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Clémentine Meunier

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# Doctorat de l'Université de Toulouse

préparé à Toulouse INP

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Réintégrer l'élevage dans les fermes et territoires de cultures: motivations des agriculteurs, contextes sociotechniques, pratiques et durabilité des fermes

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Thèse présentée et soutenue, le 3 décembre 2024 par  
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## **École doctorale**

SEVAB - Sciences Ecologiques, Vétérinaires, Agronomiques et Bioingenieries

## **Spécialité**

Agrosystèmes, écosystèmes et environnement

## **Unité de recherche**

AGIR - Laboratoire Agroécologie, Innovations, terRitoires

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M. Emeric Pillet, ITAB



# Reintegrating livestock in specialized crop farms and regions

Farmers' motivations, sociotechnical contexts, practices and farm sustainability



*A ma mère*



## Preface

### Funders and research laboratory

This Ph.D. study was funded by the AgroEcoSystem and the ACT divisions of the French National Research Institute for Agriculture, Food and Environment (INRAE), as well as the Occitanie Region. It received additional funding from the two research projects in which it was included: the European Union Horizon 2020 MIXED project, and the ERA-NET project Mi Bicycle, funded under the joint call ERA-NET Cofund SusAn, FACCE ERA-GAS, ICT-AGRI-FOOD and SusCrop. I thank these funders for enabling my Ph.D. study.

It was led at INRAE – UMR 1248 AGIR, in Toulouse, France.

### Stays in foreign research laboratories

During this Ph.D. study, I had the chance to visit three foreign research laboratories. I spent two weeks to collaborate with Amelie Gaudin's lab, in the Department of Plant Sciences of Davis University, in Davis, California, USA. I also spent two weeks in the Aberdeen Campus of SRUC (Scotland's Rural College) to collaborate with Cairistiona F.E. Topp, Christine A. Watson and Robin L. Walker. These two collaborations led to the results of the second chapter of this Ph.D. study. I also spent three months at the Institute of Agricultural and Forestry Economics of the University of Natural Resources and Life Sciences in Vienna (AFO-BOKU), collaborating with Ika Darnhofer. This collaboration led to the results of the fourth chapter of this Ph.D. study.

### Some precisions for reading this Ph.D. manuscript

This Ph.D. manuscript is divided into six main sections, i.e. the general introduction, followed by four chapters in the form of research paper that have already been published or submitted to scientific journals, and the general discussion. To ease the reading, coloured pages, corresponding to the colour attributed to each chapter, delineate the sections of the manuscript.

A glossary of concepts mobilized in the manuscript is provided at the beginning of the manuscript. Concepts defined in this glossary are identified by an asterisk at their first occurrence in the manuscript.



## List of contributions

### Academic publications

#### *Papers published before the beginning of this Ph.D. study*

**Meunier, C.**, Casagrande, M., Rosiès, B., Bedoussac, L., Topp, C.F.E., Walker, R.L., Watson, C.A., Martin, G., 2022b. Interplay: A game for the participatory design of locally adapted cereal–legume intercroppings. *Agricultural Systems* 201. <https://doi.org/10.1016/j.agsy.2022.103438>

**Meunier, C.**, Alletto, L., Bedoussac, L., Bergez, J.E., Casadebaig, P., Constantin, J., Gaudio, N., Mahmoud, R., Aubertot, J.N., Celette, F., Guinet, M., Jeuffroy, M.H., Robin, M.H., Médiène, S., Fontaine, L., Nicolardot, B., Pelzer, E., Souchère, V., Voisin, A.S., Rosiès, B., Casagrande, M., Martin, G., 2022a. A modelling chain combining soft and hard models to assess a bundle of ecosystem services provided by a diversity of cereal-legume intercroppings. *European Journal of Agronomy* 132. <https://doi.org/10.1016/j.eja.2021.126412>

Gaudio, N., Louarn, G., Barillot, R., **Meunier, C.**, Vezy, R., Launay, M., 2022. Exploring complementarities between modelling approaches that enable upscaling from plant community functioning to ecosystem services as a way to support agroecological transition. *In Silico Plants* 4, 1–13. <https://doi.org/10.1093/insilicoplants/diab037>

#### *Papers published or submitted to international journals during this Ph.D. study*

*(Papers that are not published yet are written in grey).*

**Meunier, C.**, Martin, G., Barnaud, C., Ryschawy, J., 2024. Bucking the trend : Crop farmers’ motivations for reintegrating livestock. *Agric. Syst.* 214. <https://doi.org/10.1016/j.agsy.2023.103820>

**Meunier, C.**, Martin, G., Fenster, T.L.D., Gaudin, A.C.M., Grillot, M., Lecole, P., Topp, C.F.E., Walker, R.L., Watson, C.A., Williams, S.R., Ryschawy, J. (n.d.). Barriers and levers for reintegrating livestock into crop farms and regions – A transversal analysis in three countries. [In revision, to be submitted to *Land Use Policy*].

**Meunier, C.**, Ryschawy, J., Martin, G. (n.d.). Reintegrating livestock onto crop farms: a step towards sustainability? [submitted to *Agricultural Systems* in September 2024].

**Meunier, C.**, Darnhofer, I., Martin, G. (n.d.). A call for change: Contributing to a transition to agroecology requires questioning our assumptions. [revisions requested by *Agroecology and Sustainable Food Systems* in September 2024].

Grillot, M., **Meunier, C.**, Claire Triolet, Ryschawy, J. Crop-livestock interactions between farms: how and why do they occur? A case-study in Southern France. [To be submitted to *Agricultural Systems* in early 2025].

## Oral communications

### *Communications in academic conferences during this Ph.D. study*

*(the name(s) of the presenter(s) is (are) underlined)*

**Meunier, C.**, Ryschawy, J., Martin, G. Reintegrating livestock onto crop farms: a step towards sustainability ? 18th Congress of the European Society for Agronomy, Aug 2024, Rennes, France.

**Meunier, C.**, Martin, G., Barnaud, C., Ryschawy, J. Bucking the trend: crop farmers' motivations for reintegrating livestock. IFSA 2024 – European Farming Systems Conference, Jun 2024, Trapani, Italy. hal-04651108v1

**Grillot, M.**, **Meunier, C.**, Claire Triolet, Ryschawy, J. Crop-livestock interactions between farms: how and why do they occur? A case-study in Southern France. IFSA 2024 – European Farming Systems Conference, Jun 2024, Trapani, Italy. hal-04651135v1

**Meunier, C.**, Martin, G., Barnaud, C., Ryschawy, J. A contre-courant: Motivations des agriculteurs à réintégrer l'élevage dans les fermes et territoires de cultures. Colloque national du RMT SPICEE: Les interactions culture-élevage, leviers de résilience des agricultures face aux crises du XXIème siècle ?, Mar 2024, Montpellier, France. hal-04548315v1

**Meunier, C.**, Martin, G., Grillot, M., Ryschawy, J. Réintégrer l'élevage sur des fermes en productions végétales - une analyse comparative des freins et leviers à travers trois régions d'étude Colloque national du RMT SPICEE: Les interactions culture-élevage, leviers de résilience des agricultures face aux crises du XXIème siècle ?, Mar 2024, Montpellier, France. hal-04548310v1

**Martin, G.**, Grillot, M., **Meunier, C.**, Marc Moraine, Ryschawy, J. Using local feed resources for livestock farming: Illusion or real promise? Joint Seminar of the FAO CIHEAM Networks on Pasture and Forage Crops and on Sheep and Goat Nutrition, Sep 2022, Catania (IT), Italy. hal-04163348v1

**Meunier, C.**, Grillot, M., Carle, S., Ryschawy, J. Farmers' perceptions of levers and barriers to crop-livestock integration beyond farm level. A case-study in France. 14th European IFSA symposium, Apr 2022, Évora, Portugal. hal-03728122v1

### *Other communications during this Ph.D. study – Contributions to further disseminate research results to farmers' groups*

**Meunier, C.**, Ryschawy, J., **Martin, G.** Reconnecter cultures et élevages : chimère ou réalité ? Colloque de l'ABC, GABB32. Déc. 2022, Pessan, France.

Other contributions to disseminate research results during this Ph.D. study - Teaching and supervision

Over my Ph.D. study, I taught above 130 hours to master students. Such teaching took diverse forms, among which lectures about my Ph.D. study results and direction of students groups to use already existing serious games and to create their own serious games on integrating sheep into vineyards and grain crop farms.

I also co-supervised the 3-month internship of a master student to collect data and provide an initial database to further improve.

Other contributions to disseminate research results before this Ph.D. study - Contributions to technical journals and other communications to farmers and citizens

Des jeux sérieux pour échanger et apprendre collectivement. Réussir – Pâtre et La Chèvre, Sept 2021. Accessed online in March 2023. Accessible at: <https://www.reussir.fr/chevre/des-jeux-serieux-pour-echanger-et-apprendre-collectivement>

Interplay : un jeu sérieux pour co-concevoir des scénarios d'association céréale-légumineuse. Campagne de faits marquants AgroEcosystème 2022. Accessed online in Oct. 2024. Accessible at: <https://www.inrae.fr/sites/default/files/pdf/Recueil%20FM2022%20AgroEcoSystem%20vf.pdf>

Interplay : un jeu sérieux pour évaluer les services fournis par les associations céréales-légumineuses. Actualités 50 ans du centre Occitanie Toulouse, Dec 2022. Accessed online in March 2023. Accessible at: <https://www.inrae.fr/actualites/interplay-jeu-serieux-evaluer-services-fournis-associations-cereales-legumineuses>

Presentation of the Interplay serious game during two events of communication to citizens organized by the association Les Petits Débrouillards, on the topics of « Numeric and Environment » (2020) et « Living Soils» (2021). Toulouse, France.

### Planning for the future

During my Ph.D., I also successfully completed the selection process to be hired permanently at INRAE UMR AGIR. I am really delighted to have the opportunity to continue my research career in this research lab, focusing on on-farm experiment.

## Acknowledgements and gratitude

*(Whereas this Ph.D. manuscript is written in English, I decided to write this section either in French or in English according to the language I used to communicate with the acknowledgement recipients).*

Although this Ph.D. thesis is in my name, it could not have resulted more of a collective achievement, fuelled by strong interactions, collaborations and sharing. I would here like to acknowledge and sincerely thank all the people who contributed, directly or indirectly, to enable this work. Despite having multiplied words (as often...), I am still not sure I found the right ones to express how grateful I am for sharing this extraordinary professional and personal adventure with all of you. So maybe I should just say:

# Thank You.

But, well... As a “good Ph.D. student”, it felt not enough. So, in the next section, I elaborate a little more...

First, I would like to sincerely thank the members of my jury, for agreeing to evaluate this Ph.D. study. I thank Lee-Ann Sutherland and Mireille Navarrete for reviewing this Ph.D. study, and Renske Hijbeek and Alberto Bernués for evaluating it. I do also thank Emeric Pillet as an invited jury. I am much looking forward to further discussing with you!

Mes pensées se tournent ensuite vers mes deux encadrants, Julie Ryschawy et Guillaume Martin, pour tout ce que vous avez pu m’apporter au cours de ce beau voyage qu’est la thèse.

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During this Ph.D. study, I also got the chance to collaborate with foreign research laboratories. I would like to thank warmly these researchers and their teams who dedicated some of their precious time to supporting my work, and further exchanging with me about the differences in farming throughout the world.

Un remerciement particulièrement chaleureux à Ika Darnhofer pour m’avoir accueillie pendant trois mois dans ton bureau de Vienne où, au-delà de la chercheuse, j’ai rencontré une femme réellement inspirante. Je suis très reconnaissante de la richesse de nos échanges qui ont non seulement changé ma vision de la recherche, mais aussi du chemin de vie bien au-delà. Merci également pour ton

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## Glossaries

### Glossary of acronyms

*This glossary of acronyms is arranged alphabetically.*

- AFO: Institute of Agricultural and Forestry Economics
- AGIR: AGroecologie, Innovations, TeRritoires (Agroecology, Innovations and Territories)
- BOKU: University of Natural Resources and Life Sciences, Vienna
- CAP: Common Agricultural Policy
- CO<sub>2</sub>: Carbon dioxide
- CH<sub>4</sub>: methane
- GHG: GreenHouse Gas emissions
- ha: hectares
- ICLS: Integrated Crop-Livestock Systems
- INRAE: French National Research Institute for Agriculture, Food and the Environment
- Mi Bicycle project: Mitigation and adaptation through better biomass cycling in crop-livestock systems of North and Western Europe
- MIXED project: Multi-actor and transdisciplinary development of efficient and resilient MIXED farming and agroforestry-systems
- MJ: Megajoules
- kg: kilograms
- N: Nitrogen
- N<sub>2</sub>O: Nitrous oxide
- SRUC: Scotland's Rural College
- t: tons
- UAA: Utilized Agricultural Area
- UMR: Unité Mixte de Recherche (joint research unit)
- USA: United States of America

## Glossary of concepts

*This glossary of concepts is arranged alphabetically. It briefly summarizes some of the concepts mobilized in the manuscript (signalled by an asterisk), and defined in the specific context of this Ph.D. study.*

- **Actionable knowledge:** knowledge that is directly implementable by the users whom it is intended to engage (most often farmers in this Ph.D. study)
- **Diversified farming system:** farming system intentionally including biodiversity at diverse spatial levels and/or temporal scales
- **Economies of agglomeration:** reduction of production costs resulting of firms and people locating near one another, for instance in specialized crop or livestock regions. Such reduction of costs are mostly due to savings in transport costs, as well as in easy access to all the knowledge and services needed for a specific production.
- **Economies of scale:** *reduction of production costs resulting of making and selling farm products in large quantities.* In this Ph.D. study, such economies of scale are mostly related to the expansion of farms and to the intensification and specialization of farm production.
- **Economies of scope:** reduction of production costs resulting of sharing resources, processes, and skills in producing a larger range of products. In this Ph.D. study, such economies of scope are mostly related to integrated crop-livestock systems (e.g. using livestock manure produced on farm to decrease crop production costs due to reducing reliance on synthetic fertilisers).
- **Energy-neutral farms:** farms that produce as much energy as they consume
- **High-input specialized farms:** farms that rely on high levels of inputs (e.g. fertilizers, pesticides, concentrate feeds) to produce one type of crop or one type of livestock
- **Integrated crop-livestock systems:** farming systems that combine crop and livestock enterprises in interaction, with a wide diversity of spatial, temporal and organizational intensities of integration between crop and livestock enterprises
  - **Integrated crop-livestock systems at the farm level:** farming systems which combine crop and livestock enterprises on the farm (*equivalent to mixed crop-livestock farms in this Ph.D. study*)
  - **Integrated crop-livestock systems at the regional level** farming systems which combine crop and livestock enterprises at the regional level, through a partnership between a crop and a livestock farmer, implying temporarily hosting animals belonging to the livestock farmer on the crop farm (*also referred to as integration through a partnership or beyond farm level*)
- **Innovation:** Relative novelty implemented in practice

- **Livestock reintegration:** intentionally organized return of livestock onto specialized crop farms and into specialized crop regions. Such reintegration can happen at the farm or regional level (*see integrated crop-livestock systems at the farm level and integrated crop systems at the regional level*).
- **Mixed crop-livestock farms:** farms which combine crop and livestock enterprises
- **Researchers stances:** researcher's underlying beliefs, assumptions, worldviews and posture when doing research
- **Performances of an innovation:** degree to which the innovation meets initial expectations
- **Pre-niche phase of an innovation:** innovation that is implemented by pioneer actors (most often farmers in this Ph.D. study) but that, contrary to niche innovations, is not yet “anchored” in a protected market, network or ecosystem of innovation
- **Retro-innovation:** purposeful revival of historic practices, implying hybridizing them with new ideas to ground them in modernity
- **Self-sufficient farms:** farms which requires no or low levels of material (e.g. fertilisers, seeds, replacement animals, energy) or cognitive (e.g. knowledge, skills) inputs
- **Sociotechnical context:** set of determinants at the sociotechnical system level that can facilitate or hinder decisions for change of sociotechnical actors
- **Sociotechnical imaginary:** collective visions of desirable futures, shared by a diversity of actors from the sociotechnical system and institutionally stabilized
- **Sociotechnical system:** inter-related actors in interaction around technologies, practices, resources, regulations, services, infrastructure, collective representations and standards, and fulfilling a common societal function, such as farming. Such sociotechnical system can be divided into three interacted levels, according to the Multi-Level Perspective:
  - the **regime**, i.e. the currently dominant stable model of high-input specialized farming
  - the **niches**, i.e. protected spaces where innovations can be implemented
  - the **landscape**, i.e. elements of the broader context, such as cultural values, policies, climate change or market fluctuations





## Introduction

### Part I: The route to livestock reintegration: forward to the past?

#### **Objectives of this part:**

Emphasize the need to produce knowledge on the original and understudied farmer-led initiative of reintegrating livestock onto specialized crop farms and into specialized crop regions.

#### **Glossary concepts used in this part:**

Mixed crop-livestock farms, self-sufficiency, energy neutrality, high-input specialized farms, sociotechnical context, sociotechnical system, economies of scale, economies of agglomeration, diversified farming systems, integrated crop-livestock systems, integrated crop-livestock systems at the farm level, integrated crop-livestock systems at the regional level, economies of scope, livestock reintegration

#### I.1. Diversified mixed crop-livestock farms relying on multifunctionality and interactions between crop and livestock enterprises during the preindustrial era in France (1850s – 1950s)

Until the 1950s, in Europe and particularly in **France**, **preindustrial agriculture** was marked by the predominance of **diversified mixed crop-livestock farms\***, which combine several crop and livestock enterprises (Krausmann, 2004; Le Noë et al., 2018; Mazoyer and Roudart, 2002, p499). These farms were **self-sufficient\*** in that they produced more than enough to feed farm families without requiring nearly any inputs (e.g. fertilisers, seeds, replacement animals, energy) (Loehr, 1952; Mazoyer and Roudart, 2002). This self-sufficiency was ensured by a **diversity** of crops and livestock in **strong interaction**. Both the crop and livestock enterprises were **multifunctional** (Figure 1, Figure 2)(Krausmann, 2004; Mazoyer and Roudart, 2002). Diversified mixed crop-livestock farms were dominant in all French regions, with moderate differences among regions (Garnier et al., 2019). They had **low environmental impacts**, mainly due to their self-sufficiency (Garnier et al., 2019).

##### I.1.1. The multifunctional crop enterprise: providing human food and livestock feed while keeping soils fertile and weeds under control

The crop enterprise on preindustrial French farms had four main functions: i) providing **human food**, fibre and heat; ii) providing **livestock feed** and litter; iii) ensuring **soil quality**, especially fertility through nitrogen fixation and storage; and iv) promoting **biological weed control** (Rossing et al., 2007)(Figure 1).

On arable land, crop rotations thus contained a **variety of crops for human food** (e.g. beets, potatoes, wheat, barley, flax, lentils, chickpeas) that alternated with **fodder crops**, either **annual** or as **temporary pastures** (Figure 2). Fodder crops with high legume contents ensured **nitrogen fixation**, thus increasing **soil fertility** and helping to maintain crop yields in the long term. They also promoted **weed control**



and were used as **livestock feed**, either through grazing or harvesting as fodder. Along with arable land, family gardens provided all other products needed to ensure variety in farm family diets (e.g. vegetables, fruits). On soils less suited for cultivation, **permanent pastures** provided complementary feed for livestock. Woodlands produced firewood and could be grazed occasionally. Some of the harvested grain was kept as seed for the next growing season, which renewed genetic resources. Straw was used as livestock litter (Mazoyer and Roudart, 2002 p424).

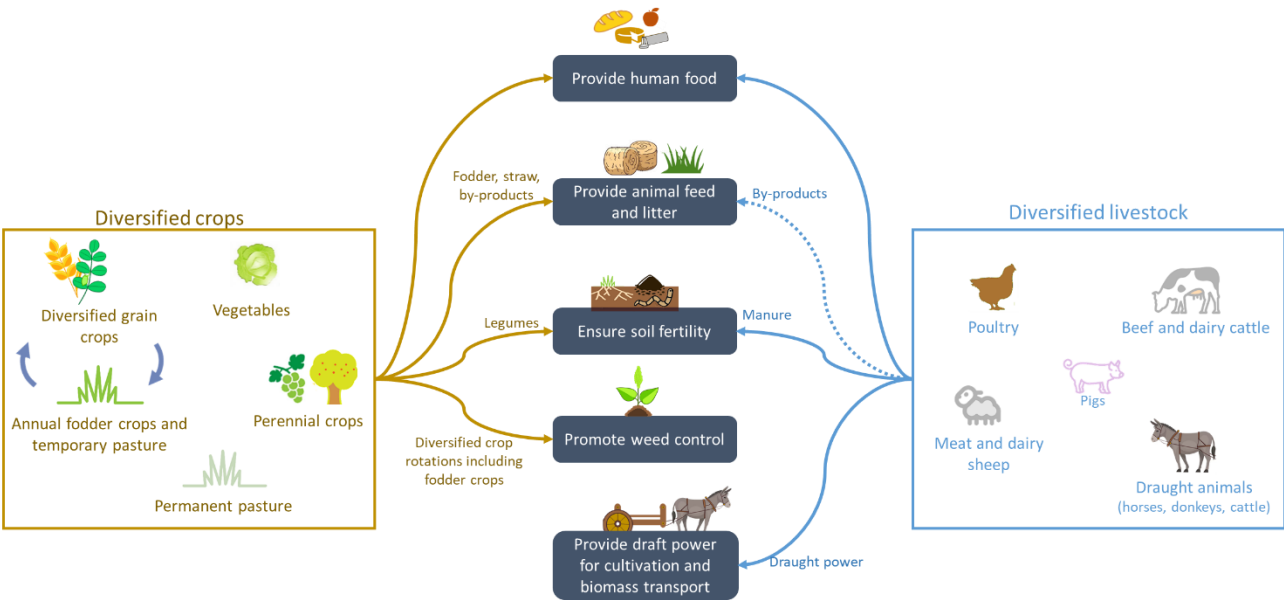


Figure 1. Main functions of the diversified crop and livestock enterprises on mixed crop-livestock farms of the preindustrial era

1.1.2. The multifunctional livestock enterprise: providing human food and draught power and contributing to soil fertility

The livestock enterprise had three main functions on preindustrial French farms: (i) providing **human food** and fibre, (ii) providing **draught power** for **cultivation** and biomass **transport** and (iii) contributing to **soil fertility** by converting plant biomass into **organic fertilisers** (Figure 1).

The livestock system was composed of a **diversity** of animal species, including dairy and beef cattle, small ruminants (sheep and/or goats for meat, milk and wool), pigs and poultry. It provided humans a variety of animal products for **food** and fibre. All livestock species were fed only **feed produced on the farm** (Figure 2). Monogastrics were fed grain and co-products of on-farm processing of crop and livestock products (e.g. wheat bran and whey for pigs). Ruminants **grazed outdoors** most of the year: on pastures in spring or in autumn after hay was cut, on stubble after crop harvests and occasionally in woodland. In winter, they were housed in barns, where they were fed fodder (Krausmann, 2004; Mazoyer and Roudart, 2002, p424). In mountainous areas, farmers also relied on **seasonal transhumance** to ensure sufficient livestock feed when feed production was lowest: valley farmers moved their livestock to high mountain pastures in summer (transhumance), while mountain farmers

moved their livestock to valleys in winter (reverse transhumance), often on valley farmers' fields (Brechon, 2013; Coulet, 1978).

Cattle, horses, mules and donkeys were used as **draught power**, such as for ploughing fields and temporary pastures, the only alternative being human power. **Animal traction** could also transport biomass on the farm (e.g. fodder from pastures to barns) or off the farm, as the surplus not used to feed the farm family was sold on **local markets** (Cerutti et al., 2014; Krausmann, 2004; Mazoyer and Roudart, 2002 p424; Spugnoli and Dainelli, 2013).

Livestock also promoted **soil quality** by increasing soil fertility due to **manure** production. First, they converted plant biomass into **nitrogen that was readily available** for crops (unlike the nitrogen stored in legumes, which requires more time to mineralize). Second, they provided the ability to **transfer fertility** from one place to another by **redistributing manure**: indoor livestock fed fodder from permanent pastures grown on soils less suited for cultivation produced manure that could be spread on arable land, thus transferring fertility from permanent pastures to arable land (Bernués et al., 2011; Krausmann, 2004; Mazoyer and Roudart, 2002, p424).

**Crop and livestock enterprises were thus strongly interdependent**: animals were fed crops and, in return, they helped ease crop cultivation and increase crop production by providing draught power and manure. The crop and livestock enterprises were connected by many flows of biomass, nutrients and energy (Figure 2).

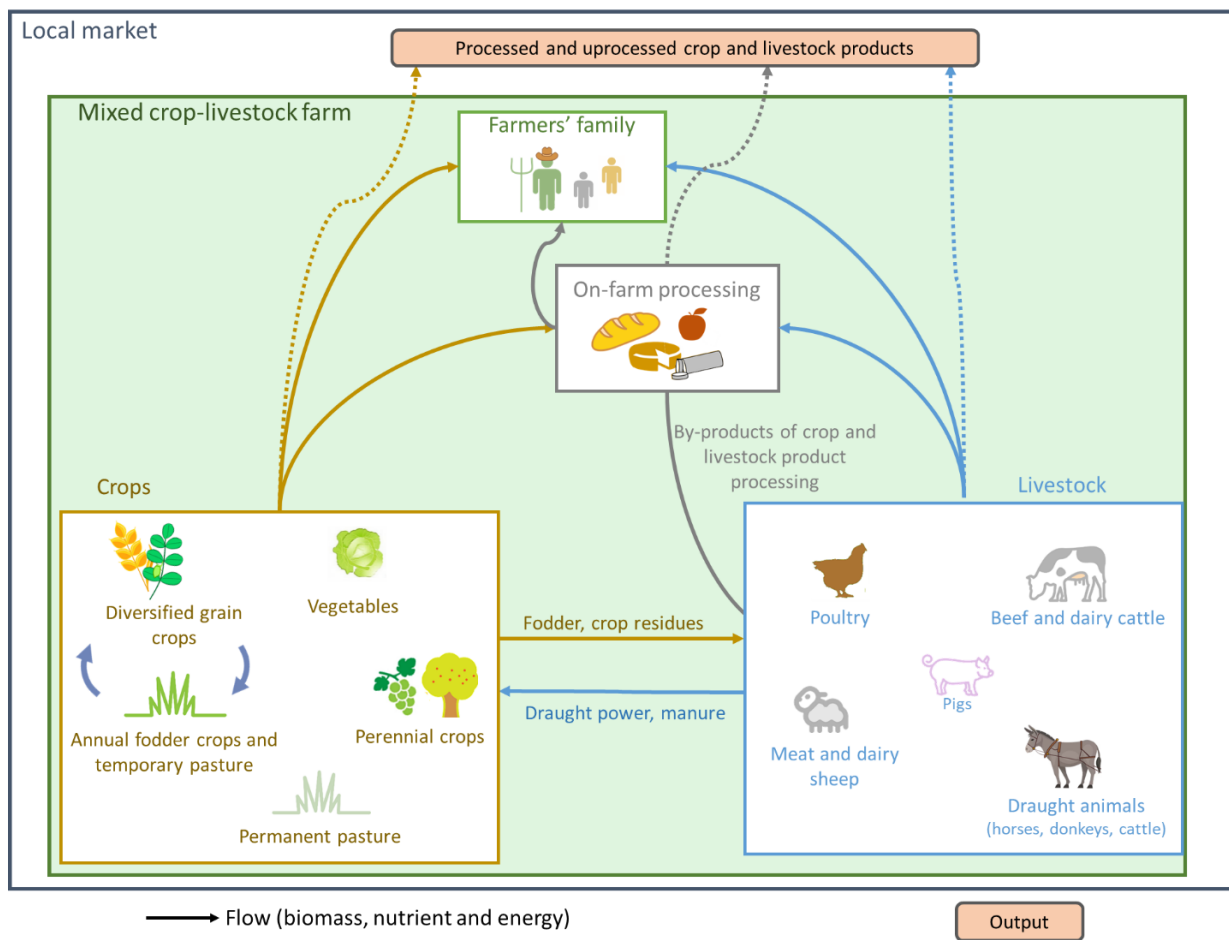


Figure 2. Biomass, nutrient and energy flows on self-sufficient mixed crop-livestock farms of the preindustrial era. Only flows between systems are shown. Flows within systems (e.g. seed renewal) are not shown.

