesses where the interconnectedness between the farming actors makes up the MiFAS boundary. As in the previous configurations the value creation processes from integrating farming enterprises are much the same, though they now transect the landscape or farming territory. In effect, there are multiple value chains existing in the boundary belonging to the various farm businesses; the amount and depth of coordination between them raises the shared value-added. Martin et al. (2016) distinguish four types of spatial, temporal and organisational coordination options between farms: global coexistence, local coexistence, complementarity and synergy. Under global coexistence no coordination takes place between farms and thus the technical and organisational options for farms are market driven. In the remaining three types, increasingly closer coordination instigates additional activities and processes that are performed by farms within the boundary. Figure 5D builds on Figure 5C in that farms within the MiFAS boundary can also integrate their own farming enterprises in addition to cross-farm interconnectedness. This configuration more closely reflects the highly synergised landscapes in Martin et al. (2016).

Finally, Figure 5E reflects a functionally diverse MiFAS boundary comprising of multiple interconnected farms that are also associated with commonly shared vertically integrated enterprises. These may include cooperatives for the acquisition of inputs (as much between farmers in the boundary and from the market) or the sales of outputs, bio-gas collection for fuel or heat, larger-scale processing, and so on. As such, this configuration provisions for internal supply chains within the boundary. This could also include the labelling, certification or standardisation of products originating from MiFAS. In essence, this configuration involves a high degree of vertical and horizontal integration and coordination, and numerous value chains though not without substantial management complexity.

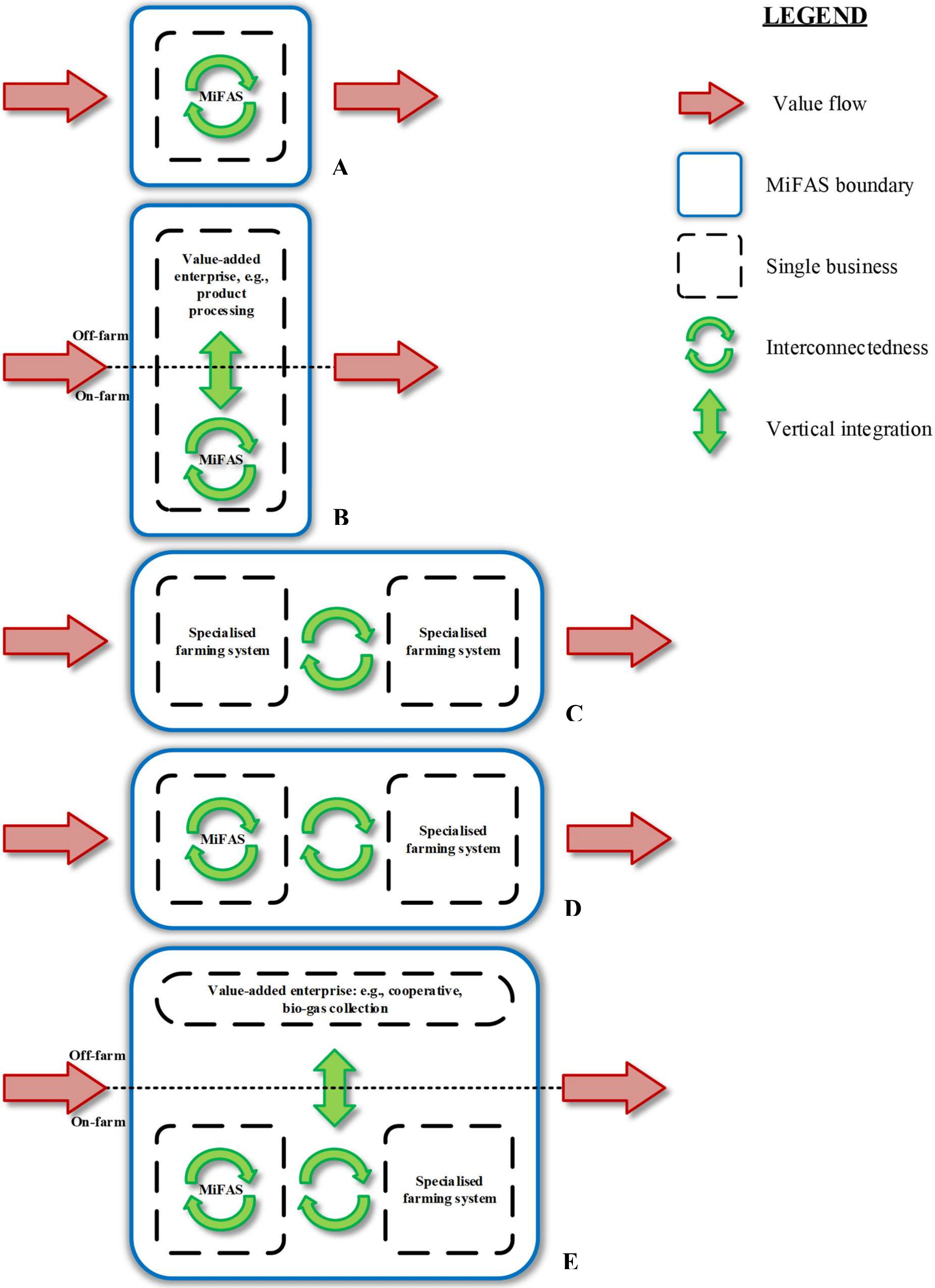

Figure 5. MiFAS configurations. A = Single-farm MiFAS, B = Single-farm integrated MiFAS, C = Multi-farm landscape MiFAS, D = Multi-farm hybrid landscape MiFAS, E = Multi-farm integrated landscape MiFAS

2.4 Value chain implications & conclusions

With this review, we are the first to systematically synthesise the literature to identify the value chain implications of MiFAS. In this process we identified four major themes that each implicate specific aspects of MiFAS value chains. We have looked at how value is created within the farming system as a consequence of farming design and the arrangement of enterprises and actors within the MiFAS boundary. We have raised the impacts that the farming environment have on MiFAS and the triggers that support or disincentivise MiFAS by allowing them to create more or less value than competing farming systems. We have also identified how ecosystem services contribute to value creation in MIFAS and the extent to which they can be internalised by expanding value chain processes. Lastly, we have also seen how MiFAS – being diversified and lacking in economy of scale – struggle to integrate value-added processes in longer supply and value chains.

Broadly speaking, MiFAS present many opportunities for value creation. The interconnectedness resulting from synergising farming enterprises are undeniably vital for value creation, from the provision of ecosystem services reducing dependence on external inputs and promoting greater resilience to production and price risks, to improved land-use efficiency compared to specialised systems particularly in vulnerable and marginal agricultural lands. Collaboration and territorial interconnectedness also amplify these benefits. Additionally, ecosystem services created in MiFAS are the linchpin for socio-ecological services that more broadly contribute towards its sustainability, creating value for the environment and the rural economy.

However, we were alerted to the fact that MiFAS face significant challenges in their value chains. The need for additional capital and labour in a sector already facing tight margins may offset the beneficial cost-cutting from reduced input requirements. All the while higher productivity is not always assured due to resource competition. Furthermore, the opportunity cost of transitioning to MiFAS from specialised systems, ranging from lost efficiency to learning curves, and the need for long-term planning is costly in the short-term. Nor is it favourable when diversified holdings are more intensive to manage. The difficulties to internalise environmental and societal value-added when both policy and market-driven approaches to support them are scant negatively contribute to the economic sustainability of MiFAS. Ongoing rural challenges such as farm succession and abandonment, while similarly impacting all manners of farms, also harm MiFAS and potentially more so due to their greater need for labour.

We find very little concrete evidence that comprehensively evaluates the value chain implications of MiFAS. While this review has incorporated value chain evidence from research across the developed world (and much more can still be attested to beyond the scope of this review), the preeminent focus of research has been on the ecological and environmental effects of integrating farming enterprises, with some implications on farm productivity. Statements on comparative yields and outputs and some costs have contributed to our analysis of MiFAS, but concrete evidence of the implications of these are few. Although we did find research that produced bio-economic models for policy scenario-building (such as in Graves et al., 2007), the literature generally presented little cross-examination of the economic implications of MiFAS, and conclusions lacked external validation. Little economic modelling or empirical analyses were present that could necessarily explain how, how much, and what kind of value is being created by MiFAS and which compared and contrasted results between MiFAS or specialised farming systems. This is particularly egregious as we therefore found limited evidence to support any hypothesis that MiFAS are (or are not) economically sustainable at present.

We take full note that the value chain implications of MiFAS have hardly been studied. To this end, economic research – value chain and otherwise – must now be conducted to systematically and quantitatively assess MiFAS. By operationalising MiFAS to facilitate comparisons on the basis of system design, which, combined with the frameworks for assessing coordination and interconnectedness in MiFAS (Bell & Moore, 2012; Martin et al., 2016; Moraine et al., 2014), we have laid the groundwork for this assessment. Naturally, we expect that the value chains and resilience differences between MiFAS and in contrast to specialised systems should be assessed. For instance, research should focus on how to enhance MiFAS value chains and to more equitably internalise social and ecological services such that it can become more economically sustainable and compete in the wider food production environment. In turn, research should inform better farming strategies and designs, policy recommendations, and market-driven incentives for MiFAS adoption.

In conclusion, many of the issues raised in the introduction could be addressed by MiFAS. MiFAS have the potential to improve yields and land-use efficiency by improving the efficiency of resources such as nutrients and land, and particularly with greater inter-farmer partnerships and collaborations. At the same time, ecosystem services in MiFAS can create greater value for the agroecosystem. In spite of these, economic challenges at the farm-level, such as high opportunity costs to adopt MiFAS and high fixed and labour costs, can reduce the overall benefits of MiFAS. Yet, bridging the gap between fundamentally globalised challenges, pervasive in the agricultural systems of the developed world, and practicably useful MiFAS requires more focus and a concerted effort to assess value chain implications. The reduction of mixed and agroforestry systems in the developed world (for instance in Europe, EUROSTAT, 2022) should serve as an indication that for such systems to prosper, the economic implications of agroecological systems must be considered with the same importance as ecosystem services. We fundamentally stress the importance of continuing to study MiFAS to quantitatively assess value chain implications and produce sound farmer, market, and policy recommendations.

3 The socio-economic consequences of switching from specialised to mixed crop-livestock farming in Europe

A more extensive version of this chapter is currently considered for publication (under review) as:

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3.1 Introduction

The European agricultural landscape is poised for significant changes. In 2019, the European Commission introduced the European Union's (EU) Green Deal to address the sweeping climate and environmental challenges that will likely define the first half of the 21st century. A key component of the Green Deal is the Farm to Fork Strategy which aims to enhance sustainable and resilient farming practices, reduce the environmental footprint of food production, develop a circular economy for resources and reduce wastage, improve productivity, and improve the wellbeing of farms and farmers (European Commission, 2019, 2020).

Agricultural diversification, including mixed crop-livestock farming, has been suggested as a farm-level adaptation (Dalgaard et al., 2003; Francis et al., 2003; Gliessman, 2007; Kremen & Miles, 2012). Mixed crop-livestock farming leverages agroecological synergies arising from the integration of both cropping and livestock practices (Martin et al., 2016). This integration benefits nutrient cycling (Soussana & Lemaire, 2014), pest control (Malézieux et al., 2009), and animal welfare (Cubbage et al., 2012; Röhrig et al., 2020). It also enhances ecosystem services (Alary et al., 2019; Campos et al., 2020; Flinzberger et al., 2020; Pavlidis & Tsihrintzis, 2018), adaptation to marginal lands (Aguilera et al., 2020; Alary et al., 2019; Cubbage et al., 2012; George et al., 2012; Nie et al., 2016; Ortega et al., 2012), and economic diversification (Bell et al., 2014; Garrett et al., 2017; Kirkegaard et al., 2014), thus strengthening farm resilience (Meuwissen et al., 2019). While environmental benefits are better understood, socio-economic impacts of mixed crop-livestock farming remain under-researched (Low et al., 2023).