### 1.1.3. Moderate differences in farming systems among French regions

As mentioned, during the preindustrial era, a diversity of crop and livestock enterprises in interaction were necessary to provide a varied diet to farm families while maintaining yields in the long term and limiting manual labour. Consequently, **most French farms were mixed crop-livestock farms**, which **differed moderately among French regions** which all had a **combination of crops, pastures and livestock** (Figure 3, in 1906) (Garnier et al., 2019; Mazoyer and Roudart, 2002). As early as 1906, some regions were already identified as grain-producing regions, such as the northern half of France, especially the Parisian Basin, whose rich loamy soils enabled high yields. These regions also often had the highest livestock density (e.g. the Parisian Basin) (Figure 3a, b), which emphasizes the **strong interdependence between crop and livestock enterprises** at this time (Figure 1, Figure 2). Permanent pastures covered more than 20% of the total agricultural area in all French regions outside of the Parisian Basin, and up to 60-80% in south-eastern France, with or without high livestock densities, which emphasizes the key role of pastures in crop enterprises (Figure 1) (Garnier et al., 2019).

#### I.1.4. Low yields and agroenvironmental impacts of preindustrial mixed crop-livestock farms

Mixed crop-livestock farms of the preindustrial era were small and had **low yields** overall (no more than ca. 3 t per ha for cereals (Mazoyer and Roudart, 2002, p. 508)). Nevertheless, these low yields covered the needs of farm families and left a small surplus that could be sold on local markets. As most of the French population farmed (76% in 1846 (Molinier, 1977)), these multiple small surpluses were sufficient to feed those who did not farm (Mazoyer and Roudart, 2002). From an environmental perspective, mixed crop-livestock farms of the preindustrial era can be considered **sustainable**. They relied on **synergies between crop and livestock enterprises**, which contributed to their self-sufficiency in biomass and nutrients (e.g. manure and feed produced on the farm, nitrogen fixation by legumes) (Figure 2). They were also **energy neutral\*** (i.e. provided all of the energy they needed), through food for farmers and feed for draught animals (Harchaoui and Chatzimpiros, 2019, 2018). They relied solely on renewable resources and did not overuse these resources (Krausmann, 2004). As they did not rely on external inputs of mechanization, energy, fertiliser or livestock feed, and as the livestock density was low, mixed-crop livestock farms of the preindustrial era had **low greenhouse gas emissions** (e.g. CO<sub>2</sub>, N<sub>2</sub>O, CH<sub>4</sub>) (Garnier et al., 2019). However, such diversified farming systems led to **busy work schedules**, due to combining management of grain crops, fodder crops, diverse livestock, on-farm processing and selling on local markets. Some tasks were also particularly arduous and time-consuming, such as manual milking. On some farms, crops were still cultivated manually. In addition, the decreasing ability of mixed-crop livestock farms of the preindustrial era to produce enough additional resources to feed an ever-growing population challenged their existence (Krausmann, 2004; Mazoyer and Roudart, 2002).

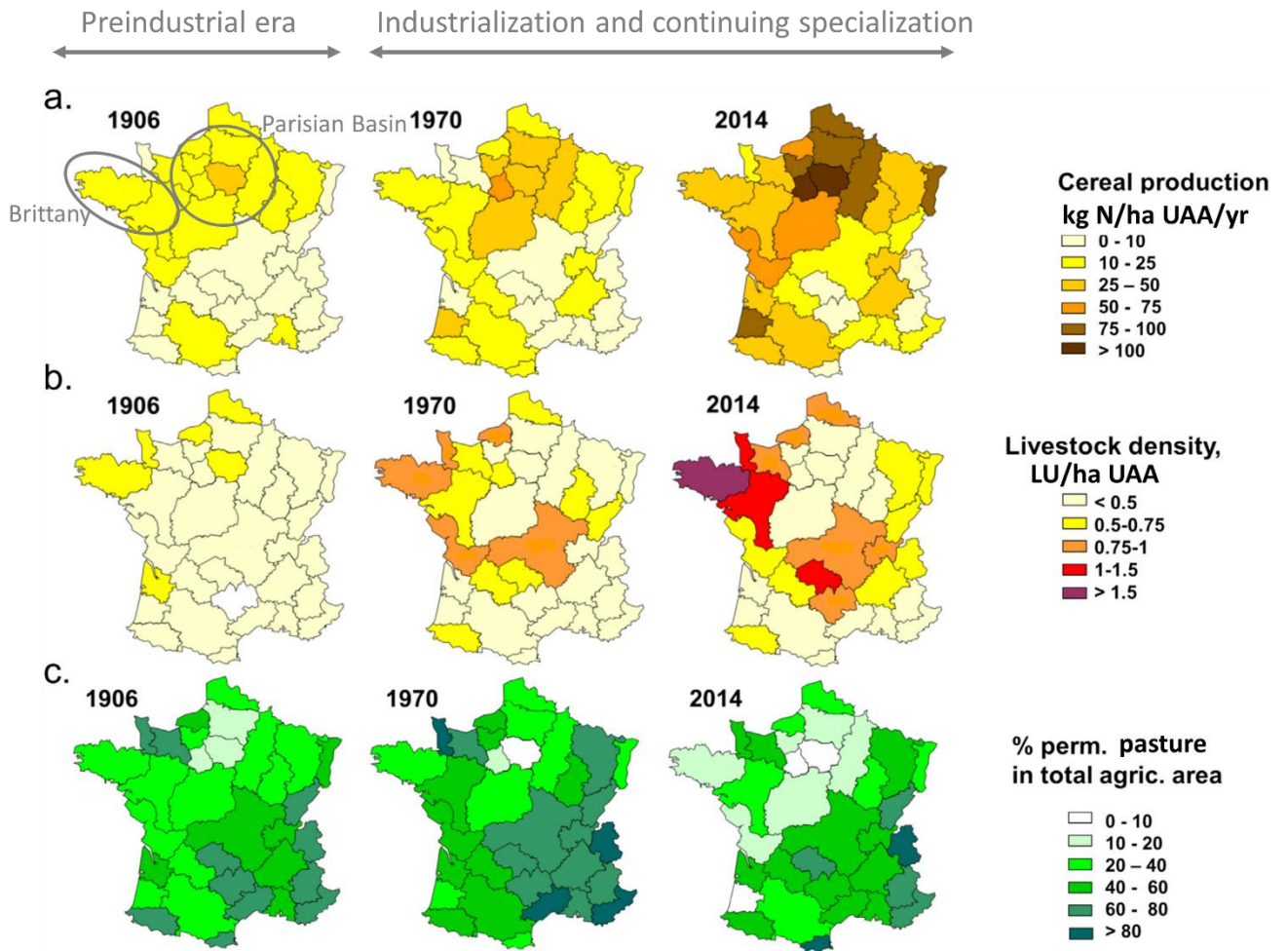


Figure 3. Maps of regional distributions in France of (a) cereal production, (b) livestock density and (c) percentage of permanent pasture in the total agricultural area for three dates (1906, 1970, 2014) representative of major periods. Adapted from Garnier et al. (2019). UAA: Utilized Agricultural Area. LU: Livestock Unit.

## 1.2. Intensification and specialization of agricultural production to feed the growing population during the second agricultural revolution (ca. 1950s), but with high environmental impacts

The second agricultural revolution and the major structural changes of which it was part made traditional mixed crop-livestock farms **obsolete**. It included a **disconnection between crop and livestock enterprises at the farm and regional levels**. Emerging **high-input specialized farms\*** greatly **increased yields and work productivity**, but they had **high environmental impacts** due to their **decreased self-sufficiency** in biomass, nutrients and energy (Garrett et al., 2020; Schiere and Kater, 2001).

## 1.2.1. Global changes leading to specialization

### 1.2.1.1. Overall context

During the 20<sup>th</sup> century, both French and global populations surged (from 41 to 65 million people in France from 1901 to 2021 (INSEE, 2023a), and from less than 2 to more than 8 billion people in the world from 1900 to 2024 (Ritchie et al., 2024)). The ever-decreasing percentage of farmers (7% of the working population in 1982, and less than 2% in 2022 (INSEE, 2023b)) in the **ever-growing global population** spurred efforts to increase farm production to **supply sufficient food**. It also **increased the cost of human labour** in farming. The simultaneous revolution in transportation (e.g. road infrastructure, ocean freight) made it easier to **exchange agricultural resources nationally and internationally**. Farmers thus needed to **produce more, at lower prices and with higher labour productivity to remain competitive at the global scale**. Farms **expanded and modernized**. They were encouraged by government initiatives, including subsidies to invest in newly developed techniques such as **mechanization, use of synthetic inputs and pesticides**, and regulation of land to favour farm expansion (Tavernier and Rimareix, 1963). From 1970 to 2010, farms with less than 50 ha of utilized agricultural area decreased from 81% to 63% of all French farms, while those with more than 100 ha increased from 2% to 18% (AGRESTE, 2010a). The mean farm size increased from 19 ha in 1970 to 53 ha in 2010 and 69 ha in 2020 (AGRESTE, 2020, 2010a; Mazoyer and Roudart, 2002; Tilman et al., 2002). On-farm processing and direct marketing were maintained only marginally.

### 1.2.1.2. Diversified mixed crop-livestock farms as obsolete...

Farmers' adoption of **mechanization, synthetic fertilisers and pesticides** drove a radical transformation of farming systems. As these new techniques fulfilled many of the functions previously ensured by diversified crop and livestock enterprises and their interactions, **mixed crop-livestock farms became obsolete** (Krausmann, 2004; Mazoyer and Roudart, 2002) (Figure 4, Figure 5). **Mechanization** replaced livestock as **source of power for transport and cultivation**. Tractor density increased by 337% from 1938-2010 (Domingues et al., 2018), as tractors, compared to animals, never needed to rest, could drag larger and heavier tools and even lift them, allowed farmers to work faster and plough deeper, and required less human labour. They required **fossil fuel energy** that could be purchased **at affordable prices**, which allowed farmers to use arable land previously used to grow feed for draught animals for other crops. **Synthetic fertilisers** provided **large amounts of soluble nitrogen that were readily available** for crops at **affordable prices**. They provided sufficient nutrients to crops rapidly **without having to rely on livestock manure or nitrogen fixation by legumes** (Schut et al., 2021). **Pesticides** were a turn-key solution to **manage pests and weeds** that **decreased the need to rely on diversified crop rotations** that included fodder crops (either annual or as temporary pastures) to break pest cycles (Jaworski et al., 2023; Martin et al., 2020b).

**Market globalization** allowed farmers to **import livestock feed** from all over the world at **affordable prices**, rather than growing it on their own farms, thus providing more land to grow crops for human food. In particular, input of **concentrate feeds with high protein contents** such as soya bean meal from the United States or South America benefited from lower prices after tariffs were eliminated by

international trade negotiations in 1967 (Chatellier and Gaigné, 2012; De Visser et al., 2014; Le Noë et al., 2018). They **replaced grain legumes** in monogastric feed **and fodder legumes** in ruminant feed.

In other words, **crop and livestock enterprises could be managed independently** by using large amounts of inexpensive and easily available inputs of biomass, nutrients and energy (Figure 5). The multifunctionality of crop and livestock enterprises decreased: their primary aim became to **produce ever more human food at ever lower prices** (Figure 4) (Krausmann, 2004; Mazoyer and Roudart, 2002).

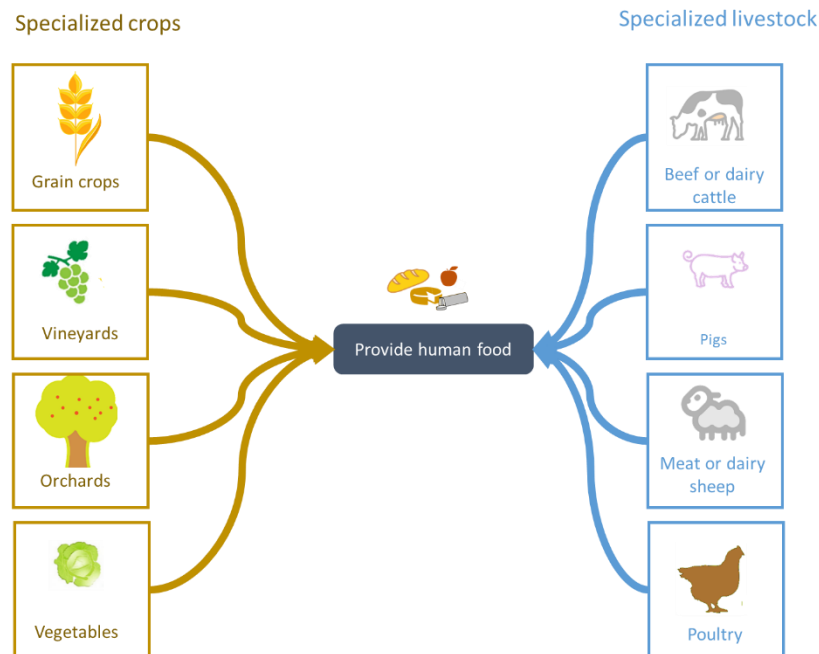


Figure 4. The main function of high-input specialized crop and livestock enterprises on farms after the second agricultural revolution

#### 1.2.1.3... leading to the specialization of farms ...

To become ever more competitive on the global market, **farms specialized** in the type of production that was the most economically beneficial given their **environmental and sociotechnical\* contexts** (e.g. soil-climate conditions, population density) (Garrett et al., 2020; Roguet et al., 2015; Schut et al., 2021). Many farms **specialized in grain crops**, whose production was promoted by the government and benefited from high selling prices and low production costs. The agricultural area dedicated to grain crops in France increased by 20% (from 9.9 to 12.3 million ha) from 1960 to 2010, while that dedicated to fodder crops decreased by 27% (from 20.0 to 14.5 million ha), respectively (Chatellier and Gaigné, 2012). These farms focused on **wheat or maize monocultures** or **simplified crop rotations**, such as rapeseed-wheat-barley, and used large amounts of inputs to maximize crop production (Figure 5). This was especially true for **large farms in lowland and valley regions**, which had already been identified as **grain-producing regions** (e.g. Parisian Basin, northern half of France) (Figure 3a in 2014).

Some **smaller farms** with little access to additional land specialized in **high-input livestock production** (e.g. in Brittany, Figure 3b in 2014). They raised mainly pigs, poultry or dairy cows using **high-yielding animal breeds, imported concentrate feeds** and (for dairy cows) relied on **maize silage** to maximize yields (Figure 5). In **mountainous area** where crops could not reach high yields due to soil-climate conditions, farms specialized in **extensive livestock production**, mainly dairy or beef cattle and meat sheep. They had low stocking rates and relied on rustic ruminant breeds that were essentially grass-fed (e.g. south-eastern France, with low cereal production, low livestock density and large areas of permanent pastures) (Figure 3). **Mixed crop-livestock farms were marginalized** and remained only in **intermediate areas** (e.g. hilly areas, certain valleys with shallow soils), where **neither crops nor livestock could be produced intensively** (Ryschawy et al., 2013; Schiere and Kater, 2001). The percentage of mixed crop-livestock farms in France decreased from 19% to 12% from 1988 to 2020, while specialized grain-crop farms increased from 37% to 52%, respectively, and specialized livestock farms decreased from 44% to 36%, respectively (AGRESTE, 2020, 2010b).

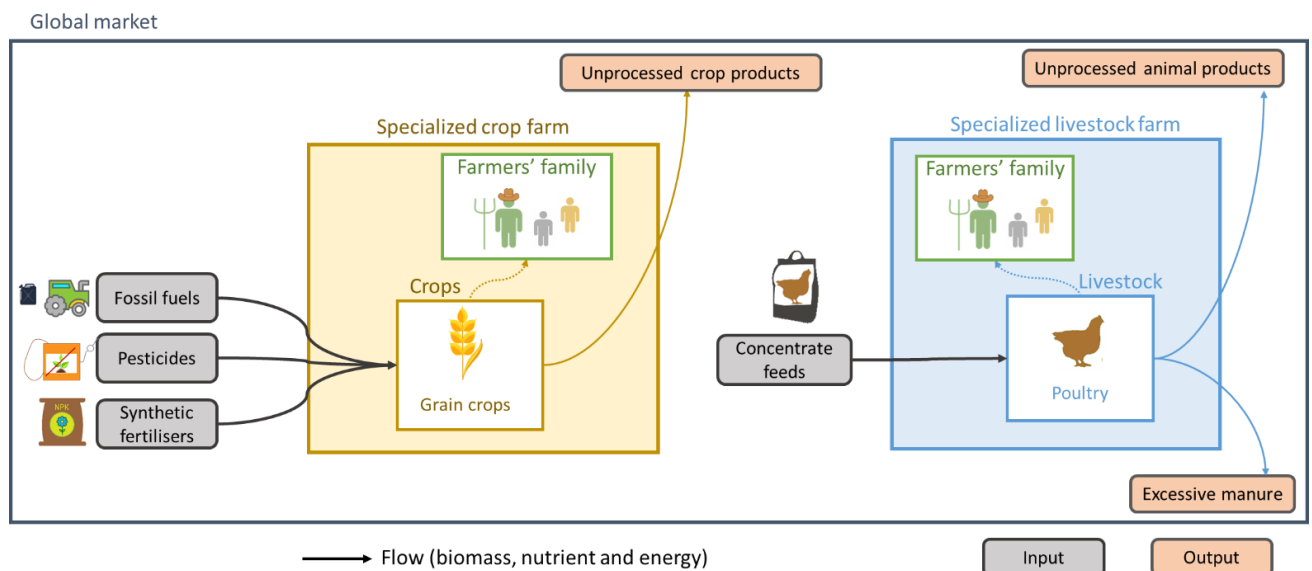


Figure 5. Biomass, nutrient and energy flows for high-input specialized crop and livestock farms (examples of specialized grain-crop and poultry farms). Only flows between systems are represented. Internal flows (e.g. seed renewal) are not shown.

#### 1.2.1.4 ...and to the specialization of regions

Overall, **by the end of the 20<sup>th</sup> century, farming in France was dominated by large farms specialized in one type of crop or livestock that relied on large amounts of inputs to obtain high yields** (Garrett et al., 2020; Roguet et al., 2015; Schut et al., 2021). As farms focused on the most economically beneficial production given their local conditions, farms from the same region often specialized in the same type of production, which led to **regional specialization** (Figure 3) (Le Noë et al., 2018). The specialization extended to the entire farming **sociotechnical system\*** (i.e. inter-related actors interacting around technologies, resources, regulations, services and infrastructure to fulfil a societal function) (here, farming) (Angeon et al., 2024; Geels, 2004). The concentration of farms specialized in



one type of production promoted the **concentration and specialization of the related agri-food sectors at the regional scale** (Chatellier and Gaigné, 2012). Establishing themselves near a large number of farmers ensured that upstream and downstream sectors could sell and buy large amounts of products with low transportation costs, which decreased their production costs through **economies of scale\* and of agglomeration\***. This trend enabled the agricultural sector to export products (e.g. cereals) to the global market at competitive prices, which helped increase its market shares and **self-reinforced the need to produce more**.

This concentration of specialized farms and sectors drove **more farmers to specialize in the dominant type of production of the region**. This specialization ensured that they would have **easy access to inputs** at low prices (e.g. fertilisers, pesticides, livestock feed). It gave them the opportunity to **share large investments** in machinery with other farmers, as done in CUMA (*Cooperatives d'Utilisation du Matériel Agricole* in French, which are cooperatives for the use of agricultural equipment), such as for harvesting machines in specialized crop regions or haying machines in specialized livestock regions (Chatellier and Gaigné, 2012; Lucas, 2021). It facilitated **hiring a workforce with specialized skills**. It also ensured that farmers would have access to all of the **services required for their production** (e.g. veterinarians in specialized livestock regions), and **processing facilities and outlets** for their products (e.g. grain storage in specialized grain-crop regions, hay-drying facilities and slaughterhouses in specialized livestock regions). It eased access to **knowledge**, through rapid information dissemination and sharing among farmers and between farmers and other specialized actors of the sociotechnical system concentrated in the region (e.g. technical advisors) (Chatellier and Gaigné, 2012). Following this trend, **research institutes, advisory services and subsidy programs specialized** towards crop or livestock systems, which led to **path dependencies toward specialization** (Garrett et al., 2020; Gil et al., 2016).

#### *1.2.1.5. Continuing specialization*

**Specialization in crop farming continues**, as shown by the decrease in the percentage of mixed crop-livestock farms in France from 12.6% to 11.9% from 2010 to 2020 (AGRESTE, 2020). Several factors explain this **continuing trend of decreasing livestock production and increasing crop production**. First, specialized crop farms have **lighter workloads**, with no need to perform daily livestock management (Bell and Moore, 2012; Martin et al., 2016). This is an **increasing preoccupation for farmers**, as the decreasing percentage of farmers in the global population strengthens their perception of an unbearable workload due to the striking contrast between their workload and those of their non-farming neighbours. Moreover, the ever-increasing number of animals and ha per worker associated with intensification and specialization generates additional workload, which is not completely compensated for by new technologies to ease livestock monitoring (e.g. cameras, sensors, automation) (Cialdella et al., 2009; Veysset et al., 2005). Second, for decades, **the costs of energy, synthetic fertilisers and pesticides** needed for specialized crop production **have increased more slowly than that of labour**, which is difficult to avoid in livestock farming (e.g. for milking or calving) (Martin et al., 2016; Peyraud et al., 2014). This led to **higher potential profits for specialized crop farms**, which also benefited from high selling prices. Third, **new norms on livestock buildings** also

made modernizing them prohibitively expensive, which **discouraged many farmers from doing so** to continue producing livestock (Martin et al., 2016; Peyraud et al., 2014). In particular, **beef cattle and meet sheep production have suffered from selling prices** that are lower than production costs, and remain **unprofitable without current Common Agricultural Policy (CAP) subsidies** (Chatellier and Gaigné, 2012). The continuous **decrease in services related to livestock production**, such as slaughterhouses or veterinarians, in regions where livestock production had been decreasing for a long time, **accelerated the abandonment of livestock production**, thus **self-reinforcing regional specialization in crop production** (Martin et al., 2016; Moraine et al., 2014). CAP subsidies that promoted maintaining permanent pastures were not sufficient to slow down this specialization (Chatellier and Gaigné, 2012). **Currently, crop production and livestock production are profoundly disconnected at both the farm and regional levels.** For instance, a map of crop production in France in 2014 is the exact opposite of the map of livestock production (Figure 3).

#### 1.2.2. Outcomes of farm intensification and specialization: increased production at high environmental costs

**The modernization and specialization of farming allowed the main aims of the second agricultural revolution to be reached: to produce more food, which was sold at lower prices.** The **surplus generated by farms** increased by a factor of 4 during the second agricultural revolution (Harchaoui and Chatzimpiros, 2018). Cereal yields surged from a mean of 3 to 10 t per ha per year (Mazoyer and Roudart, 2002, p506). Dairy cow production increased from a mean of 2000 to 10 000 L of milk per cow per year (Mazoyer and Roudart, 2002, p513), which caused milk production to increase by 145% from 1938-2010 (Domingues et al., 2018). While French agricultural production was insufficient to feed the population of France inhabitants in 1970, it increased to the point that France became a net exporter of agricultural products in 2000. In particular, France is one of the main wheat-exporting countries at the global scale (Chatellier and Gaigné, 2012). **Work productivity** also exploded. In grain-crop systems, it increased from ca. 10 ha to more than 150 ha per farm worker, with a corresponding increase from 250 to 2000 t of grain produced (Mazoyer and Roudart, 2002, p505). In livestock systems, the milking capacity of workers increased from ca. 12 to 200 dairy cows per worker per day (Mazoyer and Roudart, 2002, p506).

However, **agricultural production has been identified as one of the main contributors to exceeding planetary boundaries of sustainability** (Campbell et al., 2017; Richardson et al., 2023; Rockström et al., 2023; Steffen et al., 2015). **Environmental impacts of high-input specialized farming systems** are now widely acknowledged to contribute to climate change, biodiversity loss, disruption of biogeochemical flows, soil and water pollution, and soil erosion (Matson et al., 1997; Tilman et al., 2002). **On specialized crop farms and in specialized crop regions, the disconnection from livestock production and the simplification of crop rotations**, in particular the **drastic decrease in fodder-legume production, deprived farms of the ecosystem services provided by such crops and livestock** (Ballot et al., 2022; Schott et al., 2010). These services include nitrogen supply by legumes and manure, soil quality maintenance due to manure and carbon sequestration under grasslands (Franzluebbers et al., 2014), biodiversity promotion and pest and weed control through the presence of fodder crops, in

particular temporary and permanent pastures, diversified crop rotations and heterogeneous landscape mosaics (Bretagnolle et al., 2011). To **compensate for this loss of ecosystem services, specialized crop farms and regions became increasingly reliant on large amounts of synthetic fertilisers, pesticides and energy inputs** (Lemaire et al., 2014). This led them to become **structurally deficient in energy**, with the energy contained in their products nearly equalling the direct (e.g. fuel consumption) and indirect (e.g. energy needed to produce synthetic fertilisers) energy required to produce it (Harchaoui and Chatzimpiros, 2018). Conversely, on specialized livestock farms and in specialized livestock regions, **disconnection from crop production drove the massive increase in inputs of livestock feed**, often in the form of concentrate feed, to feed animals a standardized diet indoors, which optimized production. High-input specialized livestock systems generate **more manure** than can be spread on the arable land available, which leads to **storage, disposal and pollution problems** (Figure 5) (Lassaletta et al., 2009; Peterson et al., 2020). Specialization of farms and regions thus leads to **long-distance flows of biomass and nutrients**, which generate additional energy consumption and greenhouse gas emissions. Greenhouse gas emissions of French agriculture increased from 30 to 114 million t of CO<sub>2</sub> equivalent from 1955 to 2014, respectively (Garnier et al., 2019).

**The high environmental impacts of high-input specialized farming systems, which remain predominant today, thus raise questions about their sustainability.** Beyond these impacts, these systems **increased inequalities among farmers**. In 2018, specialized crop farmers had a higher mean income than specialized livestock farmers did, regardless the type of crop or livestock production (Figure 6)(INSEE, 2021). High-input specialized farming systems led most farmers to suffer from **low income** and poor working conditions (Chartier and Chevrier, 2015). In 2018, the mean percentage of agricultural households living under the poverty line of 11 270 € per year was 18.1%, compared to 14.8% for the entire French population (INSEE, 2021, 2020). Once again, it differed among types of production: 19.7% for mixed crop-livestock farmers, 25.1% for specialized beef-cattle farmers and 13.5% for specialized grain-crop farmers (INSEE, 2021). Farmers also face **ever more challenging conditions** (e.g. climate change, market price fluctuations, societal pressure), which have led many to call for **transforming farming systems completely** (IAASTD, 2009; IPES-Food, 2016; McGreevy et al., 2022; Prost et al., 2023; Willett et al., 2019).

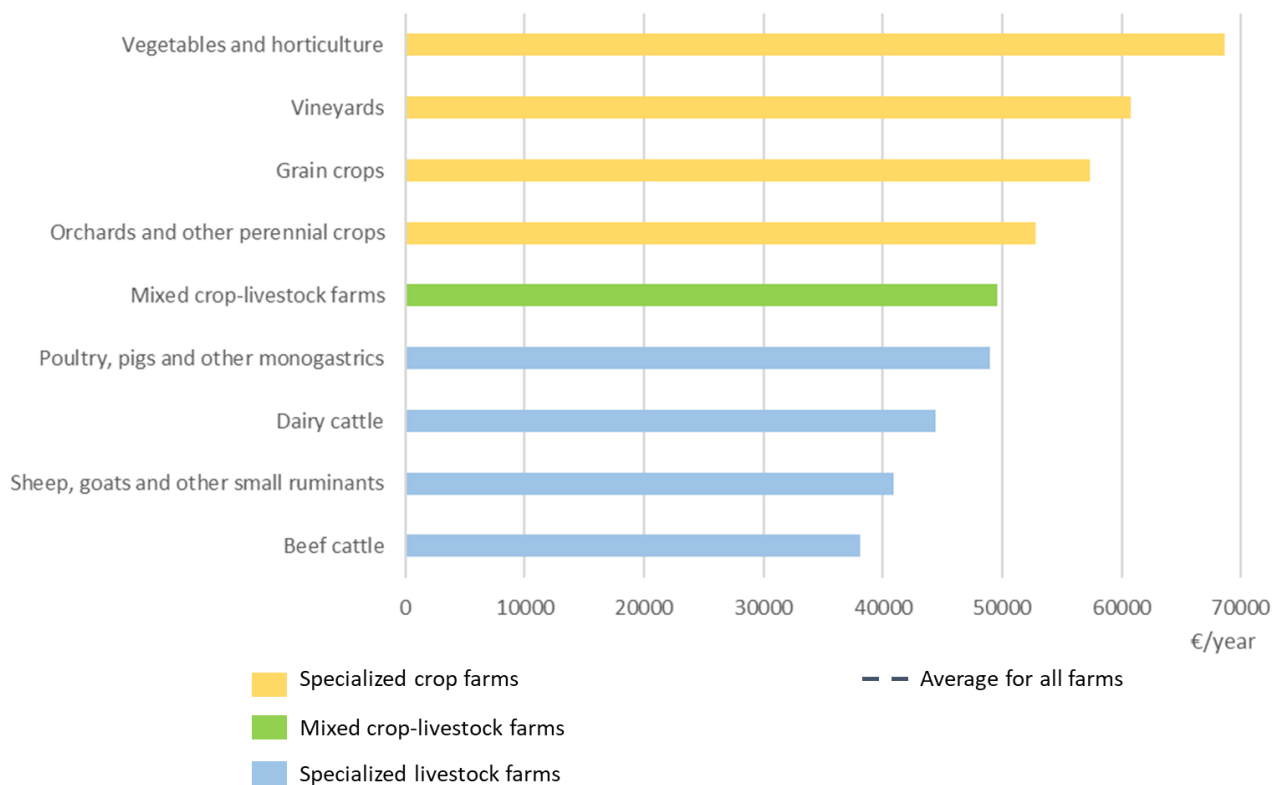


Figure 6. Mean annual farm income in France by economic and technical orientation. Adapted from INSEE (2021).

### I.3. Improving farm sustainability through agroecology (2000s – present), and reintegrating livestock as a way to do so?

#### I.3.1. Improving farm sustainability through diversity and self-sufficiency with agroecology

In response to this call, **agroecology** emerged as an **alternative critique of high-input specialized farming systems** (Altieri, 1989; Gliessman, 2018; Wezel et al., 2009). It first appeared in Latin America in the 1980s and spread across North America and Europe during the late 20<sup>th</sup> – early 21<sup>st</sup> century, in the form of niche initiatives. In France, it gained momentum in 2012, when Stéphane Le Foll (the French Minister for Agriculture from 2012-2017) widely communicated about the need to transition to agroecology and implemented the “Agroecological Project for France” (French Ministry of Agriculture Agrifood and Forestry, 2016; Lucas, 2021; Wezel and David, 2020). Beyond the continuing debate on the exact nature of agroecology (i.e. a science, a movement and/or a practice) (Francis et al., 2003; Wezel et al., 2009), **the core agroenvironmental elements of agroecological systems are widely consensual** (Barrios et al., 2020; FAO, 2018).

Agroecological systems aim at **improving farm sustainability by decreasing their reliance on inputs**. To this end, they build on increased **crop and livestock diversity**, as well as **internal biomass and nutrient cycling**. These principles of diversity and **self-sufficiency** can be enacted in different ways. In particular, crop and livestock diversity can exist at **multiple interconnected levels** (Box 1, Figure 7) and contribute to farm self-sufficiency in multiple ways (Duru et al., 2015; Kremen et al., 2012; Vialatte et

al., 2022). For instance, on-farm production of organic fertilisers caused by nitrogen fixation by legumes and/or storage of livestock manure decreases reliance on nitrogen fertilisers. On-farm production of livestock feed from grain and fodder crops decreases reliance on concentrate feeds, while diversified crop rotations decrease reliance on pesticides. **Mixed crop-livestock farms of the preindustrial era implemented such practices and relied on synergistic interactions between crop and livestock enterprises to reach self-sufficiency** (Figure 1, Figure 2). They can thus be considered as **agroecological**.

**Diversified farming systems** are defined in this manuscript following Kremen et al. (2012) as farming systems “intentionally including functional biodiversity at multiple spatial and/or temporal scales, through practices developed via traditional and/or agroecological scientific knowledge”.

**Crop and livestock diversity can exist at several interconnected spatial and temporal levels** (FAO, 2018; Vialatte et al., 2022) (Figure 7):

- at the **plant or animal level**, via the genetic diversity of plant cultivars and animal breeds (Des Roches et al., 2018; Raffard et al., 2019)
- at the **field level**, via the diversity of crop and livestock species, which can be managed **simultaneously** (e.g. intercropping (Bedoussac and et al., 2014; Jensen et al., 2020; Stomph et al., 2020), grazing several livestock species simultaneously) or **in rotation** (e.g. diversified crop rotations, grazing several livestock species rotationally) (Ballot et al., 2022; Magrini et al., 2016; Malézieux and et al., 2009; Martin et al., 2020a)
- at the **farm level**, via the diversity of crop and livestock enterprises (Bosshardt et al., 2022; Hendrickson, 2020; Martin et al., 2020a; Morel et al., 2016; Paut et al., 2019)
- at the **landscape level**, via the diversity of habitats (e.g. crop fields, hedgerows, woodland) (Neyret et al., 2023; Santos et al., 2021)

*Box 1. Diverse interconnected levels of crop and livestock diversity*

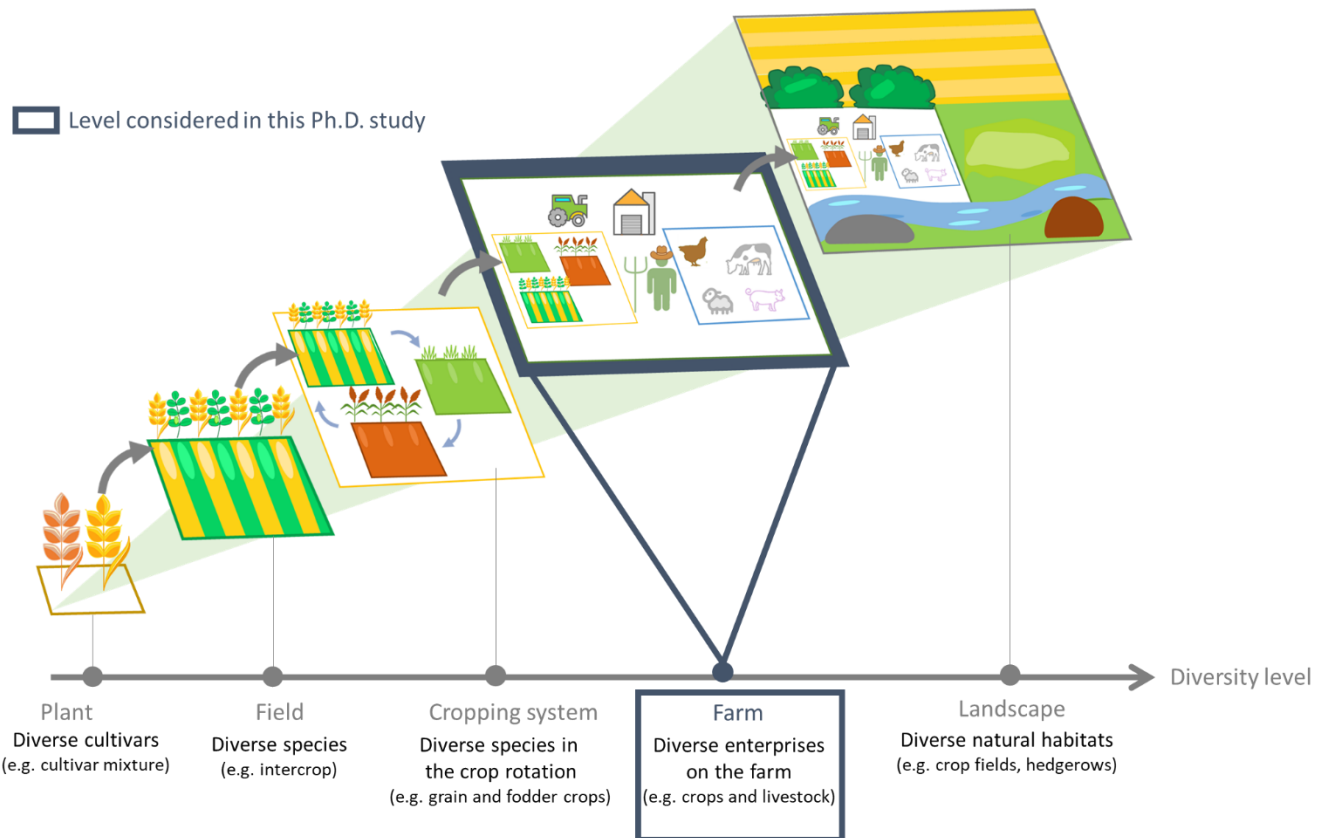


Figure 7. Interconnected levels of crop and livestock diversity, and identification of the level studied in this Ph.D. study.

The umbrella definition of agroecology encompasses a **wide variety of farming systems**, which makes it **difficult to quantify the number of agroecological farms** currently in France. In particular, there is **no specific database** that lists agroecological initiatives, which remain niche (Lucas, 2021). For instance, organic farming is likely the most widespread agroecological initiative in France. It is also the only one that can be quantified accurately, as data can easily be collected through the mandatory certification process. Organic farms represented 14% of French farms and 10% of French agricultural area in 2023 (Agence Bio, 2024). These values can serve as **proxies for the overall percentages of agroecological farms in France**. Indeed, agroecological and organic systems have similar characteristics, even though they are not exactly the same. For instance, diversity in the crop and/or livestock enterprise is a key principle of both agroecology (FAO, 2018) and organic farming (IFOAM, 2008). Even though not all agroecological systems are organic, most agroecological practices are implemented on organic farms (IFOAM, 2019). Nevertheless, organic farms can also digress from agroecological principles. This is the case in most conventionalized organic systems, which replace synthetic inputs with organic ones rather than transforming their farming systems, as required by agroecology (Darnhofer et al., 2009; Hill and MacRae, 1996).

### 1.3.2. Integrated crop-livestock systems as an example of agroecological farming system

**Integrated crop-livestock systems (ICLS)** have long been promoted as one archetype of **agroecological farming systems** for producing large amounts of food while decreasing environmental impacts

(Bonaudo et al., 2014; Garrett et al., 2020; IPCC, 2018). They rely on **synergistic interactions between the diversity in crop and livestock enterprises to increase biomass and nutrient cycling**, which can **decrease and sometimes even replace synthetic inputs and energy consumption** (e.g. livestock grazing replacing mechanical termination of cover crops) (Barrios et al., 2020; FAO, 2018; Martin et al., 2016). ICLS have thus been extensively studied for several years.

### *1.3.2.1. Diverse forms of integrated crop-livestock systems*

#### *Forms of integrated crop-livestock systems*

In the simplest definition, ICLS are **farming systems that combine crop and livestock enterprises in interaction**. This umbrella definition encompasses a **wide variety of farming systems** (Bell and Moore, 2012; Bonaudo et al., 2014; De Moraes et al., 2014; Martin et al., 2016; Schiere and Kater, 2001).

- ICLS can involve **all crop** (annual or perennial) **and livestock** (monogastric or ruminant) **species** (Assmann et al., 2014; Niles et al., 2018; Paut et al., 2021; Stark et al., 2018)
- ICLS integrate crop and livestock enterprises in two ways:
  - **on the same farm**, such as on the mixed crop-livestock farms mentioned, which is also called **ICLS at the farm level\*** (Schiere and Kater, 2001). In this Ph.D. study, I use both terms interchangeably, as the literature does not distinguish them clearly.
  - **between farms**, which is also called **ICLS at the regional level\*** (Schiere and Kater, 2001). In this case, a **crop farmer and a neighbouring livestock farmer decide to partner and coordinate their actions**. This kind of partnership can involve, for instance, adjusting the crops grown on the crop farm to sell them as feed to the livestock farm. It can also involve hosting the livestock farmers' animals to graze cover crops on the crop farm during winter. ICLS at the regional level involve **crop and livestock farmers**, and sometimes **third parties**, such as technical advisors who can **help establish and manage their partnerships** (Moojen et al., 2023).
- ICLS cover a **gradient of spatial, temporal and organizational intensities of integration between crop and livestock enterprises at the farm and/or regional level** (Figure 8). Crop and livestock enterprises can remain **spatially segregated at all times**, such as for indoor sheep on a mixed crop-livestock farm or for a crop farm and a livestock farm in a partnership without animal movement. Crop and livestock enterprises can also **be co-located at least occasionally**, such as for sheep grazing on cover crops, either on a mixed crop-livestock farm or through a partnership between farms. If crops and livestock are spatially segregated, they can be managed for **coexistence**, which implies a few occasional and opportunistic biomass flows (e.g. occasionally using sheep manure on crop fields, either on the same farm or through exchanges between farms). Spatially segregated crop and livestock enterprises can also be managed for **complementarity**, which involves adapting the crop and/or livestock enterprise to consider the interaction and promote biomass and nutrient cycling. For instance, the composition of a cover crop can be adjusted to make it more nutritious for livestock, either on a mixed crop-livestock farm or in a partnership. If crop and livestock enterprises are spatially co-located at least occasionally, this co-location can occur in **rotation**, such as grazing sheep on temporary

grassland in rotation with grain crops, either on a mixed crop-livestock farm or in a partnership. Co-location of crop and livestock enterprises can also be **synchronized**, such grazing sheep vineyard inter-rows or cereals at early stages (Bell and Moore, 2012; Martin et al., 2016; M. Moraine et al., 2017).

In recent years, the diversity of ICLS has been widely studied in **many regions of the world**, such as South America (Bonaudo et al., 2014; De Moraes et al., 2014; dos Reis et al., 2021; Peyraud et al., 2014), Africa (Smith et al., 1997; Thornton and Herrero, 2014), Asia (Devendra and Thomas, 2002; Thorne and Tanner, 2002), the USA (Garrett et al., 2020; Hendrickson, 2020; Sulc and Franzluebbers, 2014), Australia (Bell and Moore, 2012; Nie et al., 2016) and Europe (Bonaudo et al., 2014; Lazcano et al., 2022; Peterson et al., 2020; Peyraud et al., 2014; Puech and Stark, 2023; Ryschawy et al., 2012; Schut et al., 2021). Studies have long focused on **systems that integrate crop and livestock enterprises at the farm level** and that persisted throughout history (de Koeijer et al., 1995; Ryschawy et al., 2013). Although such farming systems are still documented today (Pédèches et al., 2023; Puech and Stark, 2023), more recent studies also focus on **ICLS at the regional level**, by documenting initiatives of **reconnection between crop and livestock farms in regions where both types of production still exist** (Asai et al., 2018; Garrett et al., 2020; Martin et al., 2016; Niles et al., 2018). In Western countries, most studies on ICLS have focused on **grain crops, orchards or vineyards**, while market gardens have rarely been studied (Lenssen et al., 2013; Paut et al., 2021; Ryschawy et al., 2021). Similarly, the livestock species considered are almost always **ruminants**, usually **sheep** (Brewer et al., 2023a; McKenzie et al., 2016), especially in ICLS at the regional level (Niles et al., 2018; Paut et al., 2021; Ryschawy et al., 2021), and **sometimes beef cattle**, usually for ICLS at the farm level that persisted for years (Assmann et al., 2014; Puech and Stark, 2023; Ryschawy et al., 2012). Monogastrics in ICLS have rarely been studied (Bosshardt et al., 2022; Paut et al., 2021).



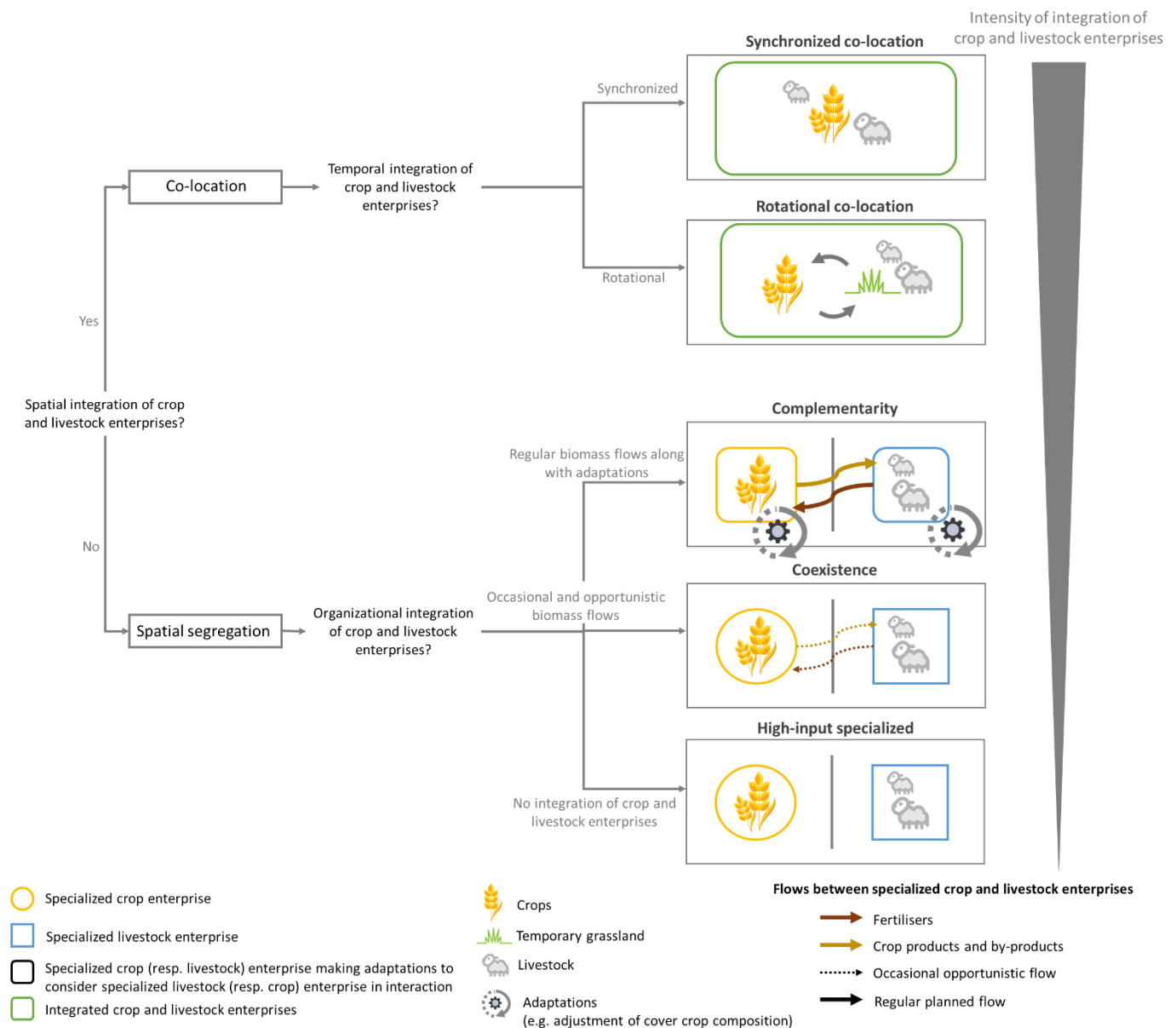


Figure 8. Spatial, temporal and organizational intensities of integration between crop and livestock enterprises at the farm or regional level

### A brief focus on mixed crop-livestock farms in the 21<sup>st</sup> century

**Mixed crop-livestock farms** are a specific form of ICLS that have been developed since the preindustrial era (section 1). The **mixed crop-livestock farms of the 21<sup>st</sup> century** are **modernized versions of those of the preindustrial era** (Figure 9). In particular, they continue to rely on **interactions between crop and livestock enterprises**, using crops to feed livestock and livestock manure to fertilize crops. However, to increase their yields and ease the workload, they also **partially specialized and implemented new techniques**. Most mixed crop-livestock farms combine a **single crop enterprise** (e.g. grain crops in rotation with fodder crops) with a **single livestock enterprise** (e.g. dairy cows). They rely on **mechanization**, which replaces animal traction (e.g. for ploughing or biomass transport) and manual work (e.g. for milking). They also use **modern transport facilities** to move livestock to distant fields more easily, which was previously done on foot. Mixed crop-livestock farms often rely on **inputs**

of **genetic materials** (e.g. seeds, semen) to benefit from higher-yielding cultivars and breeds. They use **pesticides, synthetic fertilisers and concentrate feeds** as **complementary tools** to increase and ensure crop and livestock production. For instance, concentrate feed inputs ensure that livestock needs are met if the fodder harvest is low. Farmers also rely on **new technologies** to make work easier, for instance using cameras and sensors to monitor livestock remotely or identifying cow oestrus more precisely. They often use **social media** to share knowledge with other farmers (Prost et al., 2024). They usually do not perform on-farm processing or direct marketing.

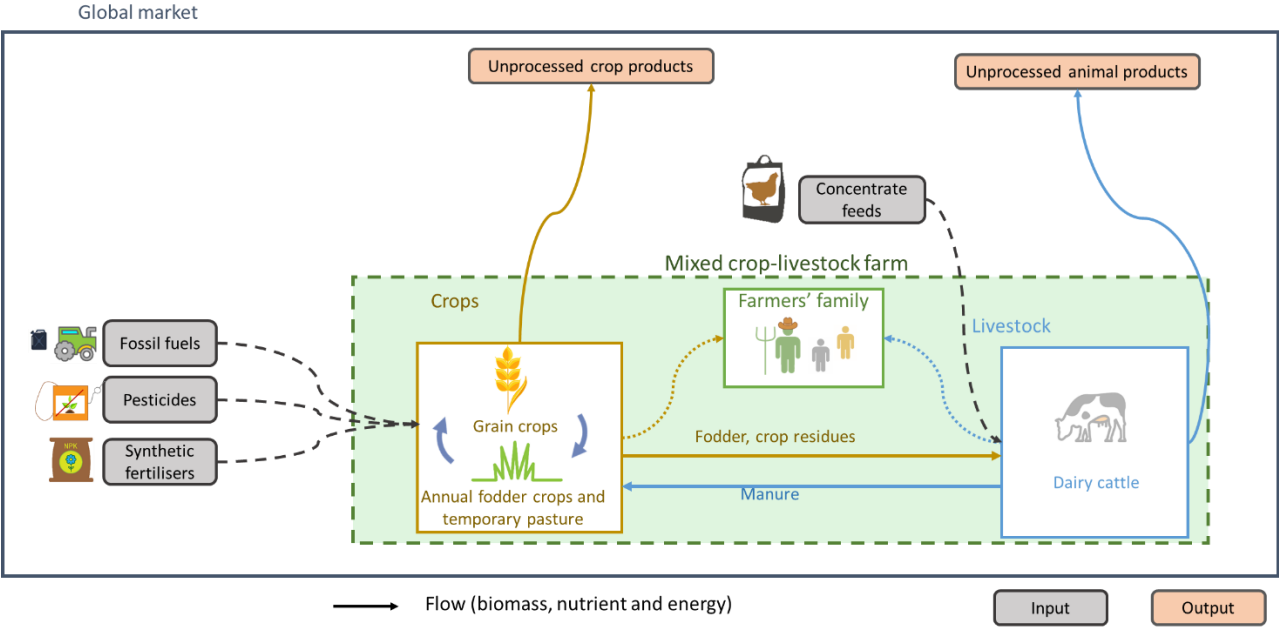


Figure 9. Biomass, nutrient and energy flows for mixed crop-livestock farms in the 21<sup>st</sup> century (example of a grain-crop – dairy cattle farm). Only flows between systems are represented. Internal flows (e.g. seed renewal) are not shown.

1.3.2.2. Sustainability of integrated crop-livestock systems and barriers to and levers for scaling them up  
 Integrated crop-livestock systems at the farm level

**ICLS at the farm level** have attracted much attention for their **expected benefits in all three dimensions of sustainability** (Figure 10). Regarding the **environmental dimension**, as mentioned (sections 1.1, 1.2 and 2.2), including **fodder legumes**, especially pastures, in crop rotations and applying **livestock manure** to crop fields helps **improve soil quality** (i.e. structure, fertility, biodiversity and microbial activity) and internal **biomass and nutrient cycling**. It thus helps **decrease soil erosion risks** (Brewer et al., 2023a; Franzluebbbers et al., 2014; Hendrickson et al., 2008; Lemaire et al., 2014) and **water pollution** due to nitrate leaching (Gil et al., 2018; Peterson et al., 2020; Schut et al., 2021). **Animal grazing** provides an **alternative to mechanization or herbicides** for managing grass in vineyard and orchard rows and inter-rows. Combined with a **diversified crop rotation** on annual crop farms, **animal grazing** also helps improve **weed management** and **biodiversity**. It thus helps decrease

**pesticide and energy consumption**, as well as **decreasing greenhouse gas emissions** (Bretagnolle et al., 2011; Brewer and Gaudin, 2020; De Moraes et al., 2014; dos Reis et al., 2021; Niles et al., 2018).

In the **economic dimension**, a **diversity of enterprises and increased self-sufficiency** in material inputs allowed by **interactions between crop and livestock enterprises** can lead to **economies of scope\* and decrease production costs**, such as by decreasing mechanization, fertiliser and pesticide inputs. ICLS can thus, in some cases, **have higher profitability and resilience to climate and market risks** than specialized crop or livestock farms (Bell et al., 2021; Gil et al., 2018; Peterson et al., 2020; Ryschawy et al., 2012; Schiere and Kater, 2001; Veysset et al., 2014). To date, fewer studies have assessed **social benefits** of ICLS at the farm level, which are however promoted as **being more acceptable to citizens** than high-input specialized crop or livestock farms (Julie Ryschawy et al., 2017; Ryschawy et al., 2021).