In this paper, we estimate changes in socio-economic farm-level indicators after farms switch from specialised farming to mixed crop-livestock farming. Mixed crop-livestock farming may potentially enhance, or at least maintain, economic performance (Low et al., 2023). Integrating cropping and livestock farming together tends to improve the relationship between outputs and inputs, resulting in increased yields and reduced variable inputs such as chemical fertilisers and pesticides (Graves et al., 2007; Moraine et al., 2014; Ryschawy et al., 2012). However, the demand for additional labour tends to increase, impacting both labour costs and workload, as was the case in mixed alfalfa and livestock production in the US (Hendrickson, 2020). However, many studies focus on small farm samples, provide qualitative or anecdotal evidence, and lack generalisable insights into the economic implications of mixed crop-livestock farming (Low et al., 2023). This paper aims to quantify the economic consequences of switching to mixed crop-livestock farming at the whole European level.

Our analysis uses 1,124,088 observations from 205,071 farms in the Farm Accountancy Data Network (FADN) from 2004 to 2018 across 28 European countries. We quantify the difference in various socio-economic indicators before and after farms switch from specialised farming types to mixed crop-livestock farming using difference-in-differences. Specifically, we make use of recent methodological advances in difference-in-differences estimation which address the potential biasing effects of differential treatment timing and treatment-effect heterogeneity (Callaway & Sant'Anna, 2021). Motivated by the review of Low et al. (2023) these indicators are unpaid labour hours (i.e., family labour), wages paid, revenues, variable costs, farm net profits, and economic productivity. While we believe that our estimates come close to causal effects, the fact that farmers can actively choose to change their farm type lets us cautiously interpret our results as “socio-economic consequences of a farm type switch from specialised to mixed crop-livestock” and not as causal effects.

Our findings show that farms switching from specialised livestock to mixed crop-livestock face statistically and economically significant lower wages, revenues, costs, profits, and productivity. This is attributed to a downsizing of livestock output and corresponding inputs. Farms switching from specialised cropping to mixed crop-livestock have significantly higher unpaid labour hours. Contrary to the evidence in the literature, switching to mixed crop-livestock farming does not improve profitability nor economic productivity. Moreover, the majority of farms in Europe become mixed crop-livestock due to reducing livestock numbers rather than by adding production activities to a specialised farm. Our results show that such switches are uncommon in the European farming landscape. We thus add a maximally extensive quantitative ex-post perspective on the consequences of switching from specialised to mixed farming to a so far largely qualitative ex-ante literature, which is crucial for an informed policy decision-making process.

In the next section we provide a brief background on mixed crop-livestock farming, followed by the empirical design. This is followed by a description of the FADN data sample and implementation. Subsequently we present our results, particularly in the form of event-plots, which we then discuss and provide concluding remarks on the implications of our research for policy.

3.2 Background

Mixed crop-livestock farming integrates cropping and livestock enterprises to “create opportunities for synergistic resource transfers” (Martin et al., 2016). Mixed crop-livestock farming can fall under agroecological farming principles (Francis et al., 2003; Kremen & Miles, 2012). In a grain-manure exchange, cereals are used to feed local livestock while their manure is used to fertilise the same fields. Thus, both crop and livestock production nominally benefit from local synergies arising from farm diversification to build resilience capacities of farming systems (Meuwissen et al., 2019).Economically, mixed crop-livestock farming is driven by economy of scope, wherein variable input costs are economised via synergies and ecosystem services arising from diversification and integration, thus reducing their consumption, and improving resilience and output qualities (Low et al., 2023). Conversely, specialised systems benefit from economy of scale, lowering variable costs while increasing output (Chavas & Kim, 2007; Chavas, 2008; Dupraz & Vermersch, 1997).

In 2019, the EU introduced the Green Deal and the Farm to Fork Strategy to promote sustainable agricultural practices, resilience against growing environmental and climate challenges, the provision of ecosystem services to reduce the negative impacts of agriculture, and to reduce the use of chemical pesticides and fertilisers (European Commission, 2019, 2020). The 2021 Strategic Plan regulation and the 2023 Common Agricultural Policy (CAP) Strategic Plans offer continued and increased economic support to farmers for boosting environmental sustainability (European Commission, 2021, 2022b). Policies remunerating carbon sequestration via the Common Agricultural Policy or through public or private initiatives would financially reward synergetic mixed crop-livestock practices such as the application of organic fertilisers, integrated crop and grazing rotations, or the addition of permanent crops such as trees on farmland. Improving biodiversity and reducing chemical fertiliser and pesticide applications imposed by mixed crop-livestock farming would also benefit from eco-scheme funding (European Commission, 2020). These developments may provide opportunities for farmers adopting mixed crop-livestock systems (Boix-Fayos & de Vente, 2023).

Mixed crop-livestock farming presents both opportunities and challenges. The review by Garrett et al., (2017) suggests that profitability can increase in mixed crop-livestock farming particularly when labour is affordable and available and total input costs are low. This can be attributed to reductions in variable input use such as of fertilisers and biocides, thereby lowering farm operating costs (Garrett et al., 2017; Malézieux et al., 2009; Moraine et al., 2014; Peyraud et al., 2014; Ryschawy et al., 2012;

Tsonkova et al., 2012). Productivity might also increase (Cubbage et al., 2012; Nie et al., 2016), though diverse integration and management practices within mixed crop-livestock farming result in varying impacts on yields and outputs (Peterson et al., 2020). Increased labour demands, especially for livestock integration, may offset cost savings (Hendrickson, 2020). Additionally, mixed crop-livestock farming reduces economies of scale (Marton et al., 2016) and may burden family labour already facing the challenges of rural abandonment and the lack of farm succession (Martin et al., 2016; Ryschawy et al., 2014). Managing multiple farming enterprises also requires the farmer to be a generalist rather than a specialist, and might perform less well due to the greater complexity of the farming system (de Roest et al., 2018; Kingwell, 2011; Marton et al., 2016).

Profitability alone does not fully capture the impact of switching to mixed crop-livestock farming. Other indicators are relevant for assessing how best to implement policy directives, such as the Farm to Fork Strategy, or to address what may drive farmers towards mixed crop-livestock farming. The diversity of farming systems means that switching to mixed crop-livestock farming may yield different outcomes depending on whether farms are switching from specialised cropping or specialised livestock. We hypothesise that the switch to mixed crop-livestock farming affects: 1) unpaid labour hours; 2) wages; 3) total revenues; 4) crop revenues; 5) livestock revenues; 6) variable costs; 7) profitability; and 8) economic productivity.

3.3 Empirical design

Difference-in-differences is a common research design to evaluate the causal effects of a given treatment, estimating the difference between the change of outcomes before and after a treatment in a treated group versus a control group (Goodman-Bacon, 2021). In its most classic form, there are two periods: the first, in which no group is treated; and a second, in which some individuals are treated (the treated group) and other individuals which are not (the control group). Assuming that both groups follow parallel paths in the pre-treatment period (the parallel-trends assumption), one can estimate the two-group/two-period average treatment effect on the treated (ATT) (Callaway & Sant'Anna, 2021). However, difference-in-differences applications often involve panels consisting of multiple treatment periods and units being treated at different times (Callaway & Sant'Anna, 2021; Goodman-Bacon, 2021; Sun & Abraham, 2021).

This paper will use the framework set by Callaway and Sant'Anna (2021). We are most interested in evaluating the dynamic effects of switching from specialised to mixed crop-livestock farming, namely using the event-study-type aggregation. This seems most intuitive as we have an expectedly substantial amount of heterogeneity in our data and a sufficiently long panel and thus the aggregation options offered by Callaway and Sant'Anna (2021) seem the most attractive to our case. In particular, parallel-trends tests based on group-time ATTs, and plotting event-study-type aggregations, are valid in the presence of dynamic treatment effects.

Forming event-study-type aggregations such as proposed by Callaway and Sant'Anna (2021) and plotting them in event-plots offers a way to (visually) verify whether the parallel-trends assumption plausibly holds in the pre-treatment period of the study (Roth, 2024). If no significant non-parallel trend can be identified in the pre-treatment period, then we may assume that the yet-to-be-treated groups and the never-treated control group follow pre-treatment parallel-trends and that differences identified post-treatment may be causally attributed to the treatment (Huntington-Klein, 2022).

3.4 Data & implementation

3.4.1 Dataset – Farm Accountancy Data Network

Our analysis makes use of the FADN which contains farm accountancy data from across EU Member States and is the foremost dataset for conducting agricultural-economics research in Europe. As a panel dataset, it consists of unique farm IDs, years, and economic variables. The FADN is harmonised across EU Member States and farms. It is representative of the commercial agricultural holdings of the EU, conferring to the dataset important practical use for quantitatively studying the European farming landscape.

Our data sample contains 205,071 farm IDs with observations dating from 2004 to 2018, spread across clearly defined territorial units (NUTS2). In total the dataset comprises 1,124,088 farm-year observations from all 28 EU Member States, including the United Kingdom. Farms may be present for all years in the dataset, though farms can enter and drop out of the dataset throughout the years for no specified cause, making the panel unbalanced. For each farm holding, and each year for as long as they are present in the dataset, we look at several key variables of interest in the FADN's standard results, in Euros (€) or otherwise: unpaid labour (by hours), wages paid, revenues (including crop and livestock revenues separately), variable costs, and farm net profit. We also produce a Bennet-Lowe indicator variable, derived from the standard results of the FADN, representing economic productivity (Ang, 2019). In Table 1, we present some summary statistics of our sample of the FADN. Since we are estimating group-time ATTs using ordinary least squares regression, the estimates are highly sensitive to outliers (e.g., Gujarati & Porter, 2008, pp. 55-60). As such, to reduce the impact of extreme outliers on our estimated group-time ATTs we trim the dataset by observing whether, for any dependent variable, a farm-year observation falls below the lowest 1% or above the highest 99% percentiles. In that case, that observation is dropped from the dataset. This is a standard practice when dealing with outliers in the FADN (e.g., Slijper et al., 2021).

Furthermore, the FADN classifies farm holdings based on their type, characterised by the relative contribution of standard farming outputs to the farm holding's total output. The standard output of an agricultural product is, broadly, the monetary value of the agricultural gross production at farm-gate price (European Commission, 2009). A farm holding is considered specialised if two-thirds of a holding's standard output is one of any output types; a farm is considered mixed when no output exceeds this two-thirds threshold. We use the FADN's definition of a mixed crop-livestock holding, generally: at least one-third of output is from a combination of crop products and at least one-third of output is from a combination of livestock products.

Table 1. Summary statistics by farm-year for the FADN sample

Dependent variable	Min	Max	Median	Mean	Std. dev.
Unpaid labour hours (h)	0	8,168	2,722	2,933	1,504
Wages paid (€)	0	532,375	0	12,154	39,311
Revenues (€)	2,898	2,590,646	62,516	140,174	212,204
Crop revenues (€)	0	1,455,276	23,568	71,350	139,355
Livestock revenues (€)	0	1,323,982	6,552	61,464	136,385
Variable costs (€)	1,487	1,746,223	36,450	88,411	144,308
Farm net profits (€)	-121,928	450,434	18,781	34,419	54,056
Economic productivity (€)	-1,422,194	2,589,631	33,737	78,547	128,747

3.4.2 Implementation

We perform our analyses using STATA16 (StataCorp LLC), using the *csdid* command which implements the aggregated estimators of Callaway and Sant'Anna (Callaway & Sant'Anna, 2021;

Sant'Anna & Zhao, 2020). As we do not include covariates, *csdid* defaults to estimating the group-time ATTs using outcome regression based on ordinary least squares (Callaway & Sant'Anna, 2021; Sant'Anna & Zhao, 2020).

The panel identifier is the farm ID, while the time identifier is the year. We produce the treatment identifier variable by first determining whether a farm holding has switched to mixed crop-livestock farming. Since the FADN's definition for the mixed crop-livestock type is simply a fixed ratio of farm outputs for the year, it does not explain a farm holding's reason for switching. Switches occur when output is affected, be it due to an explicit decision or anticipation to change farming type, or due to relatively low/high levels of output (volume and price) for either crop or livestock products across consecutive years. Thus, we set a conservative condition for a switch to take place. First, prior to switching to the mixed crop-livestock type, at least two consecutive years are required where the farm holding is indicated as being either specialised crop or specialised livestock types. Secondly, upon switching, the farm holding must remain with the mixed crop-livestock type for at least two more consecutive years (i.e., the switch year and a following year). Thirdly, and for consistency, we consider two ways in which farms may switch to the mixed crop-livestock type; either: from specialised cropping to the mixed crop-livestock type, or specialised livestock to the mixed crop-livestock type. This is to broadly assess how different specialisations are affected by a switch to mixed crop-livestock farming. Farms therefore need to be in the dataset for four consecutive years in order to be considered candidates for switching; all other farms that do not switch to mixed crop-livestock farming implicitly become part of the control group.

We produce results depending on the switch from either specialisation type to mixed crop-livestock farming. For each specialisation and each dependent variable we produce group-time ATTs, representing the potential effect of the treatment on the dependent variable by the difference. The various estimated group-time ATTs can then be aggregated to form meaningful and intuitive summaries of the consequences of the treatment; of which we make use of the event-study-type aggregation and their corresponding event-plots below.

As with classic difference-in-differences, the event-plots are split into pre-switch and post-switch periods. If in the pre-treatment periods there is no statistically significant non-parallel trend between the control-group and the yet-to-be-treated treated group, then the pre-treatment parallel-trends assumption holds and causality can be inferred. In the post-treatment periods, we see the consequences of the treatment on the dependent variable. In the plots **A1**-**H2** below the round dots represent the estimated, aggregated effect, while the whiskers represent a 99% confidence interval (CI).

3.4.3 Sensitivity analyses and robustness checks

In addition to producing the aggregated group-time ATTs described above, we also produce further sensitivity analyses and robustness checks to validate the quality of the main results.

With respect to Callaway and Sant'Anna (2021), we adapt the baseline model in several ways. Firstly, we estimate a model with an anticipation horizon to reflect that farmers might anticipate a switch before it takes place. Farms might need time to adjust their operations, and while the treatment is not yet "visible" in the data, the treatment has effectively begun. For this, we initially suggest a model that includes an anticipation horizon of two years. Secondly, we propose an alternative, more conservative switch criterion. For a switch to have taken place, the farm needs to remain as mixed crop-livestock for at least three years instead of two. Thirdly, we estimate the model with only the observations of switchers that have not switched back to specialised farming at any point. Fourthly, we estimate the model by using the not-yet-treated as the control group instead of the never-treated. This is to test the validity of the parallel-trends assumption and to partly alleviate endogeneity concerns.

For further model robustness, we estimate the above using other recently suggested difference-in-differences models that allow for differential timing (Borusyak et al., 2024; de Chaisemartin & D'Haultfœuille, 2023b; Sun & Abraham, 2021). First, we estimate, for the sake of comparison and contrast, a basic dynamic two-way fixed effects model. Beyond this, we estimate several alternative difference-in-differences models that are robust to heterogenous treatment timing. To this end, we additionally estimate models based on Sun and Abraham (2021), de Chaisemartin and D'Haultfœuille (2023b), and Borusyak et al. (2024). It should be noted that Callaway and Sant'Anna (2021) require weaker conditions for the parallel-trends assumption than all the other difference-in-differences estimators described (de Chaisemartin & D'Haultfœuille, 2023a).

3.5 Results

3.5.1 Main results

1,035 specialised cropping farms switched to mixed crop-livestock farming and 4,513 specialised livestock farms switched to mixed crop-livestock farming out of 205,071 farms in our sample of the FADN, representing 0.5% and 2.2% of all farms, respectively. Of the 1,124,088 farm-year observations, 47.30% pertain to specialised cropping farms; 41.65% to specialised livestock farms; and 11.05% as mixed crop-livestock farms.

The main results below are divided by variable and by switch type. Letters **A** to **H** represent the dependent variables: **A**, unpaid labour hours; **B**, wages paid; **C**, cropping revenues; **D**, livestock revenues; **E**, total revenues; **F**, variable costs; **G**, farm net profits; and **H**, economic productivity. Additionally, the results are further divided along the two switch types, from specialised cropping to mixed crop-livestock farming (**1**), and from specialised livestock to mixed crop-livestock farming (**2**).

Plots **A1** to **H1** show the consequences of switching from specialised cropping to mixed crop-livestock farming on the respective variables. For this set of results it is mostly observed that the parallel-trends assumptions hold in the pre-treatment periods since difference between the average treatment effects on the never-treated controls and the average treatment effects on the not-yet-treated do not deviate significantly from 0. Thus, the post-switch consequences can potentially be interpreted causally. However, while we believe that our estimates come close to causal effects, the fact that farmers can actively choose to change their farm type lets us cautiously interpret our results as "socio-economic consequences of a farm type switch from specialised to mixed crop-livestock" and not as causal effects.

Plot **A1**, the consequences of switching from specialised cropping to mixed crop-livestock farming on unpaid labour hours, shows a significantly increased need for labour in the year of the switch itself: 77.59 extra hours relative to the reference year, 99% CI [21.00, 134.17]. By the fourth year after the switch-year, this rises (insignificantly) to 122.29 extra hours relative to the reference year, 99% CI [-8.48, 253.06]. Yet, in absolute terms, this represents only an increase of 1.03-1.05% increase in the average number of unpaid labour hours worked by specialised crop farms.

Plot **C1**, the consequences of switching from specialised cropping to mixed crop-livestock farming on crop revenues, shows a significant decrease in crop revenues in the years immediately following the switch: -€4,497.75 by the second year following the switch-year, 99% CI [-€8,303.07, -€692.43]. By the fourth year after the switch year, crop revenues decrease (insignificantly) by -€4,875.24, 99% CI [-€9,811.73, €61.25]. Conversely, plot **D1**, shows the consequences of switching from specialised cropping to mixed crop-livestock farming on livestock revenues which are significantly higher relative to the reference year for up to five years following the switch, with the greatest extent in the second year of the switch at €8,578.93, 99% CI [€4,943.12, €12,214.73]. While there are some significant kinks away from 0 in the pre-treatment period, the overall trend nonetheless appears horizontal suggesting that the parallel-trends assumption still holds. However, the consequence of switching on total revenues, plot **E1**, is nonetheless insignificant.

Plots **B1**, **F1**, **G1**, and **H1** do not show significant consequences on specialised crop switchers with the other variables of interest: wages paid, variable costs, farm net profits, and economic productivity, respectively.

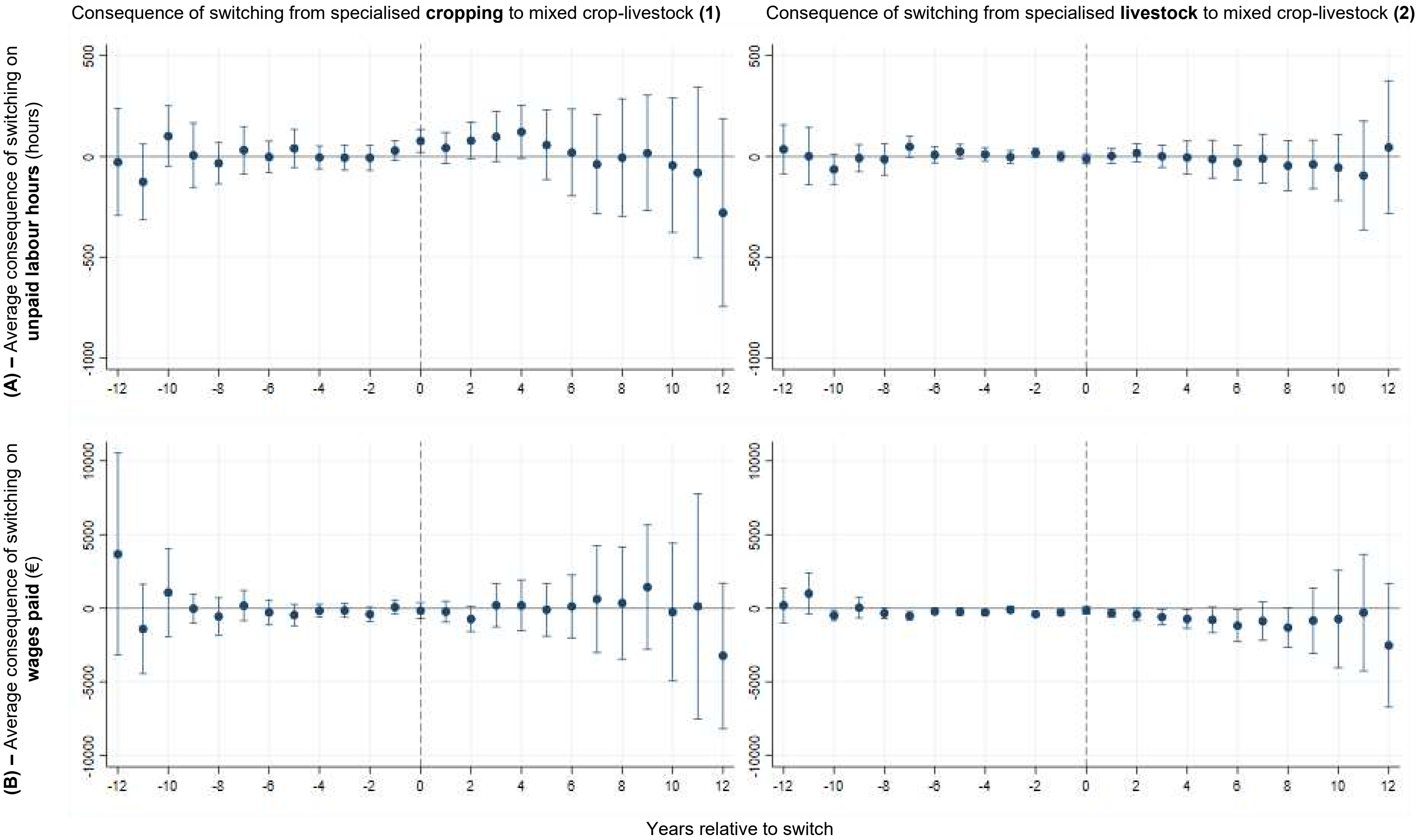
Plots **A2** to **H2** show the consequences of switching from specialised livestock to mixed crop-livestock farming on the respective variables. For this set of results significant deviations from 0 can be observed in the pre-treatment period more frequently. Yet, the extent of these deviations are generally relatively small and the aggregated ATTs form a relatively flat, horizontal trendline with very small CIs. In light of this, while the test for the parallel-trends assumption might not hold in all cases, pre-treatment differences between the treatment and control group are economically negligible.