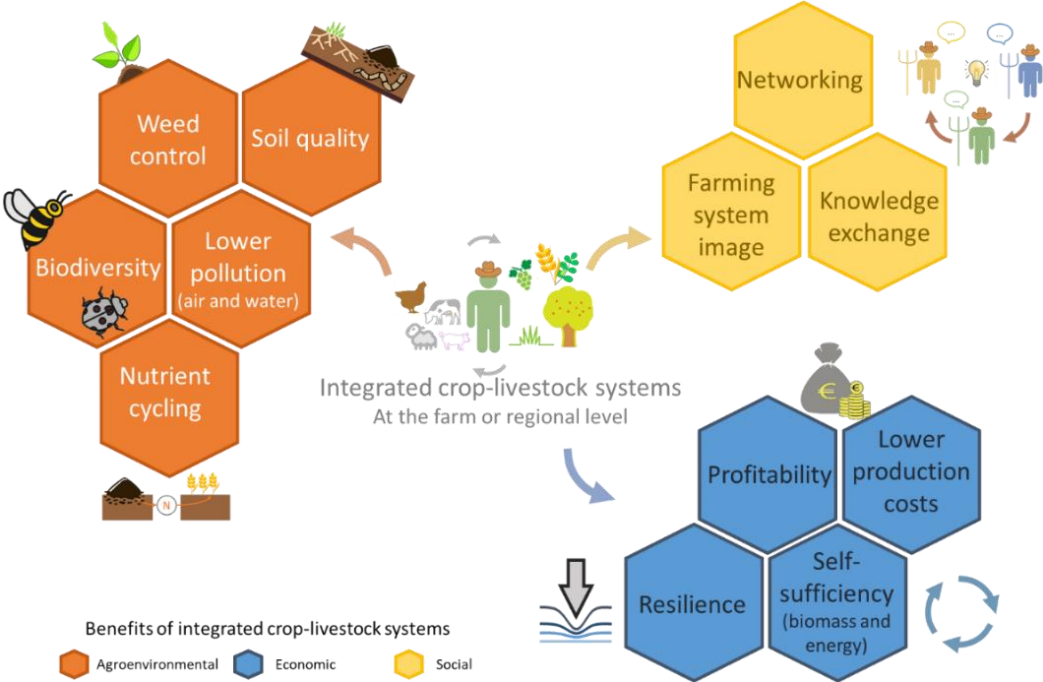


Figure 10. Agroenvironmental, economic and social benefits of integrated crop-livestock systems at the farm or regional level documented in the literature

Despite these **potential benefits**, studied by researchers and perceived by farmers (Cortner et al., 2019), there are many complex **barriers** that need to be overcome to **revert to mixed crop-livestock farms** (Figure 11). Reverting from specialized crop farms to mixed crop-livestock farms involves **expensive investments**, such as machinery for haying, livestock buildings or fences. It also implies **acquiring or re-discovering the skills and knowledge** required to manage mixed crop-livestock farms. Such knowledge, as well as the potential benefits of ICLS and ways to obtain them, have often been **long forgotten** (by farmers and technical advisors) on farms and in regions where livestock production has been decreasing for decades. Reverting to mixed crop-livestock farms also implies **increasing workloads** and may require **hiring a versatile skilled workforce**, which is also difficult to find in

specialized cropping regions (Coquil et al., 2014; Garrett et al., 2020; Martin et al., 2016; Ryschawy et al., 2013).

#### Integrated crop-livestock systems at the regional level

**ICLS at the regional level** can provide the opportunity to **remove these barriers**. Partnerships between crop and livestock farmers allow them to **benefit**, to some extent, **from the economic and environmental benefits of synergies between crop and livestock enterprises** (Figure 10) (Asai et al., 2018; Martin et al., 2016; Moraine et al., 2014). For instance, livestock farmers who provide manure to crop farmers can avoid storing and applying excess manure on their farms, thus decreasing nutrient runoff, while improving soil fertility on the crop farms. In return, the crop farmers can include fodder legumes in their crop rotations for the livestock farmers to use as feed. The former thus benefit from the related ecosystem services and help increase livestock farmers' local self-sufficiency in feed. Such partnerships require only slightly more skills, infrastructure and workload than does reverting from specialized crop or livestock production to mixed crop-livestock farming (Asai et al., 2018; Garrett et al., 2020; Martin et al., 2016). ICLS at the regional level can also contribute to **collective empowerment of farmers** through networking and knowledge exchange (Martin et al., 2016). To date, however, these advantages expected from ICLS at the regional level have **rarely been assessed on commercial farms** (Niles et al., 2018).

There are also barriers to ICLS at the regional level (Figure 11), which are related mainly to the **high costs of creating and maintaining long-term coordination and cooperation among multiple participants**, which may increase with the geographic distance between crop and livestock farms. According to previous studies (Asai et al., 2018; Julie Ryschawy et al., 2017), these costs involve the following:

- i) **identifying and collecting information** on crop and livestock farmers who could be interested in a partnership. Doing so is difficult given **regional specialization** and lack of communication between crop and livestock regions.
- ii) **finding technical knowledge** on how to integrate livestock in a specialized cropping system, such as how to manage sheep grazing of winter cereals at early stages. Doing so is complicated, as the **continuing specialization of the entire sociotechnical system** toward either crop or livestock production has led farmers to forget how to manage interactions between crop and livestock enterprises.
- iii) **making collective decisions**, such as about the appropriate dates to start and stop grazing the crop farm's cover crop. These decisions can be difficult, as the crop and livestock farmers can differ in their habits, mind-sets and viewpoints inherited from their **history of specialization**, and need to consider **trade-offs between individual and collective objectives**. For instance, the crop farmer may want the livestock farmer to leave earlier to be able to sow the next crop, while the livestock farmer may want to stay longer to benefit from the available feed resource until the livestock can be moved to mountain pastures in the summer.

- iv) **monitoring partnerships**, such as transporting manure to the crop farm, ensuring partner satisfaction or resolving conflicts

Regan et al. (2017) and Godinot et al. (2024) also emphasized the **risk** of ICLS at the regional level becoming an **open gate to more intensive farming practices if farm self-sufficiency is not emphasized first**. For instance, having access to additional livestock feed and additional land on which to apply manure may lead livestock farmers to increase their stocking rate or number of milking cows per ha. Such intensification **risks decreasing the potential agroenvironmental benefits of ICLS at the regional level**. Ultimately, **despite their recognized advantages and the amount of research on ICLS, all forms of ICLS face barriers that lead them to remain niche systems within a context in France of high-input specialized farming increasingly dominated by crop production** (Garrett et al., 2020).

#### *1.2.3.3. Reintegrating livestock: an agroecological farmer-led initiative in need of more research*

In sum, in France, **specialization in crop production** has continued since the 1950s, and the number of mixed crop-livestock farms has continued to decrease. They are becoming ever more marginalized into regions where neither crops nor livestock in high-input specialized farming systems can reach high yields. The number of high-input specialized crop farms, especially grain-crop farms, has continued to increase, leading to regions dominated by wheat, barley, maize and rapeseed production (e.g. the Parisian Basin, Figure 3). In these **specialized crop regions**, the **knowledge, infrastructure and services around livestock production have decreased drastically** (e.g. few livestock farmers, slaughterhouses, veterinarians, or advisors who have knowledge on livestock or mixed crop-livestock production). The number of **livestock farms has continued to decrease**, as livestock production has **concentrated** in high-input livestock systems, in regions where livestock production has dominated for decades (e.g. Brittany) (Figure 3) (Chatellier and Gaigné, 2012; Domingues et al., 2018; Garnier et al., 2019). The continuing concentration of high-input specialized livestock farms has given rise to **criticism of and societal pressure on livestock production due to its environmental impacts and animal-welfare issues**. This societal pressure has progressively spread to **all types of livestock** production in France.

In such an unfavourable and complex context, **some farmers are opposing the trends of specialization in high-input crop production and abandonment and concentration of livestock production into specialized regions**. They **reintegrate** (i.e. intentionally organize the return of) **livestock onto specialized crop farms and into specialized crop regions where the livestock sociotechnical system has almost completely disappeared**. Livestock reintegration thus consists of the **process of change from a specialized crop farm to a farm that includes both crop and livestock enterprises**. It shares similarities with ICLS. Like in ICLS, livestock can be reintegrated **at the farm or regional level** and involve **diverse types of crop production** (annuals: grain crops, market gardens; perennials: vineyards, orchards) and **livestock production** (ruminants: sheep, cattle; monogastrics: pigs, poultry) (Figure 11, Figure 12). Also like in ICLS, livestock reintegration is an **agroecological** initiative, as it increases diversity at the farm level (Figure 7) and can lead to synergistic interactions between crop and livestock enterprises. It can thus **benefit from the advantages of ICLS** described previously. However, reintegrating livestock onto specialized crop farms and into specialized crop regions implies

overcoming barriers that are stronger than simply maintaining ICLS or reconnecting crop and livestock enterprises at the farm level or in regions where both types of production still exist (Garrett et al., 2020; Ryschawy et al., 2021). In particular, the nearly complete **disappearance of livestock-oriented knowledge, skills, infrastructure, equipment and services** in specialized crop regions hinder the emergence and scaling up of livestock reintegration (Figure 11) (Cortner et al., 2019). Farmers who are reintegrating livestock seem to have overcome these barriers to reject the trend of specialization in crop production at farm and regional levels.

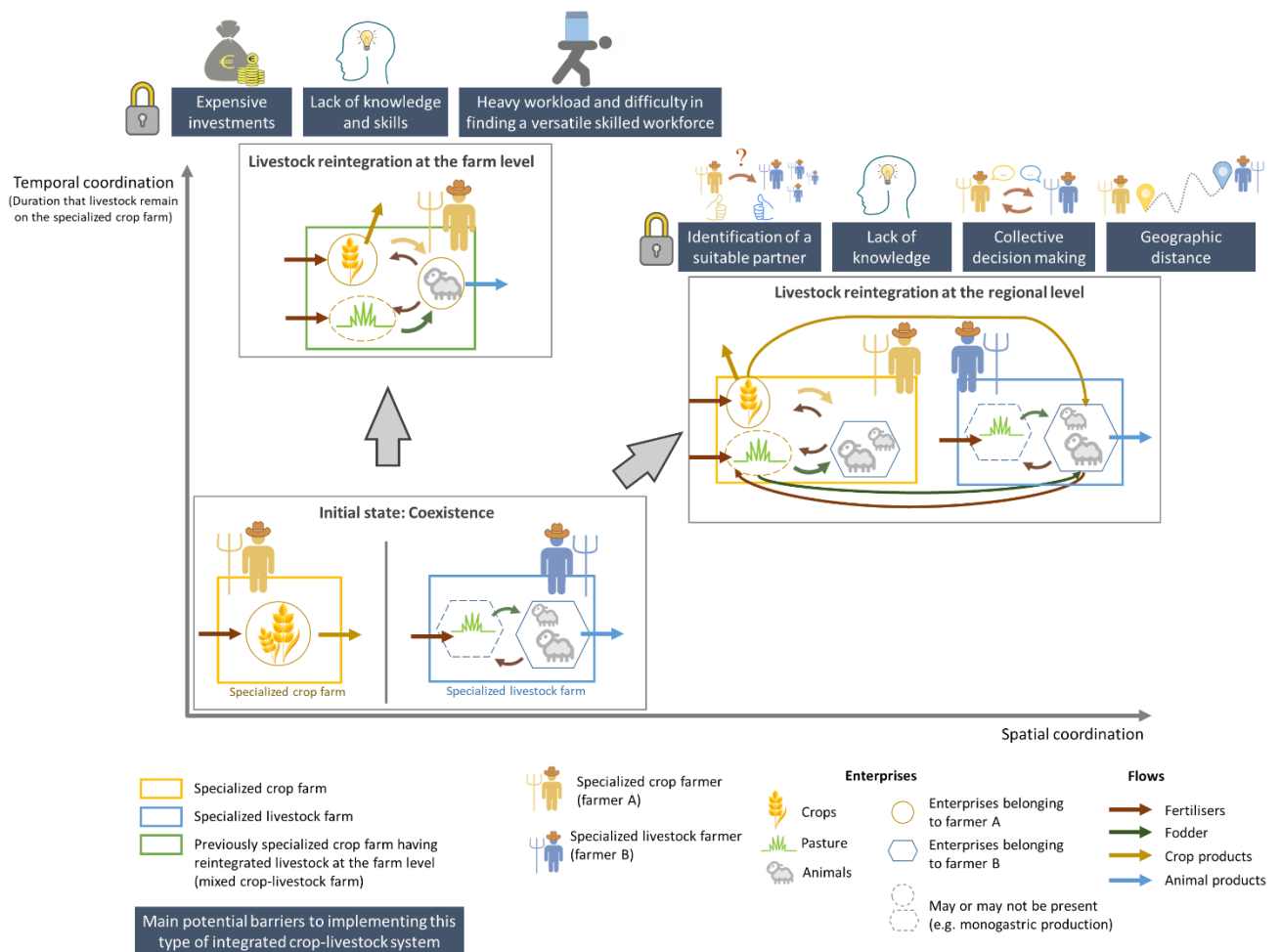


Figure 11. Temporal and spatial coordination for reintegrating livestock at farm and regional levels, and the main potential barriers for each type of implementation of integrated crop-livestock systems

To date, the recent **farmer-led initiative** of reintegrating livestock into specialized crop farms and regions has been **understudied**. To my knowledge, no study has focused on the **motivations** and **contexts** that lead farmers to reintegrate livestock onto specialized crop farms and into specialized crop regions, nor on the **resulting changes in farming practices** and **impacts** beyond this reintegration. These issues need to be studied to obtain **initial insights into whether scaling up of livestock reintegration should be continued, and if so, how**. This is the operational challenge that I highlighted my Ph.D. study:

**Operational challenge: Producing knowledge on why, in which contexts, how and with what impacts farmers reintegrate livestock into specialized crop farms and regions**

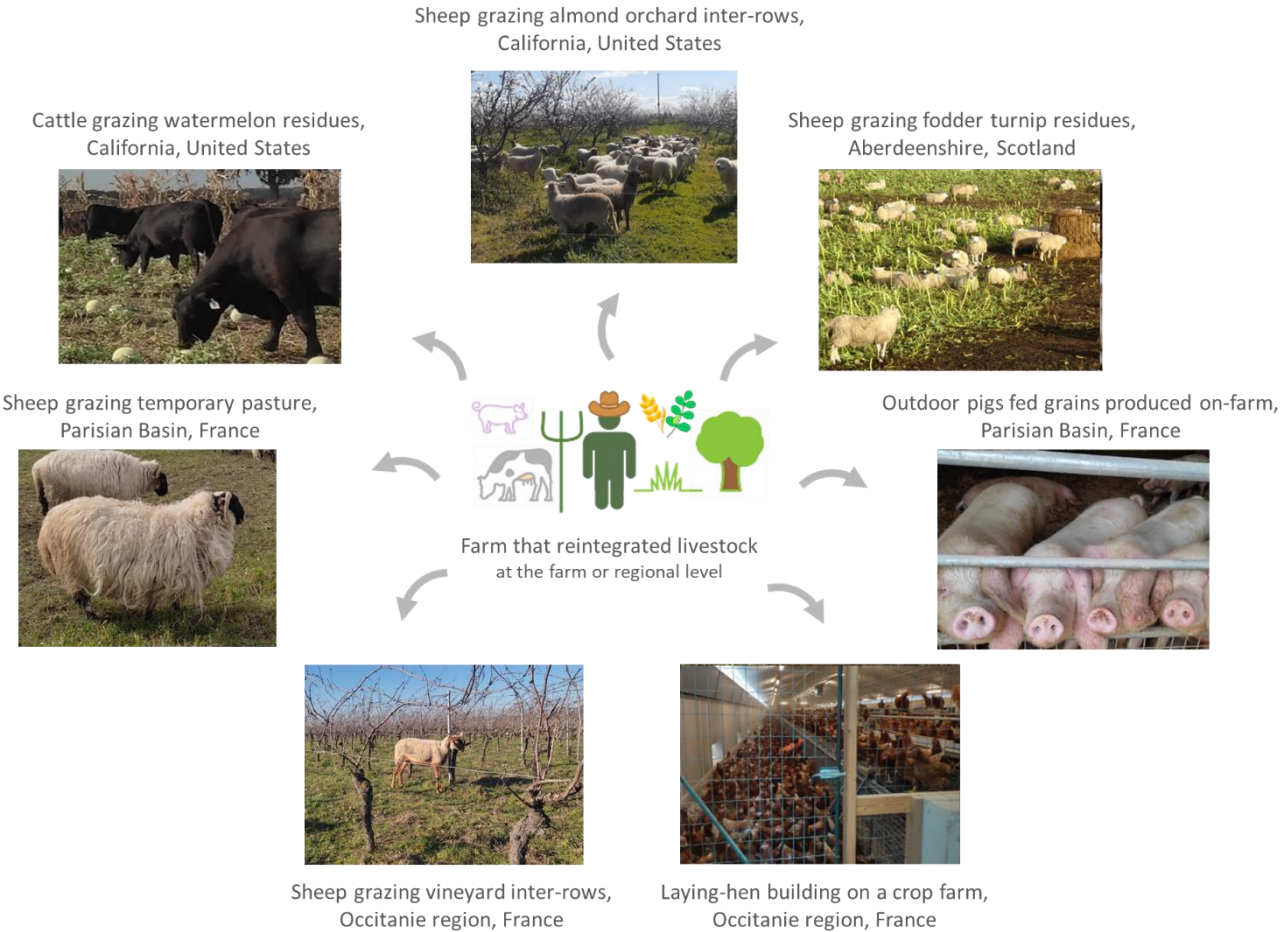


Figure 12. The diversity of farming systems that reintegrated livestock encountered during this Ph.D. study. Credits: Sheep grazing almond orchard inter-rows: T.L.D. Fenster; Sheep grazing fodder turnip residues: C. Watson; All others: C. Meunier.

#### 1.4. Key messages of Part I

- **Mixed crop-livestock farms** were dominant in all French regions in the preindustrial era. They relied on a **diversity of multifunctional crop and livestock enterprises in strong interaction**. They were **self-sufficient** and had **low yields** and **environmental impacts**.
- During the second agricultural revolution, **inputs** replaced many functions previously fulfilled by diversified crop and livestock systems, and the main aim became to produce large amounts of human food. **Farms and regions specialized toward** either **high-input crop or high-input livestock production**. This **disconnection between crop and livestock** extended to the **entire sociotechnical system**. High-input specialized crop and livestock farms currently remain the **dominant model**. They have **high yields** but generate **high environmental impacts**.
- Since the 2000s, to improve the sustainability of agricultural production, **agroecology** has emphasized farm **diversity** and **self-sufficiency**. **ICLS at the farm or regional level** are common agroecological farming systems that can be more **sustainable** than high-input specialized crop or livestock systems. However, they face many **technical and organizational barriers**, which has caused them to remain a **niche** system.
- Opposing the current trend, some pioneer farmers have **reintegrated livestock onto specialized crop farms and into specialized crop regions** in France. However, they suffer from the **disappearance of the livestock sociotechnical system** and from a **lack of knowledge on livestock reintegration**. This farmer-led initiative has been **understudied**. Understanding the **motivations, contexts, changes in farming practices** and **impacts** beyond livestock reintegration is key to determining whether **scaling up of such systems should be supported, and if so, how**.

*Box 2. Key messages of Part I*



## Part II. Methodological challenges to studying livestock reintegration as an agroecological innovation

### Objectives of Part II:

- Emphasize the methodological challenges raised by studying agroecological innovations such as reintegrating livestock onto specialized crop farms and into specialized crop regions
- Stress the need to supplement the existing framework of innovation tracking to produce contextualized knowledge on agroecological innovations such as reintegrating livestock onto specialized crop farms and into specialized crop regions

### New glossary concepts used in Part II:

Innovation, sociotechnical imaginary, retro-innovation, researchers' stances, performances of an innovation, actionable knowledge

### II.1. Reintegrating livestock into specialized crop farms and regions: an agroecological (retro-)innovation

Since it was first theorized by the economist Schumpeter, **innovation\*** has been **defined in many ways**, depending on the period and discipline (Baregheh et al., 2009; Faure et al., 2018; Rogers, 1983). These definitions all converge on **two conditions** for an innovation: i) introducing a **novelty** (technical, organizational, institutional) in an organization (here, a farm) and ii) **implementing this novelty in practice**.

For livestock reintegration, the second condition has been met: it has already been **implemented in practice**, as it has been **observed** (but not studied) **on a few pioneer farms** (Figure 12). The **novelty** of reintegrating livestock (the first condition), however, **can be challenged**. Indeed, as described in Part I, ICLS **existed in the past**. This was true at the farm level, as most farms were mixed crop-livestock farms during the preindustrial era (at the latest), and at the regional level, as partnerships that involved moving one farmer's livestock to the fields of another farmer already existed through transhumance and reverse transhumance (Brechon, 2013; Coulet, 1978). Moreover, mixed crop-livestock farms **still exist in some areas of France** and even **remain the dominant farming system in many regions of the world** outside of Western countries (Garrett et al., 2020; Stark et al., 2018).

However, innovating includes **changing a previous way of doing things** and is thus **contextual** (Faure et al., 2018; Rogers, 1983; Salembier et al., 2021). Consequently, innovation does not refer to something new as in "never having been done by anyone, anywhere, before". Instead, it emphasizes the **relative novelty** of an object in a given situation, at a specific place and time. In other words, what is deemed "new" in a specific region during a specific period can be common in another region or at another time (Boulestreau et al., 2022). For livestock reintegration, what is new is not integrating crop and livestock enterprises at the farm or regional level. The novelty is that, **in the context of continuing specialization in crop production, in regions where livestock production and services have been**

nearly absent for decades, farmers who have usually grown only crops decide to reintegrate livestock onto their farms. This implies overcoming many **sociotechnical barriers**, in particular a lack of knowledge on technical methods to implement it successfully and on what benefits to expect from it, as well as a lack of outlets. Despite the increasing development of agroecology, the mainstream **sociotechnical imaginary\*** of **industrial agriculture and the techno-centric vision of progress**, built over decades of intensification, industrialization and specialization of agriculture (Box 3), remains dominant. This sociotechnical imaginary may also hinder livestock reintegration, as reported for other practices inherited from or inspired by traditional ways of farming (e.g. grazing cows, organic farming) (Polzin, 2024; Shortall, 2019). Initiatives that challenge this industrial vision of progress face resistance due to fear and suspicion, as they conjure up images of “old practices”, associated with periods of poverty, hunger and malnutrition, as expressed by a German government minister: “We do not need an agricultural turn back into the last century” (cited by Polzin (2024)). Those who do it are seen as naïve laggards who cannot resist the “temptation to long for a romantic kind of agriculture” (expressed by another German minister (Polzin, 2024)) that will never feed the world.

Sociotechnical imaginaries are defined as “**collectively** held, institutionally stabilized, and publicly performed **visions of desirable futures**, animated by shared understanding of forms of social life and social order attainable through, and supportive of, advances in science and technology.” (Jasanoff and Kim, 2015, p.4). As shared visions of desirable futures, sociotechnical imaginaries play a **key role in favouring or hindering the scaling up of niche practices**, such as reintegrating livestock. They shape research and policy directions, allocation of funds, communication about development priorities, as well as beliefs about and acceptance of a specific practice (by farmers, advisors, citizens) (Rudek, 2022). Diverse sociotechnical imaginaries exist around the same practice and can facilitate or hinder its development (Polzin, 2024; Rudek, 2022; Shortall, 2019).

*Box 3. Definition of sociotechnical imaginaries*

As **pioneers** in their specialized crop region, farmers who reintegrate livestock cannot rely on inspiring examples from their neighbours, but instead only on **their own motivations and adaptive capacity to learn**, through trial and error, how to reintegrate livestock into a farming system that meets their **current objectives and constraints** (Moojen et al., 2024). Reintegrating livestock thus requires **much more than applying a pre-existing recipe** (van Keulen and Schiere, 2004). It requires **remembering practices** of integrated crop-livestock farming that have been **long forgotten in the region** and **hybridizing** them with **new ideas to ground them in modernity** and **adapt** them to the **current context** of high-input specialized farming. Such “purposeful revival of historic practices” (Zagata et al., 2020) seem to match the conceptualization of a specific type of innovation called **retro-innovation\*** (Kilis et al., 2022; León-Bravo et al., 2019; Stuiver, 2006; Zagata et al., 2020).

## II.2. Methodological challenges when studying agroecological innovations

### II.2.1. Characteristics of agroecological innovations that make them challenging to study

**Agroecological innovations**, such as livestock reintegration, include **transformative changes in farming practices that influence the entire farming system**. They aim at providing a diversity of ecosystem services by concretely implementing the principles of agroecology, such as diversity, synergies, recycling and resilience, to sustainably take advantage of specific local characteristics (Boeraeve et al., 2020; FAO, 2018; Garbach et al., 2017; Magne et al., 2024). Some of their characteristics make them particularly **challenging to study**. In particular, agroecological innovations are:

- **Locally adapted** to specific socio-ecological, sociotechnical and socio-economic conditions of the farm (Toffolini et al., 2019). They also address **farmers' objectives**, which can vary greatly among farmers, as well as for a given farmer, over time. This characteristic causes agroecological innovations to take a **wide diversity of forms**.
- **Complex**, as they rely on diversity and interactions (Duru et al., 2015). These interactions may involve **multiple temporal scales**, with more or less immediate impacts; **multiple spatial levels**, from the field to the farm and the region; and **multiple actors**.
- **Ever-evolving**, as they often require time for **trial and error** before reaching a dynamic steady state of equilibrium (which they sometimes never reach). This characteristic results in high **uncertainty** in future states of the system, as its evolution cannot be perfectly planned or controlled (Toffolini et al., 2019).
- **Multi-performing**, as they provide a **diversity of ecosystem services** and address diverse and variable **farmers' objectives** (Magne et al., 2024).

Consequently, studying agroecological innovations requires addressing **methodological challenges** and invites researchers to supplement the tools and methods that they use to produce knowledge. It also raises questions about their **stances\*** (Hazard et al., 2020). These challenges apply to livestock reintegration as well as to other examples of agroecological innovation.

### II.2.2 Methodological challenges to address when studying agroecological innovations

#### II.2.2.1. Challenge 1: Defining appropriate system boundaries to the agroecological innovation studied

Studying agroecological innovations requires carefully defining the **boundaries of the system** to study.

##### Spatial boundaries

In most high-input specialized cropping systems, **one crop** is grown **per year per field**. This crop **interacts little** with other farm enterprises or with the local environment of the field and farm, as its **outcomes are driven mainly by large amounts of inputs**, used to **standardize** and **control** production conditions. Thus, the **field** serves easily as the unit of analysis (Affholder et al., 2013; Grassini et al., 2015; Van Rees et al., 2014).

In agroecological systems, **several crops and/or animals may interact in the same field during some or all of the growing season** (e.g. intercropping, sheep grazing cereals at early stages). Animals can

belong to the same farmer who owns the crops, or to another farmer in the region (Niles et al., 2018; Ryschawy et al., 2021). Thus, **defining appropriate spatial system boundaries to study a particular agroecological innovation is not straightforward** and requires carefully considering the **interactions** involved. It often calls for using **multi-level approaches** to study **levels from the field to the farm and region** (Benoît et al., 2012; Prost et al., 2023; Salembier et al., 2018).

#### Temporal boundaries

High-input specialized cropping systems include mainly **annual crops**. Outside of particular climate or market events, they often remain relatively **stable over multiple years**, for instance for wheat or maize monocultures or well-defined crop rotations such as rapeseed-wheat-barley. The time unit used to study them is usually one **year** (Hyles et al., 2020; Mueller et al., 2012; Schils et al., 2018).

Conversely, agroecological systems often include a **diversity of annual and perennial species** (e.g. lucerne, mixture of species in temporary pastures) that have **different temporal dynamics**. Unlike annual crops, perennial crops may require several years to establish, reach maturity and produce (Magne et al., 2024). Moreover, agroecological systems build on farmers' adaptive capacity and can **vary greatly over several years**. This is especially true as most agroecological systems are still **"in the making"** (Toffolini et al., 2019), which implies that their practices continue to evolve. Transitioning to agroecology requires time and **trial and error** (Darnhofer, 2021; Toffolini et al., 2019). Studying agroecological systems thus requires **carefully defining the timeframe considered** and calls for **flexible frameworks** that allow for **long-term monitoring** using **multi-year analyses**.

#### II.2.2.2. Challenge 2: Deriving generic knowledge on agroecological innovations by studying a wide diversity of locally-adapted and ever-evolving farming systems

High-input specialized cropping systems are characterized by **homogeneity** and **control**. They emphasize mainly **producing large amounts of food** (Figure 4) by relying on high **input** use to **standardize** production conditions and **free the farm from the local soil-climate context** as much as possible. Most agricultural studies of such systems focus on plant growth and production at the **plant or field** level (Hyles et al., 2020; Sheehan and Bentley, 2021; Van Ittersum et al., 2013). Researchers rely mainly on **experiments**, conducted under highly controlled conditions **at research stations or in laboratories**, to build **statistically relevant cause-effect relationships** between one limiting factor (e.g. nitrogen) and an expected outcome, usually the yield (Salembier et al., 2018; Woodward and Ross, 2021). They combine these relationships in **simulation models**, from which they derive **standardized recommendations** and **decision rules** to be transmitted to farmers (Jones et al., 2017; Keating and Thorburn, 2018; McCown et al., 2006).

Fewer agricultural studies consider **farmers' practices** (Doré et al., 2011; Sebillotte, 1974; Sebillotte and Papy, 2011). Such studies rely on **statistically representative samples of farmers** (in a region or for a specific farming practice) that they survey to build **statistically relevant relationships between practices and contexts**, usually limited to soil-climate conditions. Researchers often aim at i) identifying new elements that explain **why crop production is not as high as they predicted** (e.g.

agrarian diagnosis (Doré et al., 2009, 1997; Meynard and David, 1992), yield gap analysis (Van Ittersum et al., 2013)) or ii) **identifying farm types for which different recommendations need to be made** (e.g. production system, soil-climate conditions) (Salembier, 2019). Results are often used as a basis for new experiments to i) confirm their hypotheses about new elements to include in their models and ii) adjust their recommendations to individual types of farm.

Agroecological systems are **diverse**, as they aim at taking advantage of **local conditions**, and **ever-evolving**, as they are continuously “**in-the-making**” (Prost et al., 2023; Toffolini et al., 2019). Farmers design agroecological innovations that align with the diverse **interactions** and **trade-offs** that occur **on the farm** and **between the farm and its environment**. Their choices are guided by **determinants** that act at the **individual level** (e.g. objectives, values, risk perception, preferences), **field level** (e.g. annual pest pressure), **farm level** (e.g. available equipment) and **sociotechnical-system level** (e.g. lack of outlets in the region, public policies). These determinants can thus be **psycho-cognitive**, **agroenvironmental** and **socio-economic** (de Boon et al., 2024; Foguesatto et al., 2020; Geels, 2011, 2004). Because these determinants **evolve**, farmers rely on **trial and error** to adapt their farming systems in successive steps, which results in diverse practices that have a variety of impacts (Chantre and Cardona, 2014; Darnhofer et al., 2010; Revoyron et al., 2022).

Studying agroecological systems requires **characterizing how a diversity of ever-evolving and inter-related determinants led farmers to implement a specific agroecological innovation**. This calls for **broadening the scope of agricultural sciences**, from plant and field levels to **multi-level approaches** (Geels, 2011, 2004). It also calls for considering **diverse actors** in the sociotechnical system that includes the innovation considered. It invites borrowing methodological frameworks and tools from **several disciplines** to understand in-depth the diverse determinants that lead to an innovation (Darnhofer et al., 2012; de Boon et al., 2024; Geels, 2011). It requires highlighting the **dynamic dimension of change** to determine how farmers adapted their farming system to **evolving objectives**, **contextual factors**, **emerging events** and **unexpected outcomes** of their practices (Chantre and Cardona, 2014; Coquil et al., 2014; Gosnell et al., 2019).

The wide diversity of agroecological systems and innovations clearly **challenges researchers' mainstream use of statistical analyses**. Controls and replicates are not possible. Collating the results of multiple analytical experiments is not sufficient to address the huge number of combinations of the multiple, inter-related and ever-evolving determinants, practices and outcomes of farms. The uniqueness of agroecological systems also challenges the ability to build statistically representative samples of farmers, especially pioneering farmers who implement agroecological innovations (e.g. livestock reintegration), who are often difficult to identify. Moreover, with such pioneer farming systems and innovations, gaining an overall sense of the number of farmers concerned is difficult, as they can rarely be identified in public data (Lucas, 2021). Thus, **deriving generic knowledge from exploratory approaches that embrace the diversity and continual evolution of agroecological systems is challenging**.

### *II.2.2.3. Challenge 3: Assessing the multi-performances of agroecological innovations*

To determine whether an agroecological innovation should be supported, it is important to assess its **performances\*** (i.e. the degree to which it meets initial expectations). Assessing the performances of agroecological systems is a challenge (Magne et al., 2024; Soulé et al., 2021).

#### *Choice of indicators*

For high-input specialized cropping systems, the main performance expected is **high levels of crop production**, usually at low cost. It can be assessed easily using indicators such as **yield, grain quality** (e.g. sanitary quality, cereal protein content) or **economic margin**. Conversely, agroecological systems can aim at meeting a **diversity of farmers' and societal objectives**. Assessing their performances requires considering this diversity and potential **trade-offs** between these objectives (Magne et al., 2024; Schanz et al., 2023), such as through **multi-criteria assessment**. As objectives vary among farmers and over time, defining assessment criteria is not straightforward (Magne et al., 2024).

#### *Reference system*

For high-input specialized cropping systems, the performances of the standardized high-input system (i.e. the amount or quality of production observed) can **be compared easily to expected performances obtained from public data or predictive models**. There is **no such data or predictive model** adapted to agroecological systems (Lucas, 2021; Magne et al., 2024). Their performances thus need to be compared to those of high-input specialized systems or to those they reached in a previous state (e.g. diachronic assessment before/after implementing an agroecological practice) (Bouttes et al., 2020; Magne et al., 2024; Nandillon et al., 2024).

### *II.2.2.4. Challenge 4: Revisiting researchers' stances and practices when producing knowledge on agroecological innovations*

Beyond methodological challenges, studying agroecological innovations also raises questions about **researchers' stances and practices**. In the **mainstream approach of research** in agricultural sciences, researchers produce **turn-key recommendations and decision rules** for managing high-input specialized farming systems. These recommendations and decision rules are transmitted to farmers in a **top-down model of dissemination of innovations** that emphasizes **regularity and standardization**.

When studying agroecological innovations, the emphasis is on **understanding connections** among the **determinants that lead farmers to implement specific novel sustainable practices, the practices themselves and their impacts**. Many researchers (e.g. farming system research, participatory research) thus call for emphasizing **farmers' experiential knowledge** to address the **complex and context-specific issues of transitioning toward agroecological systems** that are **adapted to farmers' specific conditions and objectives** (Barcellini et al., 2015; Darnhofer et al., 2010; Moraine et al., 2014; Quinio et al., 2022b). In a **bottom-up approach**, researchers' roles thus switch to include i) **identifying farmer-led agroecological innovations**, ii) **characterizing them and assessing their sustainability** by collecting qualitative and quantitative data (e.g. in-depth interviews, measurements), iii) **capitalizing on farmers' experiential knowledge** by comparing it to and **hybridizing it with other sources of knowledge** (e.g. scientific literature, farmers, technical advisors) or **producing complementary**

**knowledge** to fill knowledge gaps and iv) **disseminating this knowledge** to other farmers to promote their **adaptive and innovative capacity**, allowing them to learn, select and adapt some inspiring examples of agroecological innovations to their own contexts (Bouttes et al., 2019; Darnhofer et al., 2010; Salembier et al., 2021).

### II.3. Farmer innovation-tracking: a framework to study agroecological innovations, which can be improved

#### II.3.1. Farmer innovation tracking: identifying farmers' innovative practices to foster innovation by other farmers

One framework recently developed to **help address the four methodological challenges** raised by studying agroecological innovations is "**farmer innovation tracking**" (Salembier et al., 2021). It seeks to **identify and learn about farmers' practices** that are considered innovative to foster innovation by other farmers. By studying examples of **tracking initiatives**, including some that existed long before the emergence of this concept (e.g. Barzman et al. (1996)), Salembier et al. (2021) emphasize that **there is no single way to track farmer innovations**, as any tracking needs to be tailored to the specific objectives of study leaders, usually researchers. Nevertheless, they identify **stages in common among tracking initiatives** (Table 1), as follows (adapted from Salembier et al. (2021), with their terms in quotation marks):

- i) **Defining a tracking project** (i.e. defining **which innovation(s) study leaders are looking for**). The tracking project can be "**targeted**" (i.e. focus on specific innovations such as crop-species mixtures) or "**exploratory**" (i.e. focus on a variety of innovations that meet an overall objective such as those that promote agroecology). Study leaders can focus on innovations that are **already successfully implemented on-farm** or those that are **still under development**. They can have multiple reasons for starting a tracking project, such as to address farmers' needs, respond to policy requests or explore a researcher's idea. They need to define who will be involved in the project.
- ii) **Revealing innovations** (i.e. **identifying the farmers** who implement the innovations). Doing so is often difficult, as usually few databases contain this type of information, which leads study leaders to explore diverse options such as **relying on local networks** of technical advisors or networks of farmers already known to have particularly innovative systems; or **snowball sampling** (Lucas, 2021; Salembier et al., 2021; Sutherland et al., 2016).
- iii) **Learning about innovations by interviewing farmers**. Depending on the study, a variety of questions can cover issues such as the **functioning of the innovation** (e.g. methods of technical implementation, agronomic processes involved), the **determinants that led to implementing it** (e.g. soil-climate conditions, sociotechnical context, farmer motivations, previous steps in the trajectory of change) and **performances of the innovation, self-assessed by farmers using their own criteria**.

- iv) **Analysing learning from the innovations** (i.e. producing narratives of each farmer, understanding the agronomic processes and determinants that **influence an innovation's form and performances**)
- v) **"Generating agronomic content"**, which aims mainly at **informing design processes**, such as during co-design workshops, by providing **inspiring examples of innovative practices that increase farmers' creativity**. It can take the form of testimonials of individual farmers that describe the reasoning behind their actions and assess the innovation's performance in their system. These testimonials can sometimes hybridize farmers' experiential knowledge with functional knowledge. Other examples of "agronomic content" generated by innovation-tracking initiatives are "repertories of technical options" to reach a particular objective, "generic action logics" and "decision-making rules". This last step of innovation-tracking, which requires **generating actionable knowledge\*** (i.e. knowledge that farmers can use directly **during design processes**) (Geertsema et al., 2016; Quinio et al., 2022a), was not considered in this Ph.D. study.

*Table 1. The main focus of published studies of innovation-tracking initiatives (by stage, paraphrased from Salembier et al. (2021)) and suggested improvements. Inspired by Salembier et al. (2021). The innovation-tracking initiatives considered were published studies assessed by Salembier et al. (2021) (i.e. Barzman et al. (1996), Blanchard et al. (2018), Feike et al. (2010), Jagoret et al. (2012),*



Perinelle (2021), Richard (2018) Salembier et al. (2016) Verret et al. (2020)) and others that were published later (i.e. Boulestreau et al. (2022)).

Stage of innovation tracking	Main focus of most published innovation-tracking initiatives	Suggested improvements
<b>1. Defining a tracking project</b>	Tracking that focuses on farmers	Target diverse actors to increase understanding of the sociotechnical contexts surrounding farmers' innovations
<b>2. Revealing innovations</b>		
<b>3. Learning about innovations</b>		
<b>4. Analysing learning from the innovations</b>	Farmers' motivations ignored or reduced to their objectives	Deepen the study of farmers' motivations for implementing this innovation
	Focus on the cropping-system or farm level	Include initiatives beyond the farm level, such as cooperation among farms
	Relying only on farmers' self-assessment of performances of the innovation	Analyse the farm's sociotechnical context to increase understanding of the context that led to the innovation
	Relying only on farmers' self-assessment of performances of the innovation	Supplement farmers' self-assessments with objective assessment of the performances of the cropping system to support scaling it up
<b>5. Generating agronomic content</b>	Static approach	Combine static and dynamic approaches to highlight the evolution of relations among determinants that lead to the innovation, changes in practices and their impacts

### II.3.2. Proposals for improving the innovation-tracking framework to analyse agroecological innovations comprehensively

The “agronomic content” described by Salembier et al. (2021) that is generated by innovation tracking aims at easing other farmers' implementation of agroecological innovations that are tailored to their specific situations. To do so, it aims at providing them with **contextualized knowledge** on inspiring examples of farming systems in which agroecological principles have been successfully implemented in practice. Doing so requires including information about **the practice and its performance**, but also about **the determinants that influenced its emergence** (Salembier et al., 2021). This information is often included in farmers' individual testimonials used in design processes. To my knowledge, however, the **few published studies that can be identified explicitly as farmers' innovation-tracking initiatives do not provide such contextualized knowledge on the innovations they document** (Table

1). Instead, they usually focus on the **cropping-system or farm level**. They provide “repertoires of options” that emphasize **technical knowledge** on the innovations and their **performances**, which are nearly always **self-assessed by farmers**, and often ignore the **determinants that led to their emergence** (e.g. farmers’ motivations, sociotechnical context). They rarely compare **farmers’ self-assessments** to **objective assessments** of the **performances** of these innovations. The framework of innovation tracking can thus **be improved to increase the understanding of innovations** (Table 1).

#### *II.3.2.1. Deepening the study of farmers’ motivations for implementing agroecological innovations*

Most of the innovation-tracking initiatives that Salembier et al. (2021) studied included asking farmers about their **motivations**. Motivations have been identified as a **key determinant to consider when studying farmers’ changes in practices** (Casagrande et al., 2016; de Boon et al., 2024; Greiner and Gregg, 2011; Schoonhoven and Runhaar, 2018). However, most published studies of innovation-tracking initiatives **did not mention** farmers’ motivations for innovating (Barzman et al., 1996; Blanchard et al., 2018; Jagoret et al., 2012; Perinelle, 2021). When mentioned, farmers’ motivations were often **reduced to farmers’ objectives** (e.g. increase yield stability), which they used to assess performances of the innovation (Verret et al., 2020b). This approach ignores other elements of farmers’ motivations, such as **values, beliefs, risk preference and internalized subjective norms, which also influence individual behaviour** (e.g. changes in practices) (Ajzen, 1991; Cortner et al., 2019; Raymond et al., 2016; Stern and Dietz, 1994). To my knowledge, **farmers’ motivations** (often in the form of objectives), **practices and performances were rarely connected** (Salembier et al., 2016; Verret et al., 2020b). None of the innovation-tracking initiatives had the specific aim of identifying the **diversity and relative weights of farmers’ motivations for implementing an agroecological innovation**.

**The innovation-tracking framework could be improved by incorporating methodological tools to study farmers’ motivations in depth.** Doing so would help i) relate technical choices to initial motivations and **compare performances to these motivations** (Salembier et al., 2016); ii) **adjust communication** about these innovations accordingly and iii) promote **policy recommendations** that align with these motivations (e.g. if farmers implement a practice to promote ecosystem services, paying for ecosystem services may help it to develop).

#### *II.3.2.2. Considering the farm as embedded in a sociotechnical system*

To my knowledge, previous innovation-tracking initiatives have focused mainly on the **cropping-system or farm level** (Feike et al., 2010; Salembier et al., 2016; Verret et al., 2020b). This approach seems consistent with the main aim of tracking farmers’ innovations: to learn about their innovative practices and the performances of these practices. To my knowledge, **no study has considered agroecological innovations that involved cooperation among several farmers**, such as reintegrating livestock at the regional level.

Salembier et al. (2021) emphasize the importance of providing **contextualized knowledge** on the innovations, as the context in which they emerged defines their **validity domain** and influences their scaling up. To do so, farms need to be considered as embedded **at the crossroads of two systems**, both of which can influence farmers' changes in practices. First, farms exist in a **particular socio-ecological system** (i.e. in which social, economic, ecological, cultural, political, technological and other components are strongly related) (Petrosillo et al., 2019). At the same time, they **exist in a particular sociotechnical system**, composed of interrelated actors, their practices, knowledge and collective representations, as well as standards and rules that they adopt (Rip and Kemp, 1998) (Box 4, Figure 13).

Following the **multi-level perspective** (Geels, 2011, 2004), the **sociotechnical system** can be divided into **three interacting levels** (Figure 13):

- in the middle, the **regime** (i.e. the currently **dominant stable model of high-input specialized farming**)
- at the bottom, **technological niches**, defined as protected spaces where innovations can be implemented. Examples of technological niches include organic farming, ICLS and, in this Ph.D. study, **livestock reintegration**.
- at the top, the **landscape**, composed of elements of the broader context, such as **cultural values, policies, climate change or market fluctuations**

**Barriers** of the regime or landscape can hinder the emergence of specific niche innovations on farms and their scaling up.

*Box 4. Definition of the multi-level perspective according to Geels (2011, 2004)*

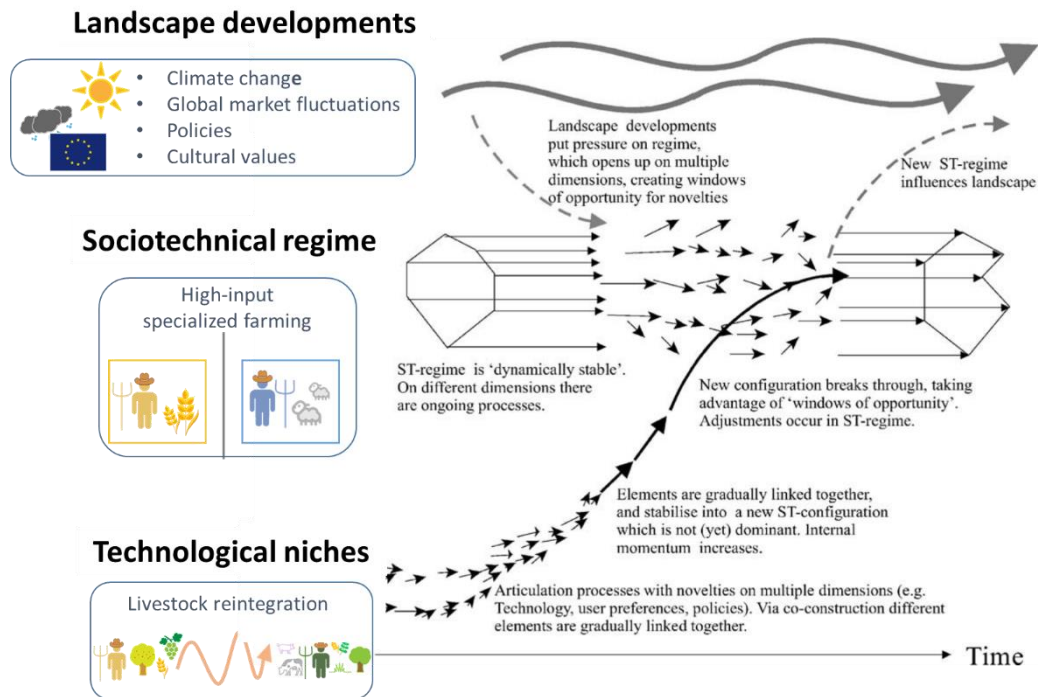


Figure 13. The multi-level perspective adapted to livestock reintegration (adapted from Geels (2004)). ST: Sociotechnical

Studying the specific context in which an agroecological innovation emerged on farms thus implies studying determinants at both the **farm level and the sociotechnical system level** (de Boon et al., 2024) using a **multi-level approach**. This may be especially true for innovations such as livestock reintegration onto specialized crop farms and into specialized crop regions, which calls for **re-creating an entire value chain**. However, published innovation-tracking initiatives **rarely documented in depth the specific contexts in which innovations emerged**, although a few studies briefly mentioned non-adopters' perception of factors that hindered innovation (Feike et al., 2010). To date, few studies have analysed in depth **sociotechnical barriers to the agroecological innovation under study**. Boulestreau et al. (2022, 2021) provide one example of how innovation tracking and sociotechnical analysis can be combined. They supplemented analysis of sociotechnical barriers to agroecological protection of vegetables by tracking coupled innovations (i.e. joint innovations at the farm and agrifood system levels). However, they focused on the conditions under which coupled innovations emerge and stressed that their study could be **supplemented by on-farm innovation tracking** (Boulestreau et al., 2022). Innovations that involve cooperation among several farmers could be considered as coupled innovations to be tracked.

**The innovation-tracking framework could be broadened to consider innovations beyond the farm level** and involve cooperation among multiple farmers and/or multiple actors of the sociotechnical system. **It could be improved by in-depth sociotechnical analysis of the barriers to and levers that support the innovation under study**. Doing so implies interviewing other actors in the sociotechnical system besides farmers. It would help **support the scaling up of innovations** by providing contextualized knowledge on inspiring examples of levers that farmers used to make an innovation

possible despite the barriers they faced. Such contextualized knowledge could be disseminated to other farmers, who could adapt it to their own specific contexts.

### *II.3.2.3. Further comparing farmers' self-assessments to objective assessments of performances of agroecological innovations*

**Published studies of innovation tracking** usually assess innovations, often as **farmers' self-assessments** of an innovation's performances (Barzman et al., 1996; Périnelle et al., 2021; Verret et al., 2020b). Building on **farmers' own performance indicators** can help ensure that an innovation is assessed using **indicators that are relevant to farmers**, thus helping produce easily actionable knowledge. It is also useful to **understand how farmers adapted their system progressively** based on their self-assessment of the extent to which an innovation met their initial expectations. However, this **incomplete and subjective assessment** may not always be relevant for other farmers (Salembier et al., 2021, 2016; Verret et al., 2020b). Moreover, as farmers may rely on different indicators, **farms cannot be compared to each other**.

**The innovation-tracking framework could be improved by integrating methodological tools that further supplement farmers' self-assessment of performances of an innovation with objective assessments**, such as by comparing them to **data from experiments** (Barzman et al., 1996) or through **multi-criteria assessments**. Indicators should still be chosen carefully to match farmers' motivations for implementing an innovation (see Challenge 3). They should also include **social and economic dimensions** of sustainability – which the few studies that assessed farmers' innovations objectively did not study in depth – rather than only focusing on agroenvironmental benefits (Blanchard et al., 2018; Salembier et al., 2016). The data needed to calculate indicators of multi-criteria assessment should be collected on farms, either through measurements or farmer interviews. Comparing farmers' self-assessments to objective assessments of performances of an agroecological innovation could help **produce robust knowledge** on the actual benefits to expect from this innovation in light of the risks taken and increased complexity of the farming system. Doing so would thus help **determine whether this innovation should be scaled up**, and if so, **help support it**.

### *II.3.2.4. From static to dynamic: considering farmers' trajectories to increase understanding of the process of change that led them to implement an agroecological innovation*

To my knowledge, previous innovation-tracking initiatives focused on describing the innovation **at the time of the interview** (Feike et al., 2010; Verret et al., 2020b). According to Salembier et al. (2021), questions are sometimes asked to learn about the trajectory that led farmers to implement an agroecological innovation in the way they are doing it at that time. However, the **responses are not capitalized on beyond using them as individual farmers' testimonials**. To my knowledge, **no study has combined farmers' innovation tracking and in-depth understanding of the trajectories that led farmers to implement an agroecological innovation**. However, understanding the **actual process of change** that led to an agroecological innovation and highlighting its **progressive nature** is key to support scaling it up (Chantre et al., 2015; Coquil et al., 2014; Revoyron et al., 2022).

**The innovation-tracking framework could be improved by dynamic understanding of the succession of events that led farmers to implement an agroecological innovation.** It would allow the following to be identified:

- i) the **successive steps in the process of change**, including how farmers' **initial situation, motivations** and **sociotechnical context** drove them to implement an agroecological innovation, and how they **adapted it over time in reaction to emerging events and to their self-assessment of the innovation's performances** (Chantre et al., 2015; Revoyron et al., 2022; Sutherland et al., 2012).
- ii) the **resources and strategies that increased farmers' adaptive capacity** and allowed them to **build on unexpected events to overcome barriers to innovation** (Chantre and Cardona, 2014; Coquil et al., 2014; Toffolini et al., 2019). The resources and strategies identified that increase farmers' adaptive capacities could be generic and not necessarily apply only to the specific innovation studied. For instance, identifying financial resources and increasing knowledge through learning as examples of resources and strategies improving farmers' adaptive capacity using a specific agroecological innovation as an example can provide insights into how to foster other innovations on farms (Bouttes et al., 2019; Darnhofer et al., 2010).

#### *II.3.2.5. Summary of proposals to improve the innovation-tracking framework*

In sum, farmers' innovation tracking provides a framework to identify farmers' innovations and learn about them. To date, most published studies have focused on determinants that lead to implementation of innovations at the **cropping-system or farm level** and have rarely considered innovations beyond the farm level or farmers' motivations or sociotechnical contexts. Most of them used a **static approach** and assessed performances of the innovation under study using **farmers' self-assessments**.

To date, **no innovation-tracking initiative has developed comprehensive understanding of an agroecological innovation by combining in-depth study of i) farmers' motivations, ii) the sociotechnical barriers they faced and levers they implemented in reaction, iii) their changes in farming practices and the related impacts on the sustainability of their farms and iv) their trajectory of change to this final state.** Building a comprehensive understanding of farmers' agroecological innovations, such as reintegrating livestock, calls for **improving the innovation-tracking framework by more systematically combining dimensions** (e.g. psycho-cognitive, socio-economic, agroenvironmental), **levels** (e.g. farmer, farm, sociotechnical system) and **disciplines** (e.g. systems agronomy, social sciences). This yielded the methodological challenge that I highlighted in my Ph.D. study:

**Methodological challenge: Improving the innovation-tracking framework by studying at multiple levels the determinants that lead to agroecological innovations and assessing their performances objectively**

## II.4. Key messages of Part II

- **Livestock reintegration** can be considered as an **agroecological innovation**, as it is both **novel** in the French context of continuing specialization in crop production and has already been **implemented in practice**. As it requires **remembering long-forgotten practices** to integrate crop and livestock enterprises and **adapting them to the current context** of high-input specialized farming, livestock reintegration seems to meet the definition of **retro-innovation**.
- Because they are **locally adapted, complex, ever evolving** and **multi-performing**, agroecological innovations, such as livestock reintegration, are **challenging to study**. Three main challenges are **methodological**: defining appropriate **system boundaries**, *deriving generic knowledge by studying a wide diversity of farming systems in continual evolution* and assessing the **multi-performance** of agroecological innovations. The fourth is **epistemological**, as agroecological innovations invite **researchers to revisit their stances and practices**.
- The **innovation-tracking framework** was recently developed to help address some of these challenges. It helps **identify farmers' innovations** and **document them to support their scaling up** by informing design processes.
- Published innovation-tracking initiatives focus mainly on **the cropping-system or farm level**, on the **agroecological dimension** of innovations, using a **static approach**, and often rely only on farmers' **self-assessments** to assess performances of an innovation. To support the scaling up of agroecological innovations, this framework can be **improved** by incorporating **multi-level approaches**, combining **several dimensions**, using **static and dynamic analyses** and **assessing performances subjectively and objectively**.

Box 5. Key messages of Part II



## Part III. Research question

Based on these **operational** and **methodological challenges**, the following **research question** emerged for this Ph.D. study:

Why, in which contexts, how and with what impacts are farmers reintegrating livestock into specialized crop farms and regions?

## Part IV. Research strategy

To address this research question, I designed a **research approach** with the following characteristics (Table 2, Figure 14):

- **Multi-level:** from the **individual farmer** to the **farm** and the **sociotechnical system** (Figure 15)
- **Multi-dimensional:** including **psycho-cognitive**, **agroenvironmental**, **sociotechnical** and marginally **socio-economic** determinants
- 1 • **Interdisciplinary:** based strongly on **systems agronomy**, which is interdisciplinary by nature,  
2 and borrowing frameworks from **social sciences**, especially **social psychology**, **sustainability**  
3 **and transition studies** and **sociology of change** (  
• Figure 16)
- **Multi-actor:** involving **farmers** and **other key actors of the sociotechnical system** surrounding livestock reintegration
- Combining **static** and **dynamic** approaches to analysing change processes
- Relying on “**targeted innovation tracking**” of livestock reintegration, as defined by Salembier et al. (2021)
- Combining **qualitative** and **quantitative** analyses of data obtained during **semi-structured interviews with a core sample of farmers** who reintegrated livestock in a wide variety of farming systems (Figure 12, Figure 17)

I thus provide **diverse and complementary perspectives** on reintegrating livestock that, once combined, allow me to understand **why, in which contexts, how and with what impacts farmers are reintegrating livestock into specialized crop farms and regions.**

Table 2. The main characteristics of the four chapters of this Ph.D. study.