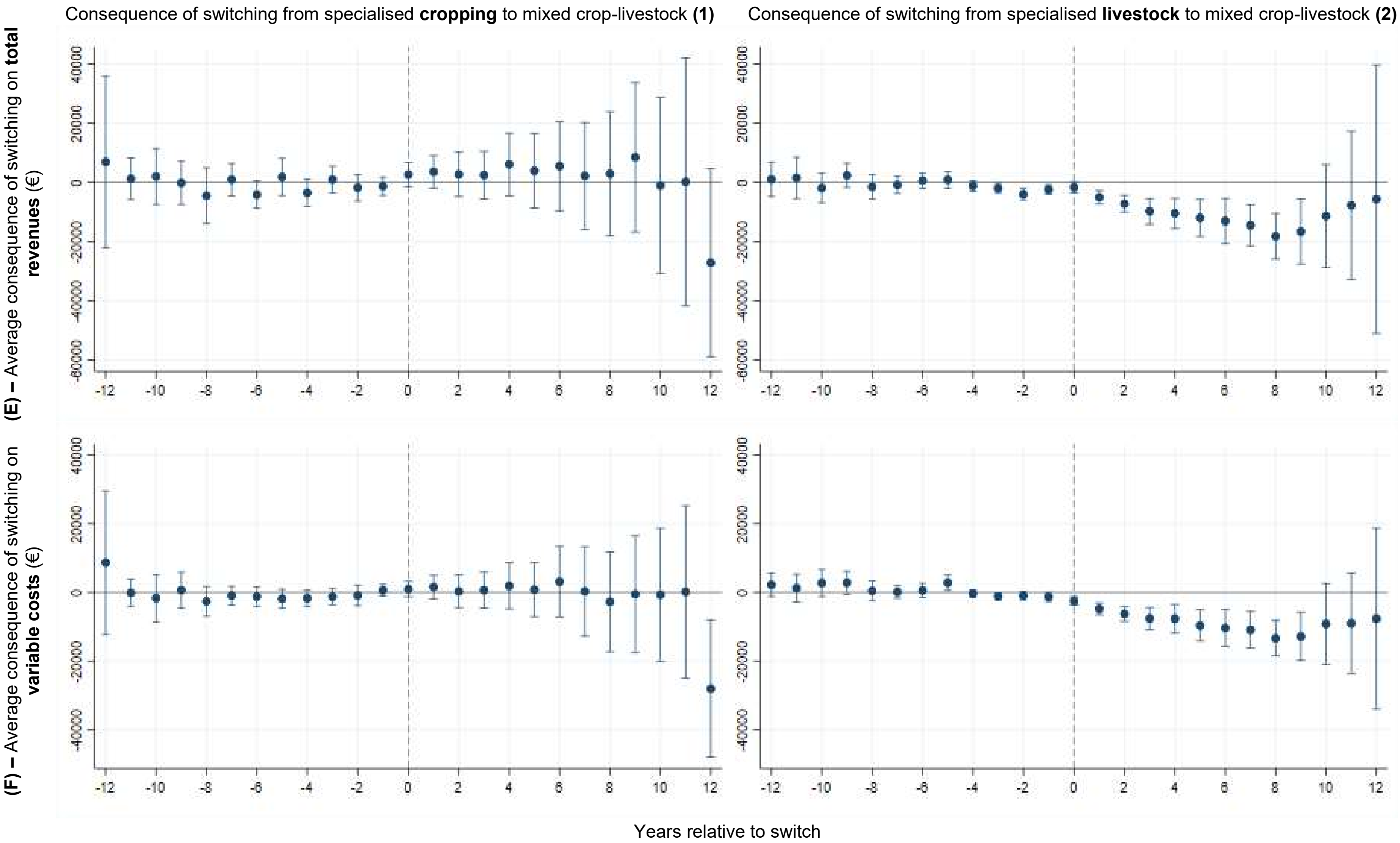
As opposed to plot **A1**, plot **A2** shows no significant consequence of switching from specialised livestock to mixed crop-livestock farming on unpaid labour hours. Plot **B2** shows the consequence of switching from specialised livestock to mixed crop-livestock farming on wages paid. After the switch there is a significant, downward trend seven years following the switch-year, showing a decreased need for paid labour up to -€1,186.08 relative to the reference year, 99% CI [-€2,274.14, -€98.01].

Plots **C2** and **D2** show the consequences of switching from specialised livestock to mixed crop-livestock farming on crop revenues and livestock revenues respectively. Crop revenues show a significant increase for two years immediately after the switch reaching €3,389.70, 99% CI [€1,516.03, €5,263.37] in the second year relative to the reference year. This then tapers off. Livestock revenues, in contrast, decrease into the 11th year following the switch with revenues at -€13,092, 99% CI [-€25,612.42, -€571.57]. In totality, plot **E2** shows the consequence of switching from specialised livestock to mixed crop-livestock farming on total revenues, decreasing for up to 10 years following the switch. The decrease is greatest in the ninth year, at -€18,165.18, 99% CI [-€25,811.76, -€10,518.61].

Plot **F2** shows the consequence of switching from specialised livestock to mixed crop-livestock farming on variable costs. Statistically significant consequences are observed up to ten years following the switch, with the ninth year seeing the greatest decrease of -€13,346.22, 99% CI [-€18,426.27, -€8,266.17].

Plots **G1** and **H1** show the consequence of switching from specialised livestock to mixed crop-livestock farming on farm net profits and economic productivity, respectively. An instant, statistically significant impact is observed in the year of the switch showing a slight increase in profitability of €1,441.96, 99% CI [€235.47, €2,648.46], whereupon the consequence of switching becomes insignificant. The plot for economic productivity shows some more deviations from 0 in the pre-treatment periods, and these are also large in comparison to the consequences post-switch indicating that the parallel-trends assumption is likely violated. With respect to the observed consequences, an instant statistically significant increase in economic productivity is observed in the year of the switch of €3,689.03, 99% CI [€1,850.50, €5,527.56]. Yet, these gains in economic productivity are offset by significant longer-term decreases by the ninth year, reducing economic productivity relative to the reference year by -€6,076.94, 99% CI [-€10,865.87, -€1,288.00]


Consequence of switching from specialised **cropping** to mixed crop-livestock **(1)**
Consequence of switching from specialised **livestock** to mixed crop-livestock **(2)**
(A) – Average consequence of switching on **unpaid labour hours** (hours)
(B) – Average consequence of switching on **wages paid** (€)
Years relative to switch


Consequence of switching from specialised **cropping** to mixed crop-livestock **(1)**
Consequence of switching from specialised **livestock** to mixed crop-livestock **(2)**
(E) – Average consequence of switching on **total revenues** (€)
(F) – Average consequence of switching on **variable costs** (€)
40000
20000
0
-20000
-40000
-60000
-12
-10
-8
-6
-4
-2
0
2
4
6
8
10
12
Years relative to switch

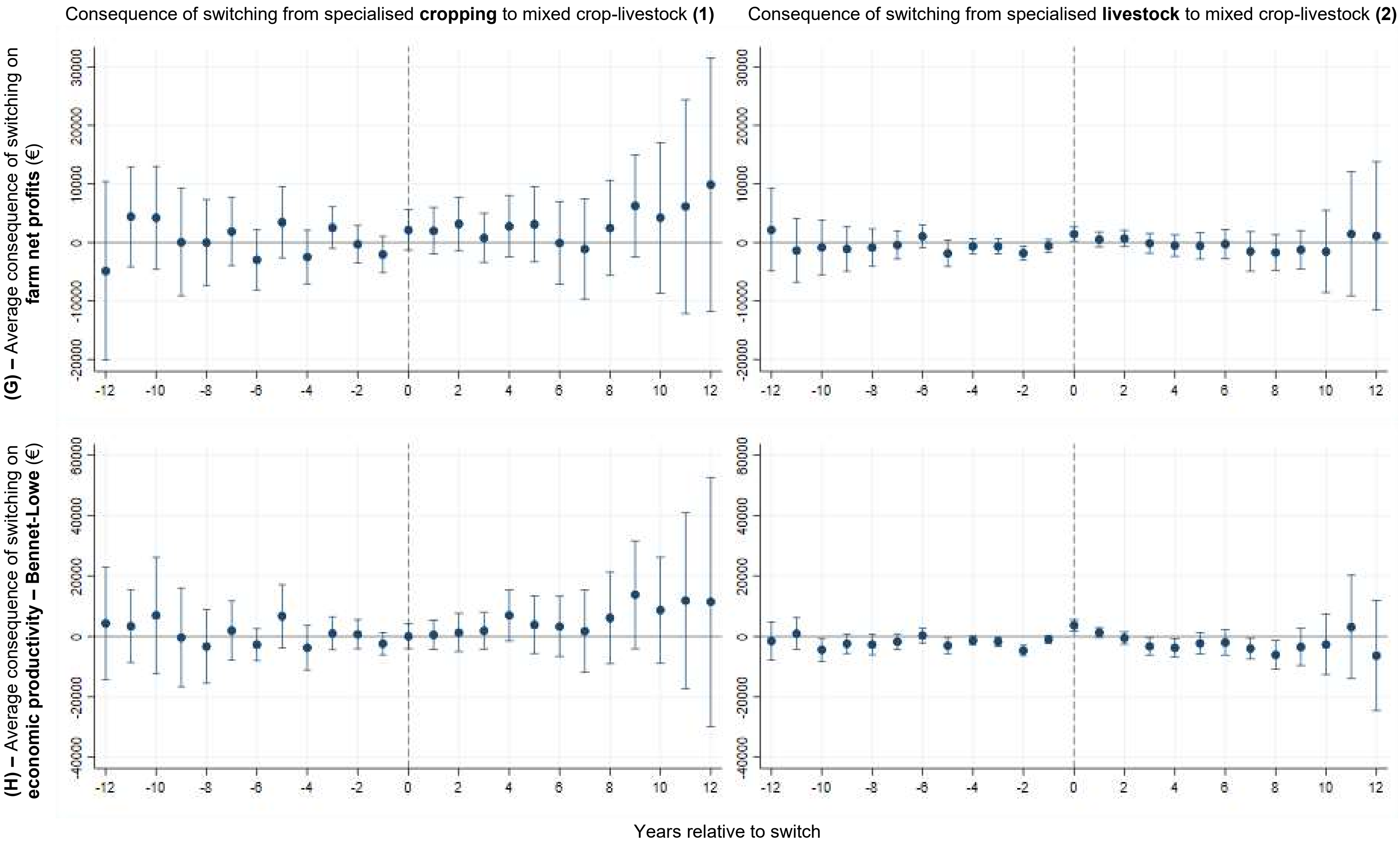

Consequence of switching from specialised **cropping** to mixed crop-livestock **(1)**
Consequence of switching from specialised **livestock** to mixed crop-livestock **(2)**
(G) – Average consequence of switching on **farm net profits** (€)
(H) – Average consequence of switching on **economic productivity – Bennet-Lowe** (€)
30000
20000
10000
0
-10000
-20000
60000
40000
20000
-40000
-12
-10
-8
-6
-4
-2
2
4
6
8
10
12
Years relative to switch

Figure 6. Plots of the event-study-type aggregated average group-time ATTs. Plots A-H by variable of interest: A, unpaid labour hours; B, wages paid; C, crop revenues; D, livestock revenues; E, total revenues; F, variable costs; G, farm net profits; and H, economic productivity; and plots by switch type: specialised cropping to mixed crop-livestock farming (1), and specialised livestock to mixed crop-livestock farming (2). All confidence intervals (CIs) are estimated at the 99% level. Standard errors are clustered by NUTS2 regions (275 clusters).