Characteristic	Chapter 1: Motivations	Chapter 2: Sociotechnical barriers and levers	Chapter 3: Changes in practices and agroenvironmental impacts	Chapter 4: Trajectories
<b>Level of analysis</b>	Individual farmer	Sociotechnical system	Farm	Farm
<b>Main dimension</b>	Socio-cognitive, socio-economic	Sociotechnical, socio-economic	Agroenvironmental	Agroenvironmental, sociotechnical, socio-economic
<b>Temporality</b>	Static	Static	Partially dynamic (Comparison between snapshots)	Dynamic
<b>Conceptual anchorage</b>	Systems agronomy, social psychology	Systems agronomy, sustainability and transition studies	Systems agronomy	Systems agronomy, sociology of change
<b>Geographic location</b>	France	Transversal analysis in Scotland, France and California (USA)	France	France
<b>Data-collection method</b>	Semi-structured interviews	Semi-structured interviews	Semi-structured interviews	Semi-structured interviews
<b>Actors interviewed</b>	Farmers (n=18)	Key actors of the sociotechnical system (n=32)	Farmers (n=15)	Farmer (n=1)
<b>Analysis method</b>	Mixed (inductive analysis and ranking)	Qualitative (inductive analysis)	Quantitative (multi-criteria assessment)	Qualitative (inductive analysis)
<b>Outcomes of livestock reintegration into specialized crop farms and regions</b>	Ranked summary of farmers' motivations	Sociotechnical barriers and levers	Examples of inspiring farming systems and their agroenvironmental impacts	Trajectories that led to reintegrating livestock

*I present the results following the same trajectory that farmers would use when considering reintegrating livestock into specialized crop farms and regions (Figure 14).*

*For a farmer, the first step along the trajectory that leads to reintegrating livestock into specialized crop farms and regions is to consider why to do so.*

In chapter 1, I **identify and rank farmers' motivations** for reintegrating livestock into specialized crop farms and regions. I combine innovation tracking and in-depth study of farmers' motivations as psycho-cognitive determinants that influence changes in practices. To do so, I focus on the level of individual farmers in France. I use an original mixed method that combines qualitative inductive analysis of farmers' semi-structured interviews and quantitative rankings of their motivations.

*Besides psycho-cognitive determinants studied in the form of farmers' motivations, other determinants (e.g. agroenvironmental, sociotechnical, socio-economic) may facilitate or hinder reintegrating livestock into specialized crop farms and regions.*

In chapter 2, I **provide transversal analysis of these sociotechnical barriers to and levers for** reintegrating livestock into specialized crop farms and regions. To do so, I widen my focus to the entire sociotechnical system and compare France to other regions of the world where livestock is being reintegrated. I rely on inductive analysis of semi-structured interviews with targeted key actors of the sociotechnical system surrounding livestock reintegration and compare the results among regions.

*When farmers have the motivation for, and have found levers to overcome the sociotechnical barriers to, livestock reintegration, they become able to reintegrate livestock into specialized crop farms and regions.*

In chapter 3, I **characterize changes in farming practices** after reintegrating livestock **and assess their agroenvironmental impacts** on farms. I focus on the farm level in France and rely on semi-structured interviews with farmers to characterize changes in practices and multi-criteria assessment of impacts of these changes. I define indicators to perform assessment according to the farmers' motivations identified in chapter 1 (arrow A, Figure 14). I provide knowledge on impacts of reintegrating livestock, thus addressing one of the main barriers identified in chapter 2: the lack of knowledge, especially about what benefits to expect (arrow B, Figure 14).

*Once farmers have reintegrated livestock, reflexive analysis of the trajectory that led them to this current state of the system may help them better envision its future evolution.*

In chapter 4, I thus provide a **typology of trajectories** that farmers followed to reintegrate livestock into specialized crop farms and regions. I focus on the farm level in France and rely on inductive analysis of farmers' semi-structured interviews. This more dynamic approach supplements the static or snapshot analyses of the previous chapters, which take a snapshot of the state of the system at a given time.

Between the diverse chapters of my Ph.D. manuscript, I included episodes of a story, retracing the journey of Eric, a farmer reintegrating livestock onto his specialized crop farm, in a specialized crop region. This story is merely fictional, but is largely inspired by all the interviews and encounters with farmers that accompanied my Ph.D. work.

Telling this story all along my Ph.D. manuscript aims at illustrating and embodying the argument I make in the related chapters, by grounding it in (I hope) a faithful transcription of farmers’ reality. It also aims at emphasizing the overall consistency of this Ph.D. work by strengthening the connection between the diverse chapters.

When writing it, I tried to make the readers feel as if they were here, on this farm, talking to Eric. Indeed, my Ph.D. work would not have been possible without farmers’ involvement. This story was my modest contribution to highlight their roles in my work and thank them. These episodes, are additional to the scientific argument, and are thus written in grey on separate pages.

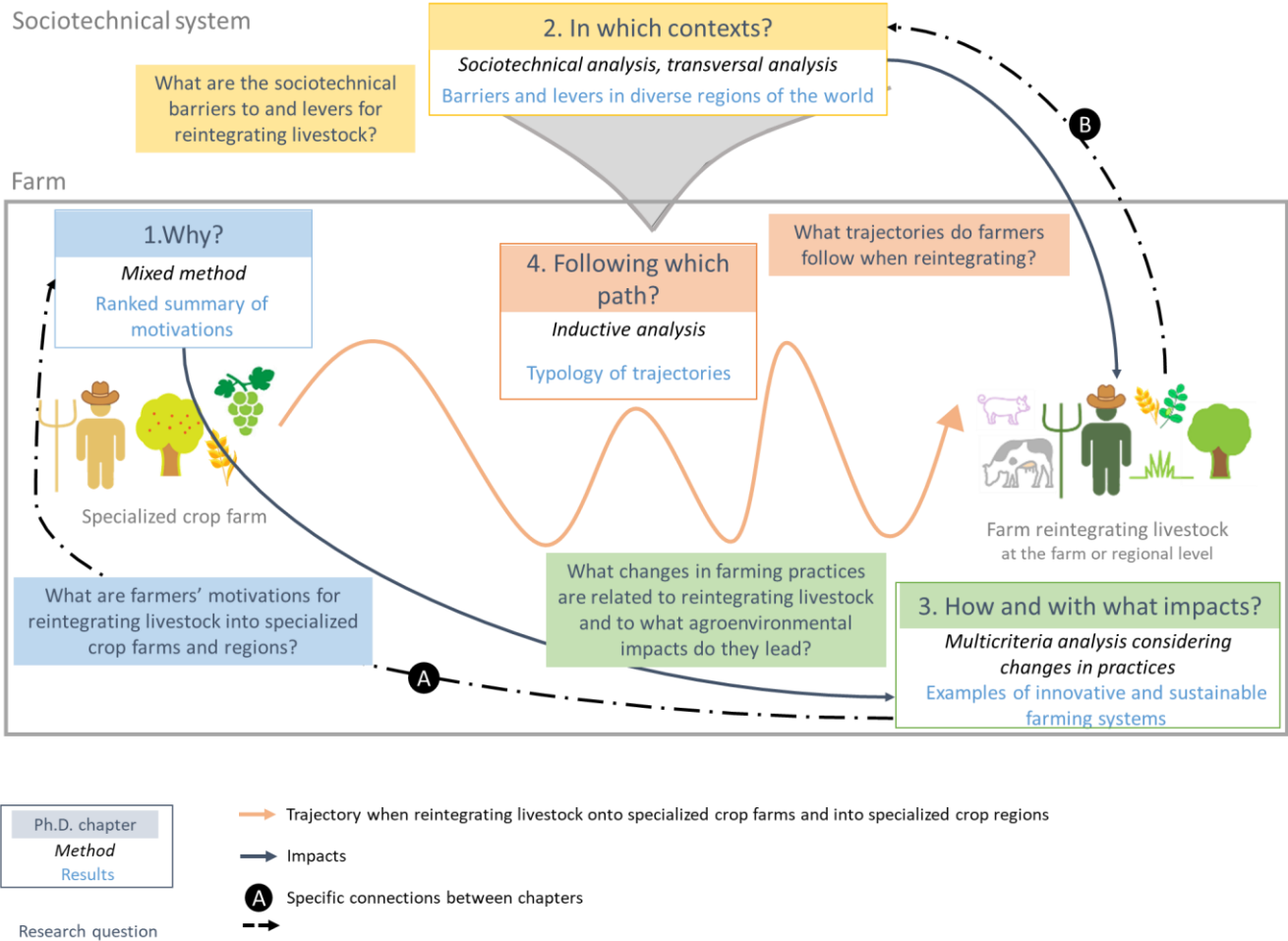


Figure 14. Positioning Ph.D. study chapters along the trajectory that farmers follow to reintegrate livestock onto specialized crop farms and into specialized crop regions

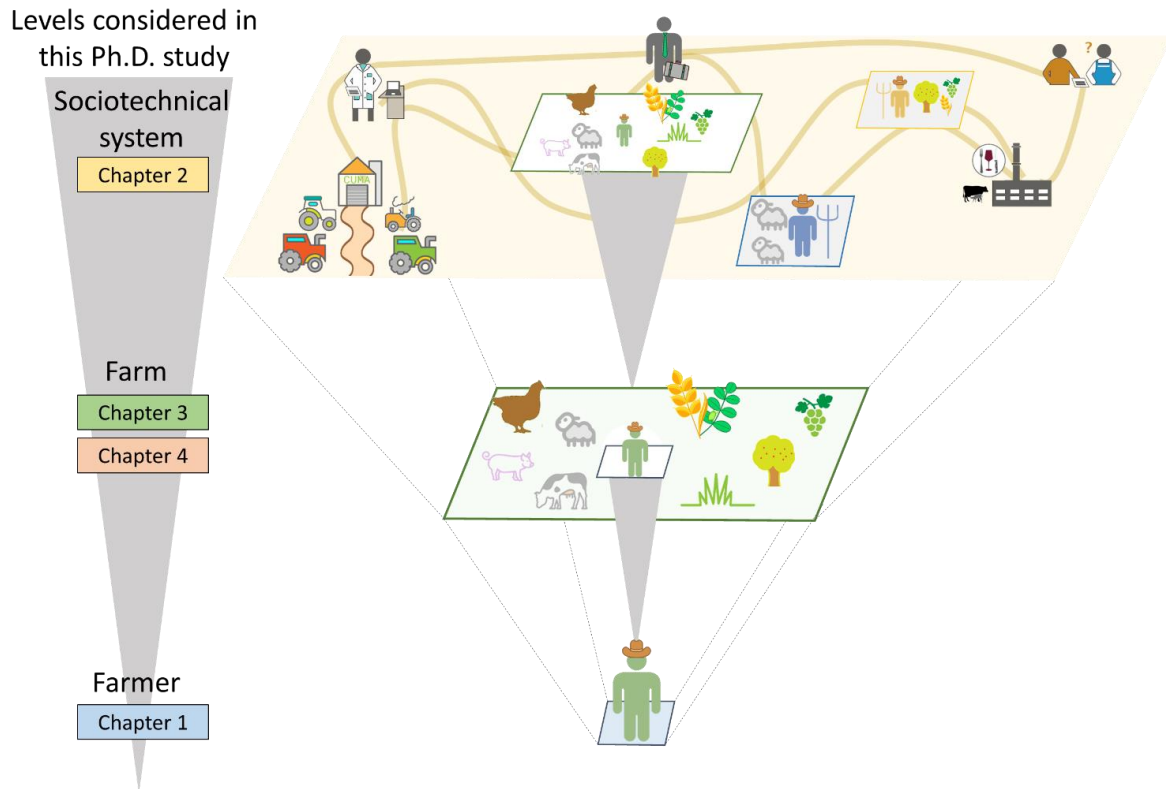


Figure 15. Multi-level approach used in this Ph.D. study to study livestock reintegration onto specialized crop farms and into specialized crop regions

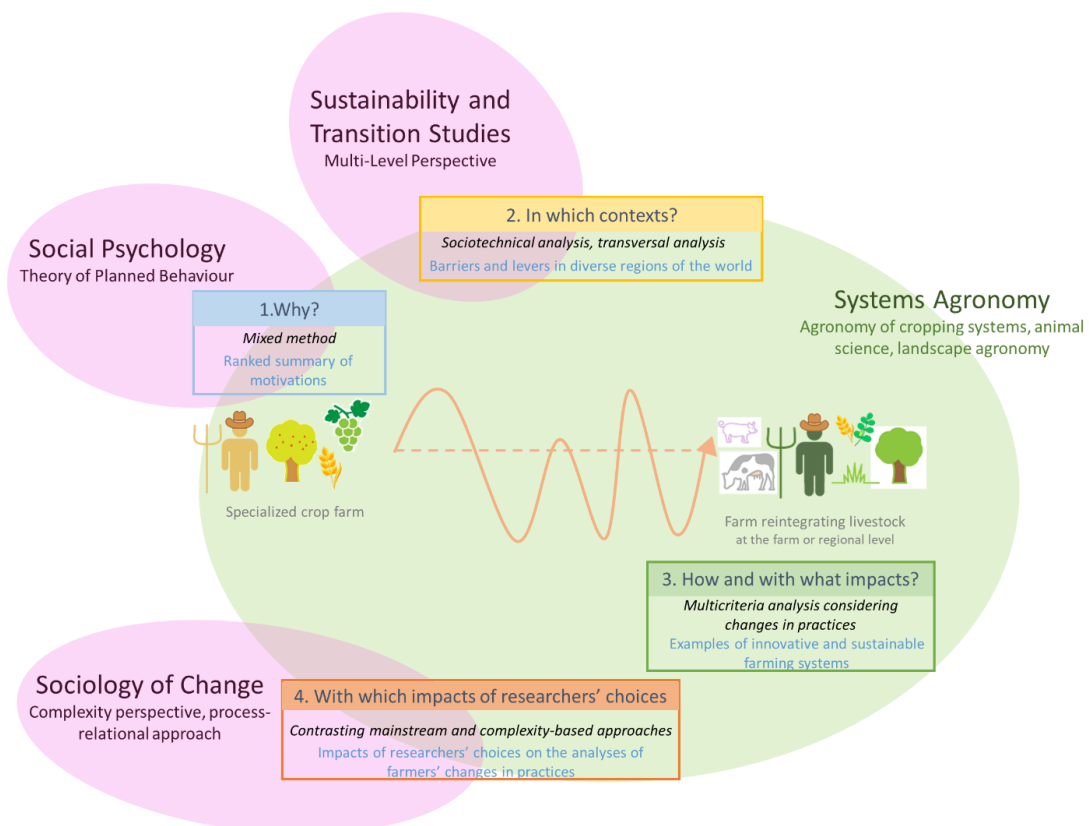


Figure 16. Interdisciplinary approach used in this Ph.D. study to study livestock reintegration onto specialized crop farms and into specialized crop regions

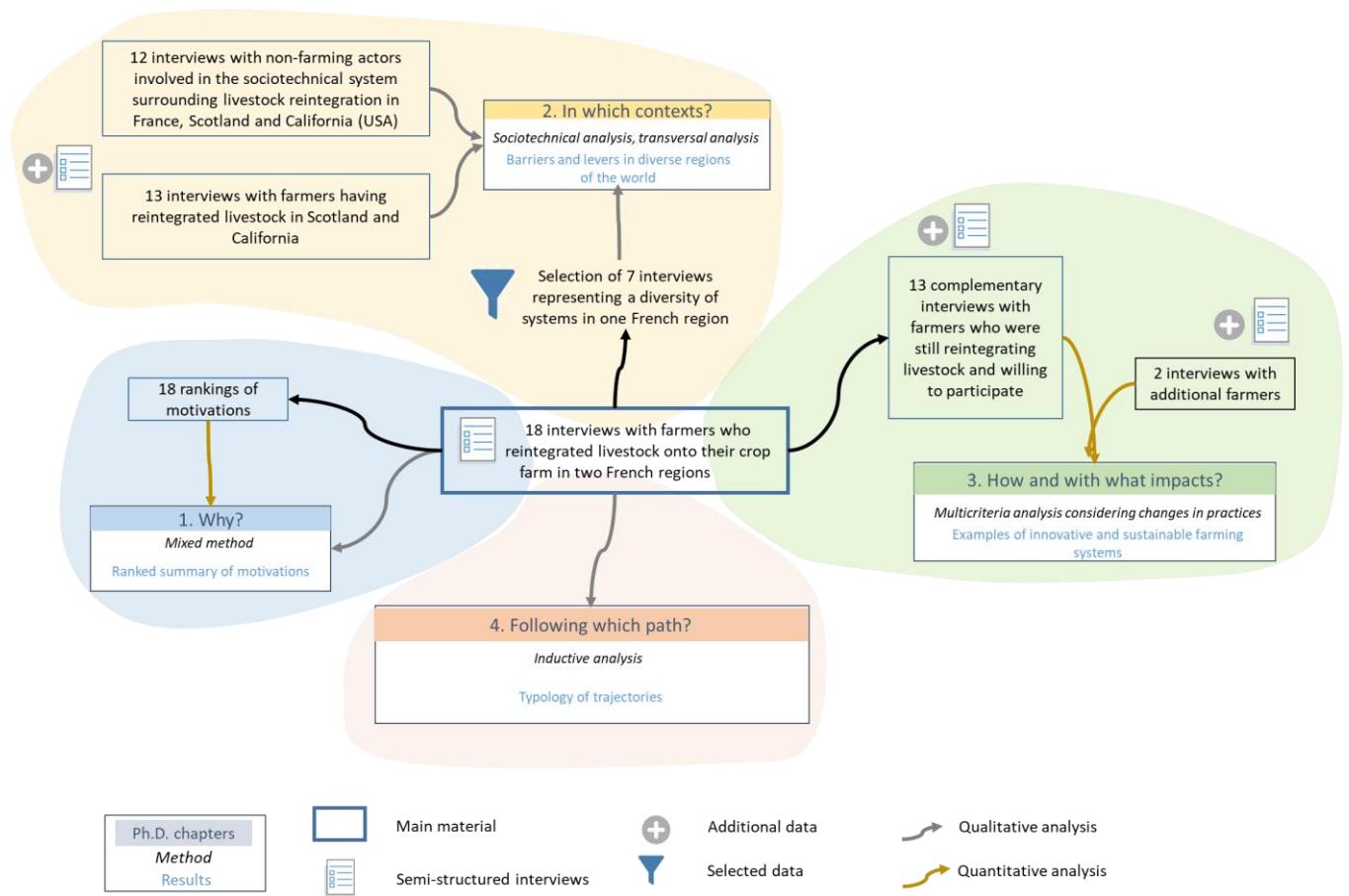


Figure 17. Organization of the data used in the chapters of this Ph.D. study

I divided my general research question into **four sub-questions**, which I addressed in the **four chapters** of this Ph.D. study. Each led to **research articles published in or submitted to international peer-reviewed journals**.

- **What are farmers' motivations for reintegrating livestock into specialized crop farms and regions?**

Chapter 1

Meunier, C., Martin, G., Barnaud, C., Ryschawy, J., 2024. Bucking the trend : Crop farmers' motivations for reintegrating livestock. *Agric. Syst.* 214.

<https://doi.org/10.1016/j.agsy.2023.103820>

- **What are the sociotechnical barriers to and levers for reintegrating livestock into specialized crop farms and regions?**

Chapter 2

Meunier, C., Martin, G., Fenster, T.L.D., Gaudin, A.C.M., Grillot, M., Lecole, P., Topp, C.F.E., Walker, R.L., Watson, C.A., Williams, S.R., Ryschawy, J. (n.d.). Barriers and levers for reintegrating livestock into crop farms and regions – A transversal analysis in three countries. [In revision, to be submitted to *Land Use Policy*].

- **What changes in farming practices are related to reintegrating livestock onto specialized crop farms and to what agroenvironmental impacts do they lead?**

Chapter 3

Meunier, C., Ryschawy, J., Martin, G. (n.d.). Reintegrating livestock onto crop farms: a step towards sustainability? [submitted to *Agricultural Systems* in September 2024]

- **What trajectories do farmers follow when reintegrating livestock into specialized crop farms and regions? What changes in researchers' stances and practices are needed to analyse these trajectories?**

Chapter 4

Meunier, C., Darnhofer, I., Martin, G. (n.d.). A call for change: Contributing to a transition to agroecology requires questioning our assumptions. [revisions requested by *Agroecology and Sustainable Food Systems* in September 2024].





## Episode 0: My grandfather, my father and I: the story of a mixed crop-livestock family farm that specialized toward grain crop production

Hi there ! I'm Eric. I'm 52 years old, and I'm a crop farmer, here, in South-Western France, in a small village of Ville-fleurie, in the Gers, not that far from Toulouse. I was born there. My family has always lived there, since... Oh, probably since the 19<sup>th</sup> century ! We always had a farm. At my grandfather's time, it did not much look like today.

My grandfather, he had cows. For milk and meat, they did both, at that time, you did not have "one breed for this, one breed for that" ... No, cows were cows, all-in-one, they gave us milk, meat, they were used in the fields, to drag tools ... Well, they were used for everything they could be used for. They were outside almost all year long, grazing in the pastures, over there, making use of the bad lands on the hills, where nothing else than grass could be grown anyhow. And in winter, they returned in the barn, close to the farm, there was a barn, here, before. It was destroyed a long time ago.

My grandfather had sheep as well, a few... I remember. When I was a kid, I came here for Easter holidays, and we always ate one of the lambs. And then, we went to the small prune orchard he had at the back on the farm, and we looked for the chocolates he had hidden there, if the hens had not eaten them before! Ah yes, he had some poultry too, just to have eggs for the family. My grandmother took care of them. There were some vines as well, a small vegetable garden... In short, a little bit of everything.

And then, the farm changed, quite progressively. Due to the market, the prices, the "modernization" they called it. My grandfather had to abandon livestock farming, the cows first, it was too strenuous work. The sheep and hens remained a little longer, but not that much. This was sad, I found. I remember, the first time I came back to the farm, and there were no more animals these, I felt something was missing... Then, when the vines and the orchard trees became too old and began producing less, my grandfather grubbed them up, and converted everything into cereals. It paid, at that time ! They gave you subsidies to grow them. With the new synthetic fertilizers and pesticides, and the new machines, the drainage in the valley fields, he could even convert pasture land into cropland, and manage to grow wheat on the hills !

The farm stayed like that for quite a time. It was already only cereals when my father took it over, and he just continued farming this way, as he had always done. When I settled with him, after my grandfathers' retirement, it was the same. The motto was "spread fertilizer, till the soil, use pesticides, you will have high yields". It worked, actually. We could reach 8 tons of wheat per hectare during the good years, sometimes even more. We always worked hard during the summer, with a really busy harvest period. The rest of the year, it was very quiet. We could go skiing every year for Christmas, take one month of holidays. It was a nice life, somehow.

But then, my father got cancer. The doctors could not tell us for sure what caused it, you never know. Fortunately, he overcame it ! But we never wanted to spray another pesticide again on the farm, neither he nor I. So we converted to organic farming, almost twenty years ago ! We were among the firsts, and I can tell you, really, the neighbours, they chattered a lot! When they saw our dirty fields, full of weeds, they told us “You are driving nuts ! Have you seen your field? You won’t get anything out of it, spray it !”, they thought we were bad farmers. My father and I, we were afraid sometimes, it has not been a path strewn with roses, far from it ! But we were together, and we had no other options. So we kept going, and we let people talk. And then my father retired, 12 years ago.









## Chapter 1: Farmers' motivations for reintegrating livestock onto specialized crop farms and into specialized crop regions



## Reminder of the challenges and objective of this Ph.D. study

This Ph.D. study aims at providing initial insights on the understudied research topic of livestock reintegration to determine to which extent it should be sustained and how. This yielded the operational challenge of my Ph.D. study, i.e. **producing knowledge on why, in which contexts, how and with what impacts farmers reintegrate livestock into specialized crop farms and regions** (Box 6).

In France, the ongoing trend of specialization toward crop production at the farm and regional level generates high environmental impacts (Garnier et al., 2019; Lassaletta et al., 2009; Peterson et al., 2020). Opposing this trend, some pioneer farmers are reintegrating livestock onto specialized crop farms and into specialized crop regions. These farmers face a deep lack of knowledge regarding how to reintegrate livestock, and what benefits to expect from such reintegration. Livestock reintegration has been neglected by research to date.

*Box 6: Reminder of the overall context leading to the operational challenge highlighted in this Ph.D. study*

To address this operational challenge, I studied livestock reintegration as an agroecological innovation, and mostly relied on the innovation-tracking framework (Salembier et al., 2021). This yielded the methodological challenge of this Ph.D. study, i.e. **improving the innovation-tracking framework by studying at multiple levels the determinants that lead to agroecological innovations and assessing their performances objectively** (Box 7).

Studying agroecological innovations such as livestock reintegration raises methodological challenges. Contributing to address some of those challenges, the innovation-tracking framework allows revealing farmers' innovations and documenting them (Salembier et al., 2021). Published innovation-tracking initiatives mostly focused on the cropping system or farm levels, on the agroecological dimension of innovations, with a static approach and often relied on farmers' self-assessment of the innovation. To build an in-depth comprehensive analysis of farmers' agroecological innovations such as livestock reintegration, the innovation-tracking framework requires improvements.

*Box 7: Reminder of the overall context leading to the methodological challenge highlighted in this Ph.D. study*

Based on these **operational** and **methodological challenges**, the following **research question** emerged for this Ph.D. study: **Why, in which contexts, how and with what impacts are farmers reintegrating livestock into specialized crop farms and regions?**

*To introduce each chapter of my Ph.D. study, I identify specific knowledge gaps and improvements to make to the innovation-tracking framework. To conclude each chapter of my Ph.D. study, I mention how I contributed to address such knowledge gaps and improve the innovation-tracking framework.*

## Preface of Chapter 1

*As stated in the Introduction (part IV), I present my results following the same trajectory that farmers would use when considering reintegrating livestock onto specialized crop farms and into specialized crop regions. For a farmer, on the trajectory of reintegrating livestock into specialized crop farms and regions is to consider why to do so.*

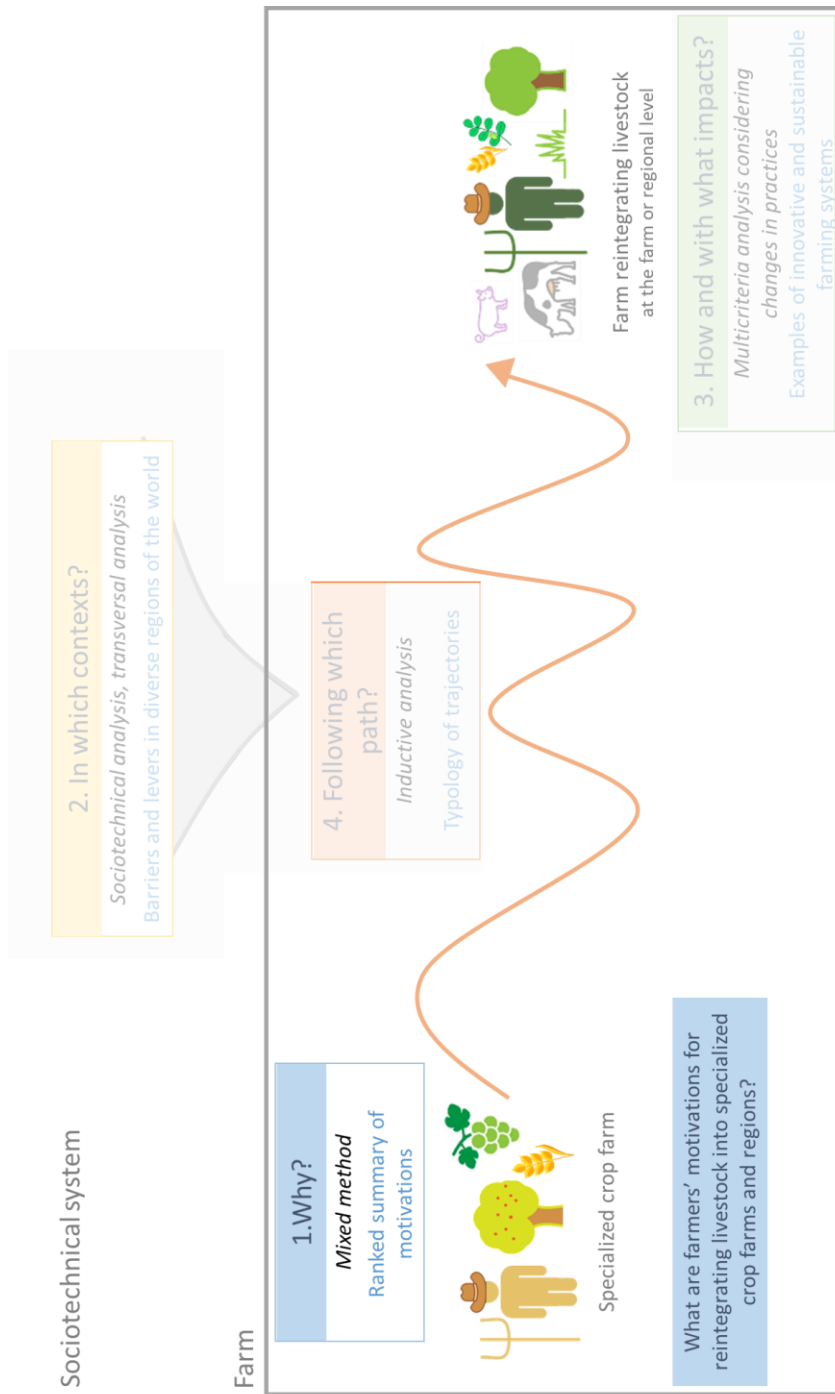
Thus, in chapter 1, I focused on **farmers' motivations** to reintegrate livestock onto specialized crop farms and into specialized crop regions as **a first determinant of change in farming practices** (Figure 18, Box 6) (de Boon et al., 2022; Greiner and Gregg, 2011; Schaffer et al., 2024). I relied on interviews with farmers to address my first research question: **What are farmers' motivations for reintegrating livestock into specialized crop farms and regions?**

In most published studies on innovation-tracking initiatives, farmers' motivations were rarely capitalized on. No specific method was presented to study them in depth (Salembier et al., 2021) (Box 7). The innovation-tracking framework could hence be improved by **combining it with methodological tools to study farmers' motivations** to implement agroecological innovations in depth.

Studying farmers' motivations could allow **aligning the sustainability assessment** of livestock reintegration and **communication on its potential benefits** with **farmers' motivations**, thus contributing to favour its scaling up.

*This chapter takes the form of a research paper, published in Agricultural Systems.*

Meunier, C., Martin, G., Barnaud, C., Ryschawy, J., 2024. Bucking the trend : Crop farmers' motivations for reintegrating livestock. Agric. Syst. 214. <https://doi.org/10.1016/j.agsy.2023.103820>



Ph.D. chapter  
**Method**  
Results

Research question

Figure 18 : Positioning Ph.D. study chapters along the trajectory that farmers follow to reintegrate livestock onto specialized crop farms and into specialized crop regions: main focus of Chapter 1 on farmers' motivations

# Bucking the trend: crop farmers' motivations for reintegrating livestock

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## Abstract

### Context

European farms and regions follow the trend of agricultural specialisation, which results in a disconnection between crop and livestock production. High-input specialised farming systems are continuing to be developed even though they generate negative environmental impacts. Despite these trends, a few pioneering farmers have intentionally reintegrated livestock onto crop farms in several regions. To date, research has rarely examined farmers' motivations to develop such systems.

### Objective

We aimed to identify French farmers' motivations for reintegrating livestock onto specialised crop farms and into crop-producing regions.

### Methods

Following innovation-tracking principles, we identified 18 crop farmers who had reintegrated livestock in two regions where crop farming predominates: Occitanie and the Parisian Basin. The farmers' profiles varied in production mode, farm size, the crops and livestock produced, and the type and duration of livestock reintegration. Semi-directed interviews focused on the farmers' motivations for having reintegrated livestock. At the end of the interviews, we asked them to select and rank 10 of 36 cards that represented their main agronomic, economic, social and environmental motivations for crop-livestock farming. We transcribed the interviews and performed inductive content analysis, which was then triangulated with the farmers' rankings of the cards.

### Results and Conclusions

Seven categories of motivations for reintegrating livestock emerged from the interviews: following personal ethical and moral values, increasing and stabilising income, promoting ecosystem services, increasing self-sufficiency and traceability, connecting to the local community, decreasing pollution and keeping the landscape open.

In both discourse analysis and motivation card rankings, agronomic motivations (including promoting ecosystem services) were predominant, especially improving soil life and fertility. Farmers ranked economic and social categories nearly equally (Figure 19). Improving and stabilising income was cited

by 17/18 farmers in their discourse, consistently with the two most-selected economic motivation cards. Strengthening social connections was the most-selected social motivation in card rankings and was mentioned by 14/18 farmers in their discourse, particularly for connections among farmers. Environmental motivation cards were selected less often, except for environmental stewardship, which was consistent with the desire to build an environmentally friendly farming system to follow personal ethical and moral values mentioned by 10 farmers in their discourse.

## Significance

This study is the first to provide a ranked summary of crop farmers' motivations for reintegrating livestock. Understanding this diversity is an initial step in incentivising, promoting and/or supporting the development of this innovative sustainable practice under favourable conditions and can encourage public actions that promote it.

## Graphical abstract

Crop farmers' motivations for reintegrating livestock at farm and regional levels

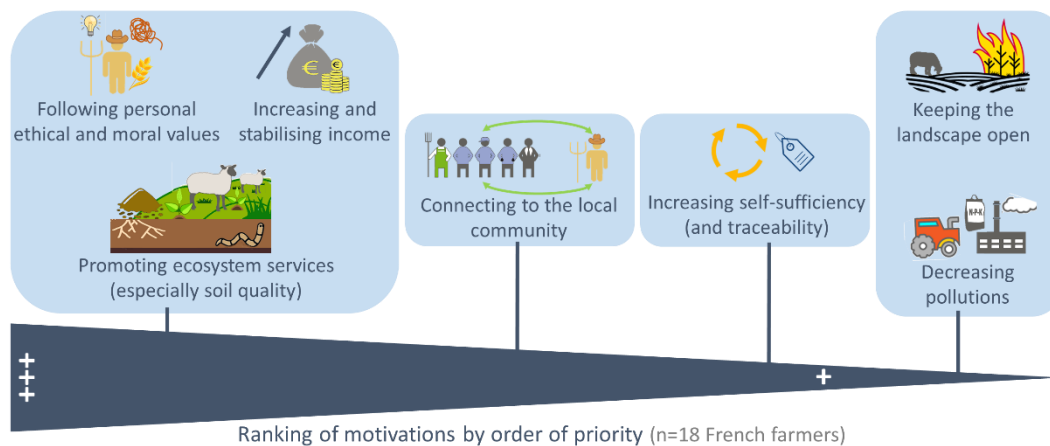


Figure 19 : Graphical abstract for Chapter 1 on farmers' motivations for reintegrating livestock

## Keywords

Crop-livestock integration, Mixed systems, Sustainability, Farmers' motivations, Innovation tracking  
Inductive content analysis

## Highlights

- Specialisation of crop or livestock production has negative environmental impacts.
- A few pioneering farmers have reintegrated livestock onto crop farms and into crop regions.
- We identified seven categories of motivations for reintegrating livestock.
- Promoting ecosystem services and following personal values were the main motivations.
- Strengthening social connections and improving income were other major motivations.

## 1. Introduction

Over the past few decades, the trend towards agricultural **specialisation** in Europe, and in France in particular, has disconnected crop and livestock farming at farm and regional levels, which has

contributed to **environmental externalities** (Garrett et al., 2020). This regional specialisation raises many issues for crop and livestock regions. Specialised crop regions are productive, but depend greatly on nutrient inputs (Peterson et al., 2020) and consume large amounts of direct and indirect energy (Harchaoui and Chatzimpiros, 2018). In comparison, specialised livestock regions are not self-sufficient in animal feed and generate excessive amounts of manure, leading to storage, disposal and pollution problems (Peterson et al., 2020). Begun in the 1950s, **specialisation still occurs in France**, with livestock production concentrating in a few regions and livestock and mixed (i.e. crop-livestock) farms decreasing elsewhere. In 1988, livestock farms were the most common type of farm in France (44% of all farms), followed by crop farms (37%) and mixed farms (19%) (AGRESTE, 2020). From 1988-2020, the number of each type of farm decreased, especially mixed farms (-75%), followed by livestock farms (-66%) and crop farms (-42%). Consequently, in 2020, crop farms were the most common type of farm (52%), followed by livestock farms (36%) and mixed farms (12%) (AGRESTE, 2020).

As explained extensively by Garrett et al. (2020), this specialisation **results from several major structural changes** that occurred during the second half of the 20<sup>th</sup> century. Liberalisation of trade forced farmers to become competitive on the global market (Ryschawy et al., 2013). To gain global market shares and protect farmers from international competition, the European Union's Common Agricultural Policy developed subsidies that focused on commodity crops and were tied to production, thereby increasing the profitability of specialised systems (Garrett et al., 2020; Schut et al., 2021). The development of labour-saving equipment and the increased cost of labour promoted the industrialisation of farming to reduce production costs, as well as its specialisation to favour economies of scale. The low prices of nitrogen fertilisers reduced farmers' reliance on livestock manure. To benefit from an agglomeration economy (i.e. clusters of related agribusinesses), specialisation also occurred at the regional level. Research agencies, advisor services and subsidy programs specialised towards crop or livestock systems, which led to path dependencies toward specialisation (Garrett et al., 2020; Gil et al., 2016). In regions where mixed farms and livestock farms have been decreasing for decades, the **livestock sociotechnical system has decreased**, with a fragmenting supply chain (e.g. few slaughterhouses, veterinarians or technical advisors) and a general lack of knowledge. These facts **challenge the practice of mixed farming and livestock farming** in several French regions.

Despite these trends, in the current context of increasing prices for energy and fertilisers (fuel and nitrogen fertilizer prices have been multiplied by 2.6 and 4.2 respectively between 2020 and 2022 in France (EUROSTAT, 2023), including a 1.6 and 1.9 multiplication between 2021 and 2022 ), **a few pioneering farmers in France** have reintegrated (i.e. intentionally organised the return of) **livestock** onto crop farms and into crop regions. These systems **may help reduce environmental impacts** of specialised agricultural production by **reconnecting crop and livestock production** (Lemaire et al., 2014) at the **farm level** (e.g. rearing livestock on the farm) or **regional level** (e.g. partnership between a crop farmer and livestock farmer, with the former hosting the latter's livestock for a specific period, for example to graze a winter cover crop). While crop-livestock integration has been studied widely in recent years (Baker et al., 2023; Paut et al., 2021; Sekaran et al., 2021), livestock reintegration **has not received much attention to date**. Understanding the **motivations** that drive farmers to reintegrate

livestock in such a challenging context is a necessary first step to assess performances of these systems in light of farmers' objectives and to incentivise, promote and/or support adoption of this sustainable practice (Cortner et al., 2019; Paut et al., 2021; Ryschawy et al., 2021).

Farmers' adoption of a practice relies on i) their **behavioural control** (which corresponds to the question: "Can I do this?"), i.e. how elements of the socio-economic context (e.g. policies, market) and farm characteristics (e.g. climate, ecology, economic and physical ability to access technology) will make it easier or more difficult to adopt a practice and ii) their **attitude** ("Do I want to do this?") (Ajzen, 1991; Cortner et al., 2019; Ryschawy et al., 2021), both influencing each other. Farmers' **attitude** towards adopting a practice is influenced by i) their **beliefs** about the practice ("What benefits do I expect from this practice?") (Ajzen, 1991); ii) their **objectives** for the farm (Ryschawy et al., 2021); iii) their **values** (Raymond et al., 2016; Stern and Dietz, 1994); iv) their **risk preference** (i.e. how willing they are to adopt practices that are considered risky) (Flaten et al., 2005; Greiner et al., 2009), which is strongly related to their perception of their ability to adopt this practice and v) **subjective norms** (Ajzen, 1991) that they have internalised ("How much do I think people want me to adopt this practice?").

To date, **no study has specifically sought in-depth understanding of the attitude** (hereafter, "motivation") **toward reintegrating livestock** onto specialised crop farms and into crop-producing regions. Few studies have focused on the conditions (including both behavioural control and attitude) that support persistence of mixed systems or reconnection of crops and livestock due to farmer cooperation beyond the farm level in regions where both types of farms still exist. They emphasised research on self-sufficiency, mitigation of market and climate risks through diversification, increased nutrient and land-use efficiency, strong cultural norms of environmental stewardship or connections to traditions as factors that support the persistence or re-emergence of mixed systems, provided that a sufficient workforce is available (Bell and Moore, 2012; Coquil et al., 2014; Garrett et al., 2020; Peterson et al., 2020; Ryschawy et al., 2013). Studies also highlighted multiple lock-ins of reconnecting crop and livestock systems through farmer cooperation beyond the farm level (Garrett et al., 2020; Martin et al., 2016; Moraine et al., 2017), especially the high costs of creating and maintaining long-term cooperation due to i) collecting information, due to the overall lack of knowledge; ii) collective decision-making when crop and livestock farmers have strongly diverging viewpoints and iii) monitoring partnerships (Asai et al., 2018).

The objective of this study was to **identify and analyse French farmers' motivations for reintegrating livestock onto crop farms and into regions**. We used the term "livestock reintegration" as we considered that nearly all farms in France used to include both crops and livestock until the 1950s (Harchaoui and Chatzimpiros, 2018). We used the term "crops" in its broadest sense, including grain crops, orchards, vineyards and vegetables.

## 2. Materials and methods

### 2.1. Case study

#### 2.1.1. Case study regions

We conducted 18 **semi-directed interviews with crop farmers who had reintegrated livestock** in order to analyse their motivations for having done so. We selected two regions where crops currently predominate but which differed in their history of livestock production: Occitanie and the Parisian Basin.

#### Occitanie

In **Occitanie** (a French region composed of the departments of Gers, Haute-Garonne and Ariège)(Figure 20), farming was traditionally dominated by self-sufficient diversified crop and mixed farms that produced mainly grain crops, followed by vineyards and orchards (Luxembourg, 1934; Perez, 1944). The dynamics of livestock and mixed farms in the Gers department represents those of the Occitanie region relatively well. In 1988, 39% of the farms were mixed (vs. a mean of 20% in France) (AGRESTE, 2020). **Livestock production has strongly decreased** and has been **replaced with specialised crop production**. From 2010-2020, 95% of the farms that disappeared were either livestock (48%) or mixed (47%) farms (AGRESTE, 2020). By 2020, the number of mixed farms had decreased to 16% of the farms (vs. a mean of 12% in France). Currently, the main type of livestock produced in Gers are poultry, beef cattle and meat sheep. Due to the department's long history of livestock production, **services and elements of the supply chain** (e.g. slaughterhouses, technical advisors) **have remained**, but they have been **reduced greatly** (e.g. several slaughterhouses have closed). Farms in Gers have a mean utilised agricultural area (UAA) of 70 ha. Gers is one of the French departments with the largest area of certified **organic farms** (30% of the farms, representing over 120 000 ha) (Agence Bio, 2020). In addition, 10% of farms in Gers process some of their production on the farm, and 20% of the farms sell some of their production directly to consumers (AGRESTE, 2020).

#### The Parisian Basin

In the **Parisian Basin** (Figure 20), **specialised cash crop farms have dominated for decades**, especially due to its rich, deep and silty soils (Bryant, 1973; Rolland and Brun, 1966). In 1988, 73% of the farms in Seine-et-Marne (the main agricultural department in this region) were specialised in crop production (mainly grain crops and beets), whereas 17% were livestock or mixed farms. By 2020, specialised crop farms had increased to 83% of the farms, whereas livestock and mixed farms had decreased to 12% (AGRESTE, 2020). Currently, the few remaining livestock farms produce mainly meat sheep (AGRESTE, 2020). The remaining **services and elements of the supply chain for livestock production are even scarcer than those in Occitanie**. Farms in Seine-et-Marne are large, with a mean UAA of 140 ha. Due to its proximity to Paris, this region benefits from a vast consumption basin, but it also experiences strong urban pressure that results in the disappearance of agricultural land. Overall, 11% of the farms are certified organic (representing 21 000 ha) (Agence Bio, 2020). In addition, 7% of the farms process



some of their production on the farm (mostly fruits, vegetables or livestock), and 22% of the farms sell some of their production directly to consumers (AGRESTE, 2020).

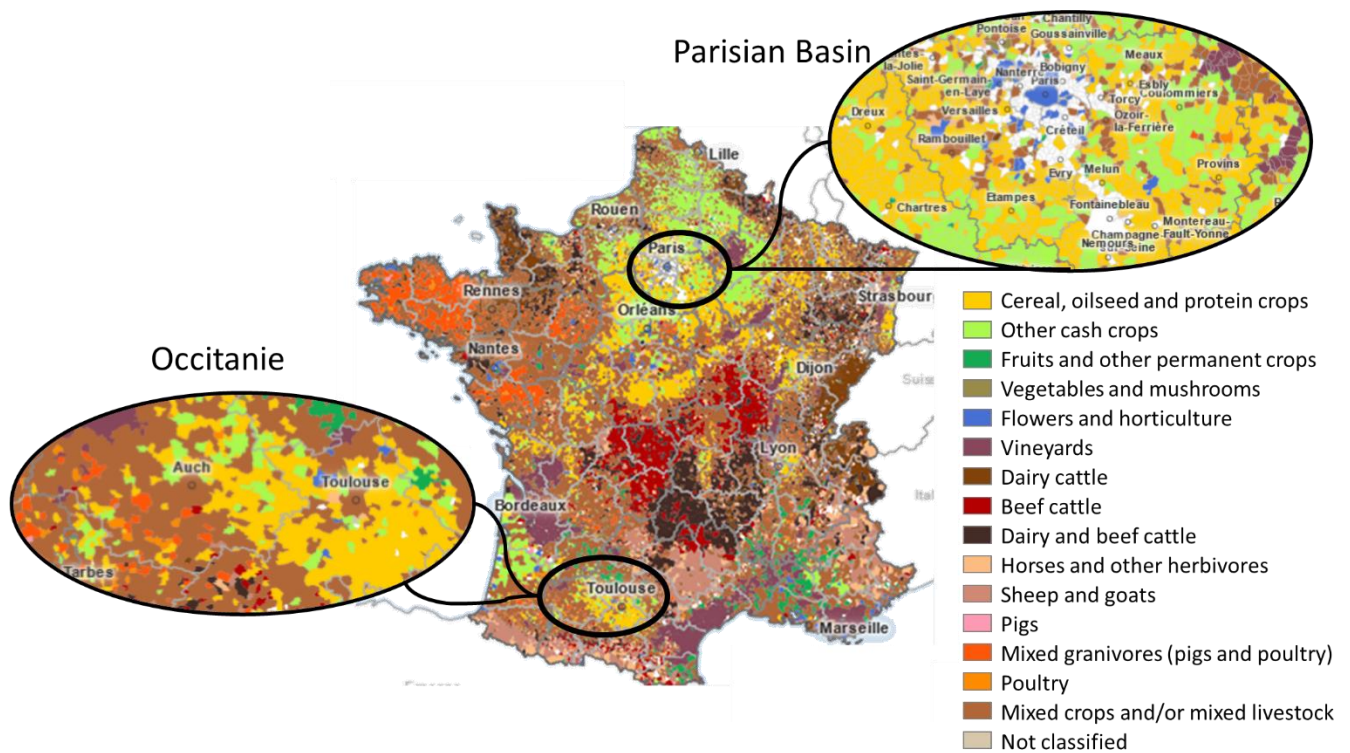


Figure 20: Main production orientation of French farms in 2020, with a focus on the two case study regions: Occitanie and the Parisian Basin (AGRESTE, 2020)

### 2.1.2. Case study farmers

#### Profiles of targeted farmers

We followed the principles of **innovation tracking** defined by Salembier et al. (2021), considering **livestock reintegration as an innovation**, as the farmers who practice it are “bucking the trend” of the decrease in the number of livestock and mixed farms. In France, few crop farmers have reintegrated livestock, and it is difficult to identify them. Because reintegrating livestock is uncommon, to identify the **variety** of crop farmers’ motivations for having done so, we included **all crop farmers we could identify** in the two regions, regardless of the production orientation or farming system. Thus, we targeted organic or conventional farmers who produced any type of crop and had reintegrated any type of livestock at the farm level or regional level. As in the case-study research approach (Eisenhardt, 1989), our objective was to identify a wide variety of motivations for reintegrating livestock rather than to obtain statistical representativeness.

### Identifying the targeted farmers and initial contact

To identify innovations, like most cases of innovation tracking studied by Salembier et al. (2021), we first identified farmers who had reintegrated livestock onto crop farms and into regions by contacting **farm advisors in our network**, as no available database exists for this type of system. We relied on diverse organisations such as the Chamber of Agriculture and Organic Farmer Group (GAB) in both regions, as well as the organisation AgroF'ile (which promotes living soils and agroforestry around Paris) in the Parisian Basin. We telephoned the identified farmers to verify they met the criteria for involvement in the study (i.e., they had reintegrated livestock on a crop farm and were willing to participate), collected general information about the farm and organised a meeting on the farm to conduct the interview. The first farmers interviewed helped us identify farmers who had reintegrated livestock outside our initial networks, which allowed us to increase the sample size using the **snowball approach**.

### Farmer profiles

We interviewed 10 farmers in Occitanie and 8 farmers in the Parisian Basin (total: 18) (Table 3) who had **diverse profiles in production mode, UAA, crop and livestock production, as well as the type and duration of livestock reintegration**. Most farms in the sample were certified **organic** (12, plus 3 in conversion), especially in Occitanie, where all farms were either organic or in conversion. The farmers had a **wide range of farm sizes** (UAA of 5-2000 ha) and **number of animals** (e.g. from 200 laying hens to 1200 ewes plus 15 000 fattening lambs).

The sample included **four types of crops**: grain crops, fruits, vineyards and vegetables. The crops varied more in Occitanie, with production of cash crops (6 farms), vineyards (3) and fruit (2), whereas nearly all farmers in the Parisian Basin grew only cash crops (7, with only 1 producing vegetables), consistent with the region orientation. Farmers had reintegrated **four types of livestock** (i.e. sheep, beef cattle, pigs, broilers or laying hens), resulting in eight combinations of crops and livestock on the farms. Most of the reintegrated animals were reared at least **partly outdoors**. Livestock reintegration occurred at the **farm level** (10 farms), the **regional level** (3) or **both** (5). In the Parisian Basin, reintegration at the farm level was the most common, with only 1 farmer who had been involved in a partnership for a few years but then stopped to reintegrate livestock on his own farm. Sheep had been reintegrated at the farm and regional levels, whereas broilers and laying hens had been reintegrated only at the farm level. The duration of livestock reintegration varied greatly (1-24 years), but most farmers had **reintegrated livestock recently** (mean of 5.6 years and median of 4 years).

Table 3: Profiles of the 18 farmers interviewed in the Occitanie (O) or Parisian Basin (PB) regions. Younger: less than 35 years old; Middle: between 35 and 55 years old, Senior: over 55 years old. School: high school or university.

Farmer	Region	Production mode	Crops	Livestock	Level of reintegration	Years reintegrated	UAA in 2022 (ha)	Type and no. of animals in 2022	Outdoors/ indoors	Gender	Age	Prior connection to livestock farming
F1	O	Conversion	Vineyard	Meat sheep	Regional	2	30 (+ 30 in grain crops)	120 ewes	Outdoors + field with shelter	Male	Younger	No
F2	O	Organic	Vineyard	Meat sheep	Farm and Regional	1	70 (+ 30 in nuts)	35 owned sheep + 130 hosted sheep in winter	Outdoors	Male	Senior	Family
F3	O	Organic	Vineyard Grain crops	Meat sheep	Farm and Regional	4	2000, of which 80 in vineyards and 100 in pasture	1000 ewes	Outdoors (+ fold)	Male	Younger	School
F4	O	Organic	Orchard	Meat sheep	Regional	2	45 in plums (+ 230 in grain crops)	Hosted ewes	Outdoors	Male	Middle	No
F5	O	Organic	Orchard	Meat sheep	Farm	4	80	12 ewes + 1 ram	Outdoors	Male	Middle	Family
F6	O	Organic	Grain crops	Meat sheep	Farm and Regional	4	200 (of which 40 in pasture) + mountain pasture	200 ewes + 45 other sheep	Outdoors	Male	Middle	No
F7	O	Conversion/ Conventional	Grain crops	Meat sheep	Regional	2	500 (+20 in vineyards)	Hosted ewes	Outdoors	Male	Younger	No
F8	O	Organic	Grain crops	Broilers	Farm (+Regional)	9	130 (of which 10 in pasture)	2 × 8000 broilers (+ renting a field to a neighbour to graze cattle)	Free range	Male	Middle	Family
F9	O	Organic	Grain crops	Laying hens	Farm	14	350	10 000 laying hens	Free range	Male	Senior	Family

F10	O	Organic	Grain crops	Laying hens	Farm	2	29 (of which 5 in permanent pasture)	6000 laying hens	Free range	Male	Middle	Family
F11	PB	Conventional	Grain crops	Meat sheep	Farm (+Regional)	10	650	550 ewes	Mixed indoors/outdoors	Male	Middle	Family
F12	PB	Organic	Grain crops	Sheep for wool	Farm	5	165	30 ewes and castrated males	Outdoors + field with shelter	Male	Younger	Family
F13	PB	Organic	Grain crops	Meat sheep	Farm	3	190	18 ewes + other sheep	Outdoors	Male	Middle	Family
F14	PB	Conventional	Grain crops	Meat sheep	Farm	24	500	1200 ewes + 15 000 fattening lambs	Mainly indoors, partly outdoors	Male	Senior	No
F15	PB	Organic	Grain crops	Laying hens, beef cattle	Farm	5	230 (of which 30 in pasture)	9000 laying hens + 20 beef cattle	Free range for hens, mixed indoors/outdoors for cattle	Male	Younger	Family
F16	PB	Conventional	Grain crops	Laying hens	Farm	2	160	8000 laying hens	Free range	Male	Younger	Family
F17	PB	Organic	Vegetables	Laying hens	Farm	4	5	200 laying hens	Free range	Male	Younger	No
F18	PB	Conversion	Grain crops	Pigs	Farm	5	140	1 boar + 6 sows	Free range	Male	Middle	Family

## 2.2. Data collection

The interviews were conducted from fall 2021 to spring 2022 by one researcher (C.M.). They lasted 1.0-3.5 hours (mean of 2.0 hours) depending on the complexity of the system and availability of the farmer. All interviews were conducted on the farm, except for one farmer whose schedule allowed only a telephone interview. When the farmer had enough time, the interview was supplemented by a visit to the farm.

We designed two interview guides to interview crop farmers who had reintegrated livestock at the farm or regional level, respectively. The two guides were similar, differing only in the inclusion of certain questions that targeted specific characteristics of the systems: on-farm livestock production for the former, and opportunities and difficulties of establishing a partnership with a livestock farmer for the latter. The guides included questions aimed at helping farmers **mention all the factors that motivated them to reintegrate livestock** (Ajzen, 1991) (Table 4). Questions focused on the farmers' i) **beliefs** about livestock reintegration, ii) overall **objectives** for the farm, iii) **values** and their influence on livestock reintegration, iv) **perception of the risks** involved in reintegrating livestock and v) **internalised subjective norms** and how the farmer's relatives reacted to his/her idea to reintegrate livestock. Other topics were also mentioned, as the variety of questions helped us understand the overall functioning of the farm and identify some of the farmer's motivations for reintegrating livestock, even when the farmer might not have mentioned them when specifically asked.