3.5.2 Sensitivities on the baseline model

Generally, the coefficients of event-study-type aggregated ATTs are highly comparable with the baseline Callaway and Sant'Anna (2021) model and between each other. All combinations of switch type and dependent variable show almost identical pre-switch as well as post-switch trends. Between sensitivity analyses, coefficients and 99% confidence intervals might be slightly different but are otherwise comparatively similar with the baseline model.

3.5.3 Model robustness – more estimation models

The results of the additional estimation models described in section 3.4.3. tend to show somewhat variable results with respect to the baseline model and between them. Between Callaway and Sant'Anna (2021), Borusyak et al. (2024), Sun and Abraham (2021), and de Chaisemartin and D'Haultfœuille (2023b), an important comparison is that post-treatment consequences appear to be relatively similar. However, visual confirmations for pre-switch parallel-trends often show differences between models, with more violations observed with Sun and Abraham (2021) and de Chaisemartin and D'Haultfœuille (2023b) models, which however come with more restrictive parallel-trends assumptions than Callaway and Sant'Anna (2021). Furthermore, the Sun and Abraham (2021) models often show positive differences between switcher farms and the control group in both the pre-switch and post-switch periods. Pre-switch, the Borusyak et al. (2024) models tend to show very large confidence intervals. The two-way fixed effects model most often shows very large confidence intervals that often distort a visual comparison with the other models.

In summary, a comparative assessment of the results of the additional estimation models appears to show post-switch consequences, generally inconclusive as for accepting pre-switch parallel-trends and the consequences of switching to mixed crop-livestock farming on the various dependent variables. All the estimation models estimate 99% confidence intervals with the exception of Sun & Abraham (2021) since there is no option to change the confidence from 95%.

3.6 Discussion

This paper is the first to perform an ex-post analysis of the socio-economic impact of switching from specialised to mixed crop-livestock farming, using a comprehensive dataset of European farms. Unlike prior studies, our analysis covers a wide range of farms of different economic sizes, geographies, and practices across the European farming landscape.

The literature widely suggests that mixed crop-livestock farming reduces variable costs by utilising synergies, such as using local organic fertilisers instead of synthetic fertilisers and integrating grazing into crop rotations for mechanical weeding rather than applying herbicides (Malézieux et al., 2009; Russelle et al., 2007; Ryschawy et al., 2012; Tsonkova et al., 2012; Wilkins, 2008). However, our analysis shows mixed results. For specialised crop switchers variable costs do not decrease at all. On the other hand, specialised livestock farms that switch show significant reductions in variable costs, and are also accompanied by significantly reduced total revenues. This appears to be due to a highly significant reduction of livestock revenue in spite of a small, short-term increase in crop revenues.

Labour requirements are suggested to increase after switching (Hendrickson et al., 2008). Our results confirm this trend, particularly for specialised crop switchers, who absorb additional labour by making use of unpaid family labour, though the amount of extra unpaid labour hours are relatively insignificant with respect to the total number of unpaid labour hours worked. The literature has raised issues about family labour and paid workforce availability and farm succession (Aguilera et al., 2020; Martin et al., 2016; Ryschawy et al., 2014). In contrast, wages paid by specialised livestock switchers decrease significantly, as these farms appear to downsize their livestock operations and rely less on expensive paid labour while unpaid labour stays unaffected by the switch.

Economic productivity, measured by the Bennet-Lowe indicator, remain unchanged for specialised crop switchers, contradicting the literature's expectations that mixed crop-livestock farming would increase productivity through synergies (Bell et al., 2014; Cubbage et al., 2012 Garrett et al., 2017). Profitability is also unaffected. Even if economic productivity were to have remained unaffected on average by the switch, the literature expects that reducing variable costs or improving yield and output would affect farms' profitability, though this also not the case for specialised crop switchers (Garrett et al., 2017; Kirkegaard et al., 2014; Peyraud et al., 2014; Sneessens et al., 2016). For specialised livestock switchers, profitability only increases slightly and temporarily after switching, but long-term economic productivity declines significantly by about 9.07% relative to the average of specialised livestock farms, indicating that downsizing livestock leads to a loss of scale efficiency.

We draw two key evaluations of the consequences of switching on economic performance. First, the only significant consequence for specialised crop switchers is that their labour requirement increases following the switch, significantly fulfilled by unpaid labour. This would parsimoniously suggest that following the switch, specialised crop farms face the need for increased labour for no significant economic gain. That the increase in labour is also unremunerated may further suggest either that crop farms have available labour to fulfil the switch or that the expense of adding more paid labour is too large for farms.

Second, specialised livestock switchers reduce their livestock output which in turn reduces their costs of production. As opposed to specialised livestock switchers adopting new cropping practices to become mixed crop-livestock holdings, it appears that livestock farms draw down the relative output of livestock products with respect to cropping products. Only as a *secondary* consequence specialised livestock switchers achieve mixedness, at least on paper according to the FADN's definition of mixedness. Furthermore, our results suggest that switching from specialised livestock farming leads switchers to become less productive, with no clear trade-off between economies of scale and scope, since it seems that specialised livestock farms do not become mixed crop-livestock farms by integrating cropping activities, intended to reduce costs, but by downsizing total production (Chavas & Kim, 2007; Chavas, 2008). Evidence from France suggests that input-use efficiency varies widely across mixed crop-livestock farms. Mixed crop-livestock farms that optimally synergise cropping and livestock enterprises can achieve more economy of scope than mixed crop-livestock farms which are inefficient. With good extension services, this should imply that any policy support for mixed crop-livestock farms should be contingent on efficient practices, particularly with respect to input use (Minviel & Veysset, 2021; Mosnier et al., 2021 Veysset et al., 2014; Sneessens et al., 2016; de Roest et al., 2018; Martin et al., 2020).

The sensitivity analyses seem to show that adapting the model does not affect the outcome of the discussion. Most interestingly though, neither does using the not-yet-treated as the control. By using a more readily comparable control group, even further mitigating potential simultaneity and omitted variable biases, we still find that the result is almost identical as the baseline model. To this extent, these different sensitivities of the baseline model provide some confidence in the validity of the results. However, the additional estimation models we perform do not wholly support the underlying pre-switch parallel-trends assumptions. All the while, these assumptions tend to be more restrictive than the baseline model (Callaway & Sant'Anna, 2021; de Chaisemartin & D'Haultfœuille, 2023a), and the post-treatment consequences are generally similar. We caution that the parallel-trends assumption might not be assured in the post-switch period, and that a truly causal relationship between the switch and the potential effects on the dependent variables might not be possible. Therefore, we cautiously interpret our results as socio-economic consequences of changing from specialised to mixed crop-livestock farming and interpret changes in key socio-economic figures before and after switching. Yet, we can say, using this extremely large dataset, that the farms that do switch tend to become less productive (i.e., the specialised livestock switchers), and that switching does not conclusively provide the economic benefits described earlier (Low et al., 2023). At best, we have provided a unique, first-attempt at establishing an ex-post correlational relationship between switching and decreased economic outcomes for switcher farms based on the most recent advances in the difference-in-differences literature.

While the literature often highlights the economic benefits of mixed crop-livestock farming, we caution that these cases may be circumstantial rather than the European norm. There is stronger consensus on the positive environmental, ecological, and resilience impacts of mixed farming systems (Duru & Therond, 2015; Hendrickson et al., 2008; Kremen & Miles, 2012; Moraine et al., 2014; Riedsma et al., 2023; Russelle et al., 2007; Ryschawy et al., 2012; Soussana & Lemaire, 2014). Inconsequence – even negative consequences – on profit and economic productivity outcomes are not necessarily for the worse, as beneficial whole-system outcomes such as ecosystem service provision, animal welfare, biodiversity, and resilience to weather shocks are nonetheless desirable (Peterson et al., 2020). Yet even in this respect, as with the limited economic literature, more large-scale, quantitative research on the environmental and ecological impacts of switching to mixed crop-livestock farming is also needed to inform policy support mechanisms. (Quevedo-Cascante et al., 2023). Without clear economic benefits, any policy support for mixed crop-livestock farming must be conditioned on achieving meaningful environmental and ecological outcomes.

3.7 Conclusion

We provide the first systematic and quantitative evidence on the socio-economic consequences of switching from specialised to mixed farming in Europe. Overall, we find that switching negatively affects revenues, variable and labour costs, and economic productivity, and that most switchers do not efficiently integrate cropping and livestock enterprises.

While we used the most comprehensive farm-level economic dataset available in Europe, the FADN, it has its limitations. The narrow definition of mixedness in the FADN, expressed as a ratio of monetary outputs, lacks nuance for the cited synergies of highly integrated mixed crop-livestock farming. While we believe that our research provides an important first step to assess the impact of farm holdings switching to mixed crop-livestock farming, it is impractical to use the typology system to determine whether there are material or nutrient exchanges between cropping and livestock enterprises, and thus we cannot surely determine from this categorical variable alone whether the two are functionally synergised or detached. Furthermore, there is no indication as to whether farms cooperate with each other to form territorial synergies (Martin et al., 2016). Economic implications arising strictly from intra- or inter-farm integration are therefore unknown and systematic frameworks for doing so are limited (Low et al., 2023). Additionally, the FADN lacks relevant and insightful environmental variables, a gap that the forthcoming *Farm Sustainability Data Network* aims to address (European Commission, 2022a). These gaps open opportunities for future research.

We employed one of the most advanced difference-in-differences methods (Callaway & Sant'Anna, 2021), which accounts for treatment-effect heterogeneity due to differential treatment timing and is suitable for the characteristics of our FADN sample, especially when compared to antecedent methods such as two-way fixed effects and event-study regression. However, robustness checks suggest that non-switchers and switchers may differ even before switching. The large post-treatment confidence intervals in the statistically insignificant cases, suggest that outcomes on the economic variables might differ across geographies, growing conditions, management practices, labour and economic conditions, and farm size, which appears to be an interesting topic for future research. We also limited our analyses to identify the consequences of switching on two broad farming types: crop and livestock farming specialisations. Therefore, future research could provide further subsample estimates based on these categories. Besides, the socio-economic variables looked at here, future research could add an additional perspective on consequences of switching to more mixed farming on farm economic risks, which might offer key economic benefits to switchers that justify the small economic benefits identified.

Mixed crop-livestock farming, similarly to organic farming and agroforestry, is designed along agroecological principles (Dalgaard et al., 2003; Lampkin et al., 2015). It synergises cropping and livestock farming, and should lead to environmental benefits. Part of its attraction is its lower environmental footprint (e.g., Pavlidis & Tsihrintzis, 2018; Ryschawy et al., 2012; Soussana & Lemaire, 2014), resilience to climate change (e.g., Aguilera et al., 2020; Alary et al., 2019; Campos et al., 2020; Cubbage et al., 2012; Duru & Therond, 2015), and ability to maintain biodiversity (e.g., Duru et al., 2015; Malézieux et al., 2009) and socio-ecological value-added (e.g., Le Houérou, 1993; Lovell et al., 2010; Röhrig et al., 2020). As a whole, switching to mixed crop-livestock farming might lead to a smaller environmental footprint, but, as our results illustrate, we have found little evidence to support that adopting mixed crop-livestock farming is economically viable for farm holdings in Europe. It can be broadly reasoned that there is environmental and social value in rendering public services, which might justify public support (Pe'er et al., 2020). Yet, there are clear gaps in the manner and extent to which mixed crop-livestock farming will benefit from the changes wrought by the Green Deal and Common Agricultural Policy Strategic Plans (De Schutter et al., 2020; Pe'er et al., 2020).

To justify public support for mixed crop-livestock farming, two caveats must be addressed. First of all, our results have shown that switcher farms, particularly specialised livestock switchers, do not leverage potential economy of scope, while losing economies of scale. Any support for switching must allow switchers to mixed crop-livestock farming to become efficient and productive. Policy interventions to support the efficient mixed crop-livestock farming, such as extension and innovation services, may allow for better economic performance as well as environmental performance (Matthews, 2016). Secondly, even if switchers to mixed crop-livestock farming performed as well economically as non-switchers, any support must be contingent on the increased provision of ecosystem services and improved environmental and ecological outcomes than had switchers remained specialised. Without these, any reason to publicly support the adoption of mixed crop-livestock farming is objectionable in the first place. However, there remains a distinct lack of EU-wide, quantitative, ex-post evidence on the implications, consequences and merits of switching to such diversified mixed crop-livestock farming on environmental performance. A thorough evaluation of the environmental impacts of diversification, and supplemented by ex-post economic research (such as our own), would make for salient EU policy.

Without suitable policy interventions, our ex-post analysis shows, prior to the full implementation of the new Common Agricultural Policy, Green Deal and Farm to Fork Strategy, that switching to mixed crop-livestock farming is not sufficiently viable for European farmers at present. Furthermore, it remains that the current policy trajectory might be insufficient to capitalise on the promised environmental benefits of mixed crop-livestock farming. More research is therefore required to identify how best to support and exploit agroecological farming systems such as mixed crop-livestock farming.

4 Resilience of extensive meadow orchards against climatic extremes

A version of this chapter has been presented as:

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4.1 Introduction

Mixed farming and agroforestry systems aim to provide both economic diversification and ecological and environmental benefits, often on the same piece of land, by leveraging synergies between farming enterprises (Dalgaard et al., 2003; Kremen & Miles, 2012; Martin et al., 2016). Such benefits as reducing inputs such as fertilisers and biocides by mixed farming and agroforestry systems (Ewert et al., 2023; Garrett et al., 2017; Isbell, 2015; Isbell et al., 2017; Malézieux et al., 2009; Moraine et al., 2014; Peyraud et al., 2014; Ryschawy et al., 2012; Tsonkova et al., 2012) is of key interest for the public policy domain in Europe (2020). While diversified farms may leverage their varied outputs to cope with downside risks, e.g., adverse weather events (Aguilera et al., 2020; Cubbage et al., 2012), downstream actors relying on singular outputs originating from these farms may lack comparable resilience to identical shocks. More specifically, while mixed and agroforestry farms are able to rely on diversified income streams, downstream actors that specialise on further processing a specific outcome of one of such production activities are highly reliant on sufficient supply. Overall, there is meagre evidence on how such farming systems might impact the vital downstream food value chain (Low et al., 2023). Providing a better understanding of the resilience of value-chain partners of mixed farms against external shocks that affect the supply of single farm products is an enticing and relevant research gap.

This paper will analyse the impact that weather shocks, particularly frost shocks, have on apple meadow orchard production for a downstream processor in Switzerland. We choose this particular question for three reasons. Firstly, a prevalent example of a mixed farming and agroforestry production system is the meadow orchard, which has a long and important history in the European landscape. Meadow orchards provide a high ecosystem diversity, and these ecosystems serve as habitats for a wide range of wild species (Paesel et al., 2019). Meadow orchards are typically extensively or minimally managed (e.g. in terms of plant protection) and contrast with intensively managed orchards (Dalhaus et al., 2020). Secondly, weather shocks, such as frost, are entirely exogenous and random, thereby permitting us to isolate a direct effect of adverse weather on production. Besides this, frost poses a considerable economic and production risk during the frost-sensitive flowering phase of apple trees. Since management practices are assumed to differ between extensively managed meadow orchards and intensively managed apple orchards, frost shocks can be easily identified. Thirdly, the Swiss market for apples and other food products is highly protected (with tariffs and quotas), leading Swiss food processing companies to preferentially source locally. Local production losses, therefore, pose a unique risk to Swiss food processors, such as apple juicers, since they are relatively isolated from the European market. As such, production shocks are harder to mitigate downstream and have an outsized impact on food producers, processors, consumers, and policymakers alike.

In spite of broad literature on the ecosystem services created by meadow orchards and how these are affected by different management regimes (Steffan-Dewenter, 2003), there is no quantitative evidence on the resilience of mixed farming and agroforestry systems in general and extensive meadow orchards in particular to weather shocks (Mouron et al., 2006; Spiegel et al., 2021). On the one hand, Dalhaus et al. (2020) find that in intensively managed apple production systems farmers can largely manage the impacts of frost exposure and do not find evidence of a yield response to frost. On the other hand, Schönhart et al. (2011) find that the economic success of meadow orchards is marginal under most production conditions and that fruit yields must attain a minimum threshold to make meadow orchards profitable and lasting. Yet, exactly the risk of a weather shock that might upend meadow orchard production is entirely underexplored. This exposes a second key limitation of the literature. It is the absence of any insight into how a weather shock taking place at the farm-level might have economically important consequences for the downstream value-chain. In Switzerland, intensively produced apples, such as those studied by Dalhaus et al. (2020), are highly valued by consumers as table apples (Agrarbericht, 2024), while in contrast, extensively produced apples are not, and are processed into apple juice by local processors (Hochstamm Suisse, 2021). But since the production and profitability margins of meadow orchards are already small, even a minor shock may have serious operational implications for processors. Therefore, not only the economic success of farms but also of processors depends on a clearer overview of the risks that weather shocks pose.

We use a unique panel dataset of 1,758 observations containing collection quantities of apples originating from extensive meadow orchards from 293 collection stations in Switzerland between the years 2016 – 2021. The data is provided by one of the largest Swiss apple juice producers, Ramseier, in collaboration with the grower association, Hochstamm Suisse. Their production is fully based on (extensive) Swiss apple yields and is therefore highly dependent on the production volume arising from apple producers. We use fixed effects regression to identify the effect of a frost shock during the flowering phase on production shocks. Moreover, we use piecewise linear splines to allow for the highly non-linear effect of temperature on yield (Auffhammer et al., 2013; Blanc & Schlenker, 2017; Kolstad & Moore, 2020). We use this response function of production to temperature as an indicator for the resilience of meadow orchards to weather extremes.

We find that frost has a significant effect on the volume of apples collected by the apple juice producer, Ramseier. Since the value of these apples is low, juice apples harvested in a good year do not undergo cold storage as table apples do. Consequently, during frost years with low apple yields, the processor faces a significant input shortfall.

In section two, we provide an overview of the ecosystem benefits that are provided by meadow orchards as well as the plant physiological consequences of frost exposure during the blooming phase in apple trees. Moreover, we give an overview of the apple juice market to indicate potential value chain implications of apple supply shortages in the next sections. In section 3 we present the data used and the merging procedures together with the statistical model used. In section 4 we present our results. We end the paper with a discussion and conclusion.

4.2 Background

4.2.1 Extreme weather impact on apple supply

Frost and freezing temperatures play an important physiological role for fruiting trees, including apples. Some winter chilling is required for apple trees to leave dormancy and to form blossoms, which are then pollinated in order to become fruits (Faust et al., 1997; Powell, 1986). However, once flower buds have formed frost damage becomes a particularly important risk since even a short exposure to freezing temperatures can damage the flower and its organs. Under some frost exposure, the damage persists at fruit maturity leading to the degraded morphological quality of the fruit (Rodrigo, 2000). Yet, a bout of severe frost during this vulnerable phase can equally destroy the blossom, leading to the total loss of the fruit (Rodrigo, 2000). As such, there is a strong coincidence between late frost and the risk of frost damage to flowers. Spring frost, therefore, poses a special and critical risk for apple production. While some apple cultivars might be more resilient to late frosts, such as *Boskoop* (Dalhaus et al., 2020; Westwood, 1993), most require frost management strategies to mitigate potential losses (Dalhaus et al., 2020; Drepper et al., 2022).

Meadow orchards have a long tradition and history in Europe (Herzog, 1998). They are typically extensive production systems that consist of high-stem fruit or nut trees interspersed in grassland meadows and pastures, and are often surrounded by hedges (Paesel et al., 2019). Meadow orchards can be classed as agroforestry systems, since they consist of integrating tree productions with livestock which graze on grass and forage provided by the trees and hedges (Low et al., 2023). Livestock can benefit from shade and shelter provided by the trees, while the trees benefit from nutrient-rich manure. For farmers, meadow orchards outputs may be fruits and nuts, animal products, and forage such as hay grass. Meadow orchards provide a high ecosystem diversity, and these ecosystems serve as habitats for a wide range of wild species (Paesel et al., 2019).

Yet, this extensiveness of fruit production implies that tree management may be more limited, for example with regards to pruning, fertilisation, and frost management. Agricultural intensification and specialisation leads to more specialised management at the expense of integration management (de Roest et al., 2018; Marton et al. 2016). In meadow orchards grazing livestock seem to be economically more important than fruit, though quantitative profitability studies are extremely rare. For instance, the paper by Paesel et al. (2019) describes that the tree density of their study sites in Germany varied between 4 and 20 trees per 0.1 hectares, while Plieninger et al. (2015) define meadow orchards as having a density of 20 to 100 trees per hectare. According to Wertheim et al. (2001), the optimal density for intensive, low-stem apple orchards is between 3,000 to 6,000 trees per hectare. Low-stem orchards tend to be more productive and cost-efficient (Herzog, 1998; Paesel et al., 2019; Plieninger et al., 2015). Reflecting their frost management, Dalhaus et al. (2020) find an insignificant link between the incidence of frost conditions and yields in low-stem apple orchards. In these intensive high-value fruit production systems it is common to actively protect fruits with frost irrigation, wind turbines, or frost candles, which is not cost efficient in extensive production (Dalhaus et al., 2020; Foudi & Erdlenbruch, 2011; Snyder & Melo-Abreu, 2005). In the absence of frost management, fruit yields in extensive meadow orchards are more volatile and sensitive to frost.

In effect, the apples produced from either extensive or intensive production systems tend towards different uses; the former, usually lower in morphological quality and therefore price, tend to be processed and pressed into juice; while the latter are more prized for their quality and are sold as high-value table apples. This difference in price, quality, and intensity between low-stem and high-stem orchards might also lead to different behavioural responses of farmers to frost shocks. The decision to harvest after an extreme weather event may be motivated by the trade-off between output price and harvesting costs (or where such low yields do not justify the costs of harvesting at all). Or, the decision to harvest may be motivated by insurance and subsidy payouts against yield losses relative to normal yields (Cui, 2020; Iizumi & Ramankutty, 2015; Roberts et al., 2006). Yet, extreme and systemic weather shocks can reduce both harvested area and yields (Lesk et al., 2016). Underestimating farmers' behavioural responses to a weather shock can significantly bias the estimated production losses (Cui, 2020). Crop abandonment might be a critical factor for high-stem meadow orchard farmers since low profit margins and yields for juicing apples might disincentivise farmers to harvest surviving apples after a frost shock, while environmental subsidies for trees (and not the fruit), may further disincentivise farmers from harvesting after poor conditions. Thus, low apple supply can be exacerbated under extreme weather.

4.2.2 Apple and juice production in Switzerland

Apple production is of key relevance to Swiss agriculture. More specifically, apples represent 9.6% of total gross economic production value from all crops in Switzerland (FAO, 2022). The total acreage under apples is larger than 3,600 hectares. There are about 1.2 million high-stem apple trees in Switzerland, with the canton of Thurgau being the largest production region, followed by the canton of Lucerne (Hochstamm Suisse, 2018). In the second part of the 20th century, the area of high-stem fruits declined massively in Switzerland by about 80%, but has been stabilised, and even increased slightly, in the last two decades (Hochstamm Suisse 2018). This development was also due to governmental support for high-stem fruit production. More specifically, Swiss farmers can receive direct payments via agri-environmental schemes for high-stem fruit trees (e.g. Huber et al. 2024). For example, producers receive between 13.50 CHF and 31.50 CHF per tree per year, depending on environmental quality (see Swiss Federal Council, 2024, for details). In these programs, producers have to take biodiversity enhancing measures and the use of fertilisers and pesticides is highly restricted. Producers are obliged to carry out professional tree care and to control pests. High-stem fruit cultivation in Switzerland increasingly makes use of mechanisation such as picking machines, tree shakers and mobile hydraulic ladders, reducing labour requirements.

The production of high-stem apples used for juice and cider production vary strongly between years. For example, in 2022, commercial cideries processed 61,150 tonnes of cider apples, 40% more than in the previous year (43,461 tonnes). This was around 25% less than the average of the previous four years (81,330 tonnes) (Agrarbericht 2024). Apples produced in Switzerland are mainly consumed domestically (Gramm et al., 2019). Market protection via quotas and tariffs creates an at least to some extent protected market for Swiss producers (Huber et al., 2024). As a result, producer prices for apples are higher than in neighbouring countries. For example, prices for table apples may be above 1.2 CHF per kg (Agrarbericht 2024), while prices for juice apples are usually lower, for example 0.3 CHF per kg in 2021 (Hochstamm Suisse 2021). There are two major companies processing high stem apples, Ramseier (processing around 50,000 tonnes of cider fruits per year) and Möhl (25,000 tonnes of cider fruits per year). The use of high-stem fruits such as apples is also increasingly labelled on the end products such as juices (Figure 7)

Figure 7. Prominent Swiss, certified high-stem apple products: left, Humbel apple *schnapps* (https://www.humbel.ch/); centre, Ramseier apple and pear juice (https://www.ramseier.ch/); right, Appenzeller alcohol-free beer flavoured with apple and pear (https://appenzellerbier.ch/de/).

4.3 Data & methods

4.3.1 Production data

Data for apple production originating only from extensive meadow orchards is provided by the Swiss juicer, Ramseier, in collaboration with the Swiss grower association, Hochstamm Suisse. The balanced panel dataset includes observations represented by collection quantities (kg) of apples by Swiss postcode (293 postcodes – PLZs) over the years including 2016 to 2021, for a total of 1,758 observations. The apples are collected at collection stations per Swiss postcode, whereupon the apples are taken to processing plants and juiced, and sold thereafter as originating from extensive production. The postcodes present in this dataset can be seen in the map of Switzerland in Figure 8. It is easy to identify the production regions of Thurgau and Lucerne, where the majority of the high-stem apples sourced by Ramseier are located.

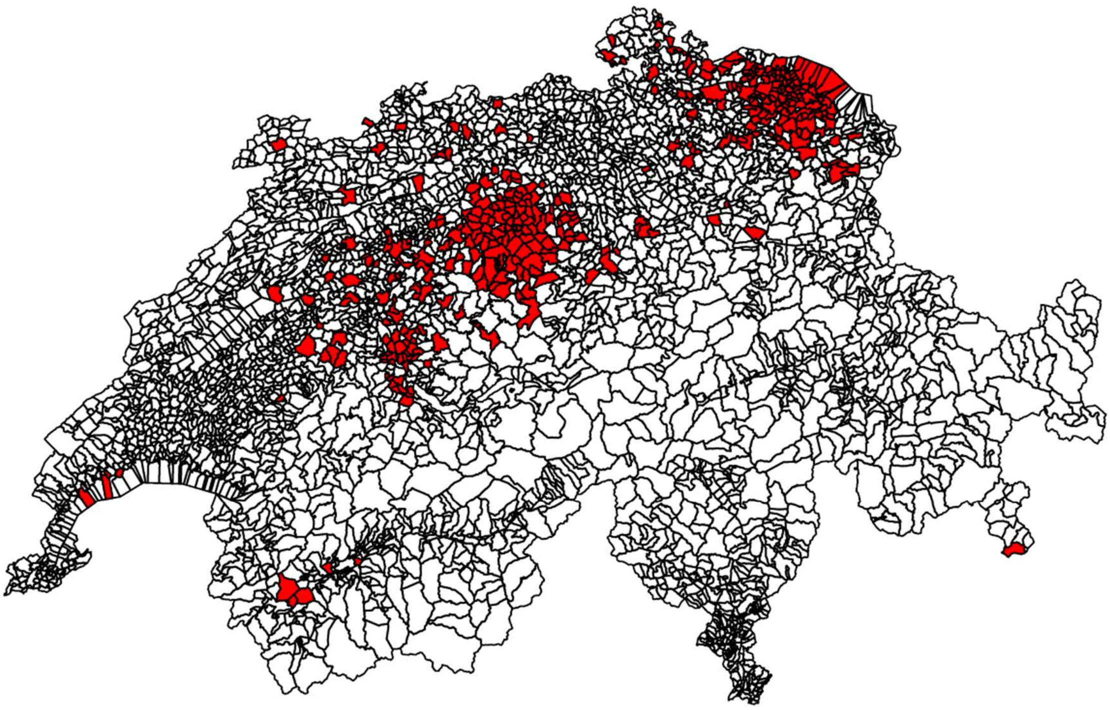

Figure 8. Map of Swiss postcodes. Production postcodes highlighted in red. Note the production clusters of the cantons of Thurgau in the northeast and Lucerne in the centre.

The collection quantity represents only the apples that are received by the collection station and not the total yields of the meadow orchards (crop abandonment hypothesis). It thus reflects the risk faced by downstream actors, not by farmers. Furthermore, the dataset does not provide the number of orchards present per postcode nor the varieties of apple trees. Thus, the dataset is representative from the processor's perspective, where the quantity of apples collected at any time have a direct effect on the processor's ability to produce apple juice in sufficient quantity and quality. The dataset not only contains positive observations of quantities of apples collected, but also null observations which represent no quantity of apples being collected at collection stations for specific years. Such an observation does not imply that no apples were produced at all, but only that farmers brought no apples to the collection station. This fact, and the variability of apples collected across postcodes and across time, offers a unique perspective on how shocks affect a processor serving a very specific market niche. The summary statistics in Table 2 below highlight the variability of collection quantities across time and the presence of non-collection.

Table 2. Yearly summary statistics of apple collection data (kgs) across 293 Swiss postcodes

YEAR	MEAN	STD. DEV.	MAX	NUMBER OF 0 OBSERVATIONS
2016	143,585.7	387,735.4	3,205,550	77 / *293*
2017	38,545.0	117,106.5	853,280	160 / *293*
2018	279,060.6	589,341.2	4,472,010	59 / *293*
2019	80,307.4	268,654.7	2,188,590	141 / *293*
2020	188,069.8	451,929.2	3,167,030	79 / *293*
2021	75,976.1	233,152.8	2,123,340	158 / *293*
ALL	**122,220.9**	**360.349.0**	**4,472,010**	**674 / *1,758***

4.3.2 Apple phenology data

To determine the flowering period of apples we use the BBCH scale. The BBCH scale describes fruit growth stages; where BBCH60 corresponds to when flowers first open, and BBCH69 corresponds to the end of flowering and all flowers have fallen (Rea & Eccel, 2006). Phenological data for Swiss apples is collected at 36 experimental stations and for several apple varieties, and can be matched with the postcodes and years of the production data described previously. Similarly to Dalhaus et al., (2020), we assign the phenological data to the collection station postcodes within the same year. Since the production data contains no information on the exact apple varieties collected, we use the earliest and latest dates within the BBCH60-69 range to determine the start and end date of the flowering period for a specific postcode. The data is available online by the meteorological service, Agrometeo (www.agrometeo.ch).

4.3.3 Weather data

We use daily minimum and maximum daily temperatures for Switzerland provided by the Swiss Meteorological Office. Specifically, we use weather data during the flowering period according to the apple phenology data described above, and for the duration of the study period of the years 2016 to 2021. Temperature data is provided as a gridded raster at a 2.5km^2 resolution. The interpolation method to produce this data is specifically characteristic of the Swiss landscape and takes into consideration non-linear temperature shifts due to elevation changes (Frei, 2014). Since the geographic size of postcodes is quite small, and the exact location of the collection point and meadow orchards are not available in our dataset, we take the centroid of the postcode as the weather reference.

As the weather data is daily, in order to obtain the amount of time, hours in a day, spent above or below the frost threshold (0℃), we approximate hourly temperatures. We follow the method as in Bucheli et al., (2022), where double-sine curves are fitted from the daily minimum to the daily maximum temperatures and thereafter to the minimum temperature of the following day. This method allows for a smooth daily transition and a more accurate estimate of the hourly temperature between days.

4.3.4 Empirical framework

We use a postcode-level fixed effects regression to model the effect that temperature exposure – namely frost shocks – has on extensive apple production during the frost-sensitive flowering period. This method has been widely used in evaluating weather effects on agricultural output (e.g., Blanc & Schlenker, 2017; Dalhaus et al., 2020; Schlenker & Roberts, 2009; Tack et al., 2015; 2017) We estimate a model of the form:

$$y_{it} = f(T_{it}, \beta) + \alpha_i + \delta_{t1}t + \delta_{t2}t^2 + \varepsilon_{it}$$

where, y_{it} is the quantity (kg) of apples collected at the collection station at postcode *i* in year *t*. Since time-invariant growing conditions vary across postcodes *i*, the postcode fixed effect parameter α_i controls for time-invariant heterogeneity. This may be due to, for example, microclimate, soil, or altitude. $\delta_{t1}t + \delta_{t2}t^2$ is the quadratic time trend that controls for time-dependent changes, such as management and technological advances over the study period. ε_{it} is the standard error. Since the error is likely to be spatially autocorrelated and heteroskedastic, we cluster the standard error by year. The function $f(T_{it}, \beta)$ reflects the potentially non-linear response of temperature exposure during the flowering period on apple collection quantities. As such, $f(T_{it}, \beta)$ is a piecewise linear model:

$$f(T_{it}, \beta) = \beta_1 T_{(-\propto,0]℃} + \beta_2 T_{[0,\propto)℃}$$

In the formula above, the temperature intervals $T_{(-\propto,0]℃}$ and $T_{[0,\propto)℃}$ measure the number of degree days below and above the cut-off temperature of 0℃, respectively, which represents the temperature at which and below frost conditions exist. β_1 and β_2 are the coefficients for the linear effects of the temperature intervals.

4.4 Results

From the approximation of hourly temperatures, based on daily minimum and maximum temperatures for our study period, cumulatively 2.1% of all hourly observations are below 0℃, while 1% of all estimated hourly temperatures are below -1.2℃. The lowest approximated temperature is -14.5℃, while the highest is 32.5℃. The median hourly temperature is 10.2℃, while the mean is 10.6℃ (st.dev. 5.7). The distribution can be observed in Figure 9.

We find that there is a clear and statistically significant effect ($p < 0.001$) of frost exposure on the quantity of apples collected by Ramseier. Figure 10 shows the temperature impact of hourly exposure during freezing and non-freezing conditions. We find that for every degree-hour of exposure to temperatures below 0℃, there is a loss of 420.5 kilograms on the quantity of apples collected. This would imply, for instance, that 10 hours of exposure to -1℃ would lead to a loss of 4,205 kilograms of apples; the same as one hour of exposure to -10℃. Conversely, as expected, there is a negligible effect of temperatures above 0℃ on collection quantities.

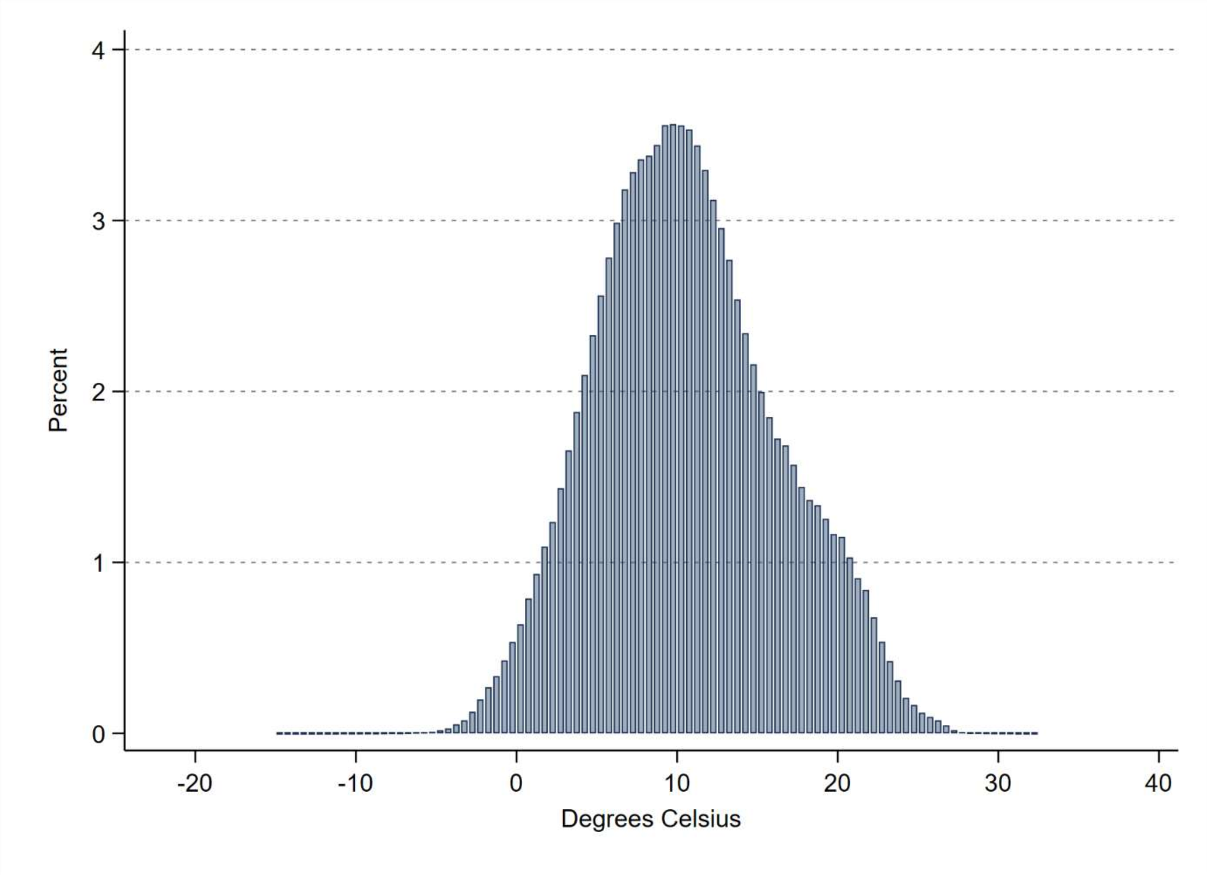

Figure 9. Distribution of approximated hourly temperatures during the flowering periods between 2016 and 2021

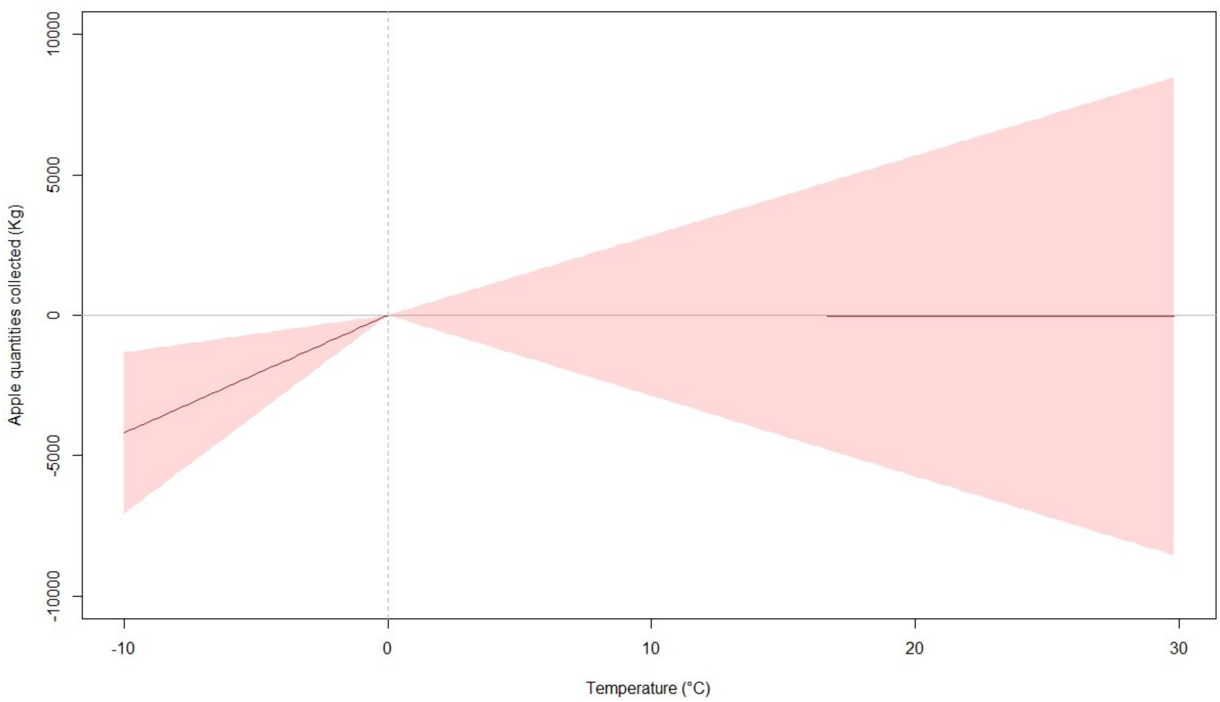

Figure 10. Estimated effect of frost exposure on the quantity of apples collected. The shaded area represents 95% confidence bands when errors are clustered by year and PLZ postcode.

4.5 Discussion & conclusion

We have found that there is a clear and statistically significant effect of frost on collected apple quantities by the downstream processor. In direct contrast to Dalhaus et al. (2020), we find that apples originating from extensive meadow orchards (as opposed to intensive low-stem apple orchards) are negatively affected by the incidence of frost during the vulnerable flowering period. Since extensive meadow orchards are less intensively managed, particularly with respect to frost management, it is evident that the response to frost shocks would naturally lead to lower productivity. For the downstream processor, this represents a liability for their operations as this would imply that during spring-frost years the availability of inputs is much reduced than in years without frost. All the while, the incidence of frost, with respect to hourly exposure, is quite low, with extremely low temperatures being increasingly unlikely. To this extent, though there is a statistically significant effect of frost on collection quantities, in absolute terms the estimate of 420.5 kilograms lost per degree-hour below 0℃ is quite small.

Even while meadow orchards might by more exposed to frost risk, due to minimal frost management (Dalhaus et al., 2020; Foudi & Erdlenbruch, 2011; Snyder & Melo-Abreu, 2005), they might conversely be economically robust against frost shocks. From our analysis of the weather data, the risk and implications of severe spring frost to extensive apple producers are relatively low. Since extensive meadow orchards are highly diversified food production systems, a minor shock to apple production may be economically negligible. In particular, if the main outputs of the meadow orchard are livestock products, while environmental subsidies are received for the trees (and not the apples), farmers' incomes might be buffered against frost risk. Moreover, the very low prices attracted by extensively produced apples versus the potentially high costs of harvesting, may further suggest that even after a minor spring frost event the farmer may simply decide to abandon the apple crop entirely as it is unprofitable (Cui, 2020; Iizumi & Ramankutty, 2015; Roberts et al., 2006).

However, the risk of frost shocks to producers is more considerable. We have found a direct correlation between frost shocks and the apple quantities collected by Ramseier. In particular, not only are there fewer apples available for collection, but there may also be a lack of incentives on the part of producers to harvest after a frost event. Critically, under the same risk, the challenges posed by it are not the same between farmers and for the downstream processors dependent on singular outputs from the farms. Moreover, the exclusive, local sourcing of Swiss farm outputs exposes Swiss processors to greater risk of supply disruptions since they are simultaneously less inclined to source inputs from outside Switzerland (e.g., via tariffs) (Huber et al., 2024) and would otherwise lose any value-added from Swiss-origin labelling and product quality recognition.

In conclusion, even economically negligible effects of frost shocks on farmers might pose more severe implications for reliant, downstream processors. While a processor such as Ramseier derives value-added from sourcing and labelling its inputs as from diversified and environmentally more sustainable meadow orchards, it is consequently much more exposed to supply disruptions on unique and critical inputs. Therefore, identifying the sources of production losses at the farm-level is vital for downstream processors, as are better mechanisms for alleviating these farm-level production risks.

5 Discussion & conclusion

Literature suggests that mixed farming and agroforestry systems create synergies between different farming activities taking place of the same piece of land. These benefits shall create economic and environmental advantages compared to specialized farming systems. We here provide threefold evidence to: i) synthesise current literature on the economic benefits of mixed farming with a particular focus on value chains; ii) quantify the socio-economic consequences of switching from specialised to mixed farming systematically and empirically based on an extensive and representative farm-level economic dataset covering entire Europe; and, iii) estimate weather induced losses for supply chain partners of mixed and agroforestry farms.

Findings of sub-chapters suggest that economic benefits of mixed farming are far more moderate than literature suggests. First, past literature on the economics of MiFAS is scarce and highly case study specific. Therefore, earlier studies lack external validity and policy decision on the support of mixed farming and agroforestry are largely based on the ecological benefits, neglecting the economic implications on farmers and value chain partners. Second, our Europe-wide quantitative assessment of switching to mixed farming and agroforestry shows that farms, which switch from specialised to mixed crop-livestock mostly do so by downsizing livestock production and only slightly increasing crop production. Therefore compared to earlier studies that suggest switching to mixed farming and agroforestry implies adding activities to a specialised farm, the reality looks different. Instead of producing more on the same land with fewer external inputs, farms that become mixed have lower revenues and productivity and must even invest slightly more into labour than during their specialised times before the switch. Third, mixed and agroforestry farms are said to be more resilient to external shocks due to diversified income streams that come from different products. However, it has been neglected so far that downstream value chain partners, which process the products of these farms further, are dependent on a steady supply. To illustrate that food processors are affected by the production of single products on the farm, we use the empirical example of extensive meadow orchard apple production in Switzerland. We show that the supply of apples from this agroforestry system is highly volatile and vulnerable to weather shocks. Therefore, supply chain partners, which specialise and label their products to show benefits of mixed farming, are exposed to substantial input risk.

Overall we conclude that the socio-economic consequences of mixed farming on productivity, efficiency, and riskiness of the production are lower than literature suggests. While this might be a reason for the so far low uptake of mixed systems in Europe, this suggests potential pathways for policy makers to support the adoption if the ecological benefits outweigh the costs of this support. More specifically, support might be provided in form of additional income support and agronomic risk management measures to reduce the volatility of production. Additionally, future research should provide further insights into the resilience effects of mixed farming outside our Swiss apple case study. For this, additional data sources on price and quantity of production from mixed farms are required and should be collected.

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