Table 4: Interview questions asked to understand farmers' motivations for reintegrating livestock

Targeted factor	Questions
Beliefs about the behaviour	Which elements influenced you to consider livestock reintegration? Why did you decide to reintegrate livestock? What motivated you to do so? Were you surprised by the results of livestock reintegration, or did you expect them? How is livestock reintegration consistent with your overall approach to the farm and its history?
Objectives	In your opinion, what are the objectives of a farmer? What are your objectives for the farm and for each type of production? Try to imagine your farm in 5 or 10 years: what does it look like?
Values	Why did you decide to reintegrate livestock? What motivated you to do so? + Follow-up questions: Was [the element mentioned, such as building an environmentally friendly system, connecting to traditions] important/relevant to you?
Risk preference	What were your concerns when you first considered reintegrating livestock? Did you think it was risky back then? And now?
(Internalised) subjective norms	How did your relatives react when you mentioned your decision to reintegrate livestock? Did you feel isolated/supported?

To conclude the interview, **verify** whether we had identified all the motivations for livestock reintegration and **rank** them, we gave farmers 36 cards that listed the main benefits of mixed farming and livestock reintegration found in the literature and supplemented by us with some benefits for farmers of adopting sustainable practices (Table 5). The cards were divided into four categories: agronomic (13: 5 for soils and 8 for other aspects), environmental (4), economic (12) and social (7). We asked farmers to **select and rank approximately 10 cards** (from any category) **that were consistent with their own motivations for reintegrating livestock** onto their crop farm. Farmers could also add cards if they believed that a major motivation was missing. We briefly discussed their rankings, related them to the motivations identified during the interview and added missing points, if necessary.

Our study procedure followed the guidelines provided by INRAE's Charter of deontology, scientific integrity and ethics (INRAE, 2020). Farmers did not belong to particularly vulnerable groups. They were explained the purpose of the interview and provided informed oral consent before beginning the interview. They were also informed that they could skip questions. The data were pseudonymised before processing (European Commission, 2020).

Table 5: Motivation cards given to the farmers during the interview

Category	Motivation card	Abbreviation	Reference(s)
Agronomic	Soils	Improving soil fertility/organic matter content	Soil Fertility (Brewer and Gaudin, 2020; Franzluebbers and Stuedemann, 2014; Veysset et al., 2014)
		Improving soil structure	Soil Structure (Brewer and Gaudin, 2020; Garrett et al., 2020)
		Promoting carbon storage in the soil	Soil Carbon Storage (Brewer and Gaudin, 2020; Franzluebbers, 2005; Veysset et al., 2014)
		Promoting erosion control	Erosion (Franzluebbers et al., 2014; Garrett et al., 2020; Martin et al., 2016)
		Improving soil life (biomass and microbial activity)	Soil Life (Brewer and Gaudin, 2020)
	Others	Reducing all types of pesticides/mechanical weeding	Pesticide (dos Reis et al., 2021; Hendrickson et al., 2008; Niles et al., 2018)
		Reducing weed pressure	Weed Pressure (Brewer and Gaudin, 2020; Hendrickson et al., 2008; Niles et al., 2018)
		Breaking pest, weed and disease cycles	Pest Cycle (Brewer and Gaudin, 2020; Hendrickson et al., 2008)
		Promoting biodiversity	Biodiversity (Ryschawy et al., 2012)
		Increasing productivity per ha	Productivity (Niles et al., 2018; Peterson et al., 2020)
		Optimising forage resources	Forage Resources (Hendrickson et al., 2008)
		Diversifying and extending crop rotations	Crop Rotations (Julie Ryschawy et al., 2017)
		Maintaining the landscape of the region	Landscape (Davies et al., 2016; Rouet-Leduc et al., 2021)
Environmental	Decreasing greenhouse gas emissions	Greenhouse Gas (dos Reis et al., 2021; Gil et al., 2018; Lazcano et al., 2022)	
	Closing nutrient cycles (nitrogen, phosphorus, potassium)	Nutrient Cycles (Lazcano et al., 2022; Ryschawy et al., 2012; Veysset et al., 2014)	
	Decreasing nitrogen loss/water pollution	Nitrogen Loss (Ryschawy et al., 2012; Veysset et al., 2014)	
	Improving environmental stewardship	Environmental Stewardship (Parker, 2013)	

Economic	Ensuring a market for specific products	Market	(Bell and Moore, 2012)
	Sharing equipment	Equipment	(Lemaire et al., 2014)
	Reducing production costs	Production Costs	(dos Reis et al., 2021; Niles et al., 2018; Ryschawy et al., 2012)
	Mitigating risks of climate and market uncertainties	Risk Mitigation	(Gil et al., 2018; Veysset et al., 2014)
	Stabilising income by diversifying production	Production Diversification	(Bell and Moore, 2012; Ryschawy et al., 2012)
	Becoming more self-sufficient	Self-Sufficiency	(dos Reis et al., 2021; Regan et al., 2017; Ryschawy et al., 2012)
	Increasing income	Income increase	(dos Reis et al., 2021; Hendrickson et al., 2008; Peterson et al., 2020)
	Sourcing inputs locally	Sourcing Locally	[Added by us]
	Ensuring a more flexible marketing method	Marketing Flexibility	[Added by us]
	Ensuring better control of the products	Product Control	[Added by us]
	Improving the traceability of purchased products	Traceability	[Added by us]
	Promoting agri-tourism	Agri-tourism	[Added by us]
Social	Improving the image of the production system	System Image	(Franzuebbers et al., 2014; Martin et al., 2016)
	Creating social connections, solidarity and mutual aid	Connections	(Julie Ryschawy et al., 2017)
	Acquiring and sharing new knowledge	Knowledge	(Julie Ryschawy et al., 2017)
	Developing networks	Networks	(Julie Ryschawy et al., 2017)
	Connecting to family history/traditions	Traditions	(Parker, 2013)
	Responding to a desire/preference/belief	Desire	(Cortner et al., 2019; Parker, 2013)
	Responding to the desire for a technical challenge	Technical Challenge	[Added by us]



## 2.3. Data analysis

### 2.3.1. Discourse analysis

To identify farmers' motivations for reintegrating livestock, we **transcribed** the 18 interviews completely and performed **inductive content analysis** (Elo and Kyngäs, 2008), which is an effective method for identifying key points during an interview and highlighting themes related to a topic. Following Perrin et al. (2020), we first performed free-floating reading of farmers' responses and identified six main topics that they had mentioned during the interview: description of the system, motivations, practices, impacts, enabling conditions, disabling conditions and perspectives. For each topic, we systematically collated all farmers' responses (i.e. the corresponding idea(s) mentioned), their identifiers (e.g. F1) and a related quote extracted from the transcription. We coded the responses by grouping them into categories and subcategories of similar ideas that emerged during the process. For instance, "Because [the sheep] provide organic matter" (F5) and "[Sheep] are above all an agronomic tool...that can provide fertility" (F6) were grouped into the category "Agronomy", subcategory "Soil" and sub-subcategory "Soil fertility". We adjusted and redefined categories to consider all the ideas that emerged from farmers' responses and formulated them as motivations (e.g. the category "Agronomy" was redefined as "Promoting ecosystem services"). The coding was double-checked separately by two researchers (G.M. and J.R.) to increase the robustness of the motivations. Results for each category and, when necessary, subcategory identified were associated with the number of farmers who mentioned it, and illustrated by anonymised quotes extracted from the interviews and translated by the authors.

### 2.3.2. Analysis of motivation cards

To rank crop farmers' motivations, we analysed their 18 rankings of the motivation cards using two indicators:

- the number of times each card had been selected, considering all the cards that farmers had selected (range: 9-18, with a mean and standard deviation of  $11 \pm 2$ ).
- the weighted sum of points attributed to each card. We allocated points to the 10 highest-ranked cards (from 10 points for rank 1 to 1 point for rank 10) and then summed all the points for each card.

We performed **multivariate analysis** to characterise farmers' motivation rankings and then related them to farming system features or farmers' profiles. We used **principal component analysis** (PCA) to explain farmers' motivation card choices, including the sum of points attributed to each category (i.e. agronomic (soils and other), environmental, economic and social).

We analysed the projection of the farmers' rankings on the factorial map according to 9 qualitative variables that described the farming system (i.e. Region, Crops, Livestock, Level of reintegration, Years reintegrated, UAA, Outdoor/Indoor system) and the farmer's profile (Age and Prior connection to livestock farming). We tested the significance of the graphic structures revealed by the PCA using the

Monte Carlo method (1 000 iterations). All tests were performed using R software version 4.3.1 (R Core Team, 2018), with significance set at  $p < 0.05$ .

### *2.3.3. Triangulating the results: comparing interview responses and motivation cards*

To increase the robustness of the results, for each farmer, we **compared the motivations identified through discourse analysis to the ranking of each motivation card** and classified the comparison into four classes:

- i) the same
- ii) nearly the same (the card could be related easily to something the farmer mentioned, but using different words)
- iii) ambiguous or unclear (i.e. the motivation was mentioned by the farmer only after he/she saw it on the card, it was more general than specific to livestock reintegration, or it was mentioned as an impact of livestock reintegration rather than a motivation for it)
- iv) different (the motivation was identified through discourse analysis but not selected in the cards, or vice versa)

When a selected card did not refer to an interview response, we rechecked the transcription to ensure that we had not missed the information, which increased the robustness of the discourse analysis. We then calculated the percentage of motivations in each class for all 18 farmers combined.

## 3. Results

### 3.1. Inductive analysis

**Seven categories of motivations for reintegrating livestock emerged** from the inductive analysis of the interviews: **promoting ecosystem services** (especially improving soil quality), **decreasing pollution**, **increasing self-sufficiency and traceability**, **increasing and stabilising income**, **connecting to the local community** (among farmers, by improving image of the system towards customers and citizens), **keeping the landscape open** (i.e. keeping agricultural land in production) and **following personal ethical and moral values** (e.g. passing down a satisfying farming system, building an environmentally friendly farming system or undertaking a technical challenge) (Figure 21).

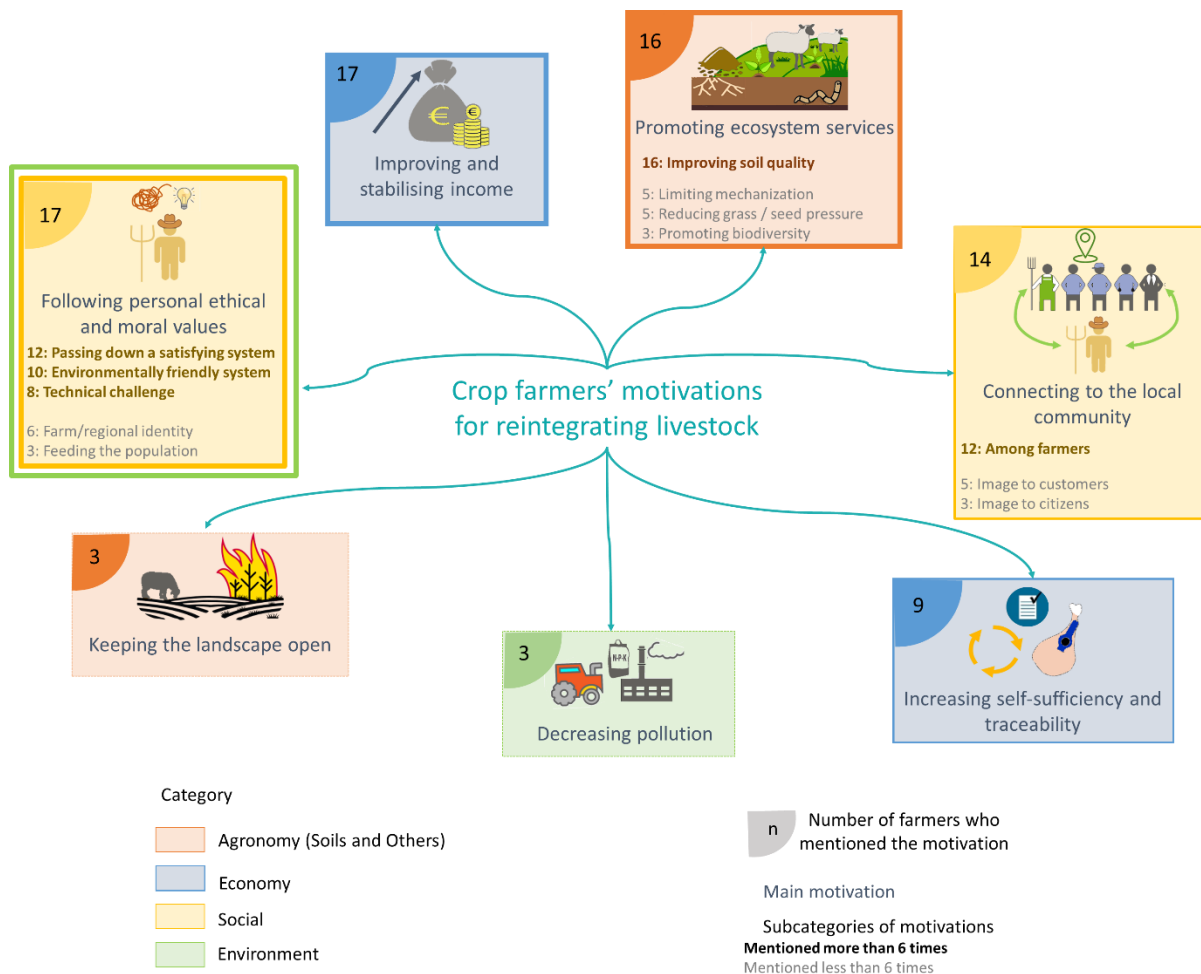


Figure 21: Overview of crop farmers' motivations for reintegrating livestock identified through discourse analysis

### Livestock reintegration to follow personal ethical and moral values

Almost all farmers (17) identified livestock reintegration as a **way to increase their overall well-being** because it **matched their many and diverse personal objectives, beliefs and values** better (F3: "I get up in the morning with pleasure. I do the things I like.").

From a personal viewpoint, 3 farmers identified livestock reintegration as a way to respond to their desire to have a **meaningful job by feeding the population**, using the animals as a way to derive value from crops that were difficult to sell (F14: "I thought 'I am 30 years old; I spend my life growing wheat that nobody needs. My job is meaningless; nobody wants my wheat'.").

Another motivation for farmers to reintegrate livestock was that having animals on the farm helped them **produce food in a way that matched their value of environmental stewardship** (Stern and Dietz, 1994) (10 farmers, e.g. F18: "I want to be able to save the Earth [and] produce things without polluting."). Farmers also wanted to be **more consistent with types of sustainable farming** (e.g. agroecology, biodynamics, mixed farming, the farm as an ecosystem) (F5: "For agroecology, I feel that having animals in a production system helps close the loop, especially in organic farming.").

For 8 farmers, reintegrating livestock onto a crop farm without knowing exactly how to do it was one way to break the routine and **undertake a technical challenge** (F13: “I like to say that I am experimenting, and then when it begins to work well, I am no longer interested.”).

From a heritage perspective, 6 farmers mentioned livestock reintegration as a way to **connect to family history** (F13: “I remember my aunt..., who brought her sheep along the paths to graze. It was amazing. I was there; I lived it.”) or **regional identity** (F18: “[A few years ago, in the region] we did not use hectares to describe farm size; we used the number of ewes. We said ‘it’s a farm with 300 ewes’. I am going to bring them back.... Go back to what they did before.”).

Livestock reintegration reassured 6 farmers about the **transmission** of their farm, as it increased its financial value, thereby echoing their desire to provide the best for future generations (F10: “It is because I have two sons; I am planning for their future.”). More concretely, having livestock on the farm helped some farmers **reduce their workload** (5 farmers, e.g. F3: “We avoid two stubble ploughings thanks to grazing.”), thus improving the balance between personal and professional life. Reintegrating livestock was also seen as a way to improve farmers’ **satisfaction in their work**, especially due to the presence of animals (11 farmers, e.g. F13: “It is really a pleasure to see animals out there.”).

#### *Livestock reintegration to increase and stabilise income*

Fourteen farmers reintegrated livestock to **increase their income** (F10: “It is simply for the money. If I could earn a living with crops, I probably would not have [reintegrated livestock]; it is easier to work in the fields.”). This increase can be related to the following:

- i) **selling new products** (6 farmers, e.g. F17: “In direct selling, customers ask for eggs...produced in the region, on a farm.”)
- ii) **using “lost” crops or land**, such as between orchard or vineyard rows or growing pasture on land where crop production would be too expensive (7 farmers, e.g. F15: “Lucerne is like medicine for the soil, so it is great that we can make the good use of it with the cows.”)
- iii) **decreasing production costs** by promoting ecosystem services and increasing self-sufficiency, as mentioned (6 farmers made a direct connection, e.g. F7: “And also saving money on mechanisation costs to produce lucerne hay [thanks to the sheep]”).

Another motivation for reintegrating livestock mentioned by 10 farmers was to stabilise income, in the following ways:

- i) **increasing farm self-sufficiency and diversifying production**, thereby depending less on fluctuating global market prices and climate events (10 farmers, e.g. F18: “I was finished with not being able to make ends meet [by] producing grain and selling it on the global market. I needed to find a ready-to-sell product, so now...all my grain will feed my sheep, pigs and chickens.”; F14: “We have four jobs, and there is always one that does not go well. [...] This year, it is a pleasure to work with the sheep. It is going to be a good year for grain, but last year was not great. It is fairly balanced; it helps to be a bit more resilient.”).

- ii) using livestock to **derive value from crops that did not grow well** (1 farmer, F18: “I can mess up with one crop because I can mow it to feed my livestock; they provide flexibility.”)

#### *Livestock reintegration to promote ecosystem services*

One motivation for reintegrating livestock was to **promote ecosystem services**, mentioned by 16/18 farmers. All of these farmers emphasised motivations regarding **soils**, especially soil life (i.e. biomass and microbial activity) (9/18, e.g. F13: “The main idea of having sheep was...to revitalise the soil.”) and fertility (14/18, e.g. F16: “It was a way to have livestock on the farm and produce our own organic matter for the fields.”), and thus soil structure (3/18). Four farmers also mentioned the expected role of reintegrating ruminants in promoting carbon storage in soils (as part of soil quality improvement) due to the decrease in greenhouse gas emissions caused by replacing mechanisation with grazing and reintroducing pasture into crop rotations. Five farmers also mentioned the expected role of ruminants in **consuming grass or weeds**, which was directly related using them to manage cover crops, thereby reducing mechanization (F1: “I think that my first objective was to stop mowing the cover crops.”) or weeds (F2: “[Sheep] are eating tall fescue a lot ... I am really happy I found this way; it’s really hard to get rid of it [without sheep]”), especially between orchard or vineyard rows, where mechanical weeding is difficult. One farmer also mentioned adding pasture to feed animals, which helps to decrease weed pressure by extending the crop rotation and breaking pest cycles (F3: “If we have sheep, we can extend the crop rotation up to 10 years. We are going to sow lucerne and pasture; this is truly long-term thinking.”). Three farmers mentioned the role of livestock in **increasing biodiversity in fields**, especially for fauna such as birds (F1: “I found sheep wool in titmouse nest boxes..., so it is useful for biodiversity; birds can use it.”) and auxiliary insects (F4: “When sheep arrive in the field, we see insects climbing the trees, so we have ladybugs and many other auxiliary insects that...help us deal with the aphids and [other pests].”).

#### *Livestock reintegration to strengthen connections with the local community*

Farmers’ motivations for reintegrating livestock were also influenced by a strong desire to **strengthen their connections to the local community** and decrease isolation (12/18 farmers). This can be related, for instance, to **having other people work on the farm** throughout the year to tend to the livestock (F12: “Livestock farming is a social support.”; F11: “Currently, on a cash crop farm, from November 15<sup>th</sup> to December 15<sup>th</sup>, nothing happens.... [...] [With livestock], you can see people on the farm every day, even during winter; there is always something happening. It is not restful, but [I like it]”). Reintegrating livestock can also be an opportunity to work with someone else, either by helping a shepherd become established (F2: “I think we can create a win-win partnership with young shepherds who do not have enough money to become established, as we want [to have livestock] but do not have the time to do all of it correctly.”) or by partnering with a livestock farmer (F6: “Integrating livestock without being a livestock farmer [means] hosting [the livestock of] someone who has problems because he does not have enough land.”).

Some farmers reintegrated livestock to strengthen their relationships with others, as having livestock can be seen as a way to **improve the image of livestock farming to citizens** (3 farmers, e.g. F11: “When

I walk across the village with my sheep, people like that.”). It can also help them **improve the image of their products to their customers** and maintaining a “licence to operate”, especially when selling directly to consumers (5 farmers, e.g. F3: “Some time ago, [the organic shop] advertised our products to show people we were practising agro-pastoralism. Clients like it, everybody likes it.”).

#### *Livestock reintegration to increase self-sufficiency and traceability*

Eight farmers reintegrated livestock to improve **farm self-sufficiency**, especially in nitrogen, by producing livestock manure (F17: “There is also the idea of reaching...self-sufficiency in nitrogen.”). Reintegrating livestock onto a farm could also provide farmers an outlet for grain or fodder legumes introduced into crop rotations, which would increase nitrogen fixation and decrease input costs.

One farmer considered self-sufficiency as a way to **improve the quality of farm inputs**, such as manure (F8: “Last year...I spread 5 tons of [imported] chicken manure per hectare; it was as if I had done nothing at all.”). Four farmers emphasised the **increased traceability** of farm products when selling directly to consumers or locally with few intermediaries (F15: “The eggs, once you collect them, ...are ready to be packed in boxes and sold. We can manage the entire supply chain on the farm and get back in touch with our customers.”).

#### *Livestock reintegration to decrease pollution*

Three farmers stated that they decided to reintegrate livestock to **decrease pollution**, especially by **promoting ecosystem services**, which helps to **decrease the use of inputs** (e.g. nitrogen fertilisers, pesticides, fuel) (F1: “I think I use my tractor less often and [use fewer nitrogen] inputs, which are hard to quantify.”). These farmers considered reintegrating grazing animals as a way to **produce food or fibre with lower environmental impacts** (F6: “Livestock farming is criticised for its impact on the climate, and this is true. However, I believe that we can perform wholesome actions. [...] The idea is to have animals grazing to...decrease mechanisation to make hay.”; F12: “When you wash [wool clothes], it doesn’t release dyes or plastic residues into water treatment plants or the sea.”).

#### *Livestock reintegration to keep the landscape open*

Another motivation for reintegrating livestock was to **help restore and maintain the landscape**, for instance by renovating an abandoned orchard (3 farmers, e.g. F2: “We do not have sheep only to produce meat. We also have sheep to maintain the land.”). One farmer also perceived having grazing livestock as an opportunity to stop spending large amounts of money to produce crops on land marginal for cultivation, without letting it turn into abandoned rangeland (F12: “It means having the chance to stop cultivating small parts of fields without feeling that we are abandoning them.”).

### 3.2. Analysis of farmers' selection and ranking of motivation cards

#### 3.2.1. Farmers' motivations for reintegrating livestock: agronomy first

Analysis of farmers' selection and ranking of motivation cards helped us **rank their motivations for reintegrating livestock**. Each card was selected at least once. One card was added by a farmer for a specific motivation (i.e. decrease the amount of strenuous work) and was not used again. The points attributed to each card and the number of times it was selected yielded similar results overall (Figure 22, Supplementary Material 1).

Farmers attributed the most points and selected the most cards from the **agronomy category** (Figure 22) (43% of the points and 41% of the cards selected). Among these cards, farmers' main concern was **the soil** (25% of the points), especially improving soil life and fertility, which were the first and second motivations, respectively, in points (8% and 6%, respectively) and the number of times selected (by 13 and 12 farmers, respectively) (Figure 22). Soil motivations were often selected by the same farmers (9 farmers selected soil life and soil fertility; 8 farmers selected soil life and soil structure). Promoting **biodiversity** was another agronomic motivation (5% of the points, selected by 9 farmers).

After agronomic motivations, **economic and social categories were selected nearly equally** by farmers (25% and 22% of the points, respectively, and 24% of the cards selected each). Economic motivations included mainly **increasing and stabilising income by diversifying production** (5% of the points each, and selected by 8 and 7 farmers, respectively, with 5 farmers selecting both). Increasing self-sufficiency was attributed 4% of the points and was selected by 6 farmers. The social motivations selected regarded **creating social connections** (5% of the points, selected by 12 farmers), **responding to a desire/preference/belief** (4% of the points, selected by 7 farmers) and acquiring and sharing new knowledge (only 3% of the points, because although selected by 8 farmers, it was ranked low, with a mean of 4.0 points). Farmers attributed the fewest points and selected the fewest cards in the environmental category (9% of the points and 10% of the cards), in which the motivation selected most was the **desire to improve environmental stewardship** and to close nutrient cycles (5% and 3% of the points, respectively, selected by 8 farmers each).

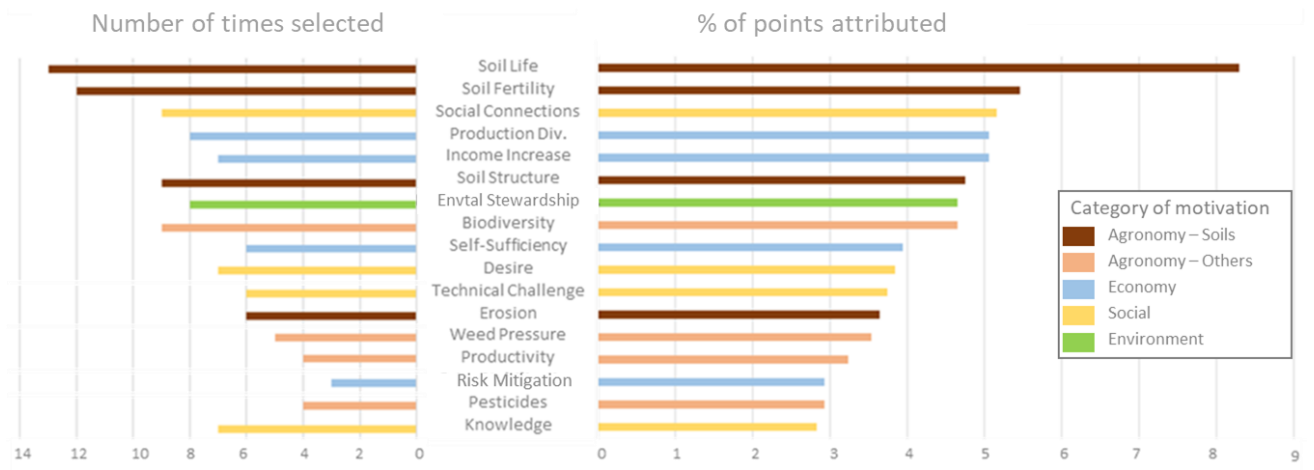


Figure 22: Number of times selected and percentage of points allocated by farmers when ranking the cards for the most-selected motivations, by category. To increase readability, the graph shows only motivations selected by more than 6 farmers, or allocated more than 2.5% of the points. See Supplementary Material 1 for details. Div.: Diversification, Envntl: Environmental

### 3.2.2. Differences in motivations for reintegrating livestock among farmers' systems

The PCA distributed categories of motivations according to farmers' rankings. On the factorial map, axis 1 (53.6% of the variance explained) distinguished agronomic and soil from economic motivations, whereas axis 2 (24.9% of the variance explained) clearly distinguished social from environmental motivations (Figure 23A).

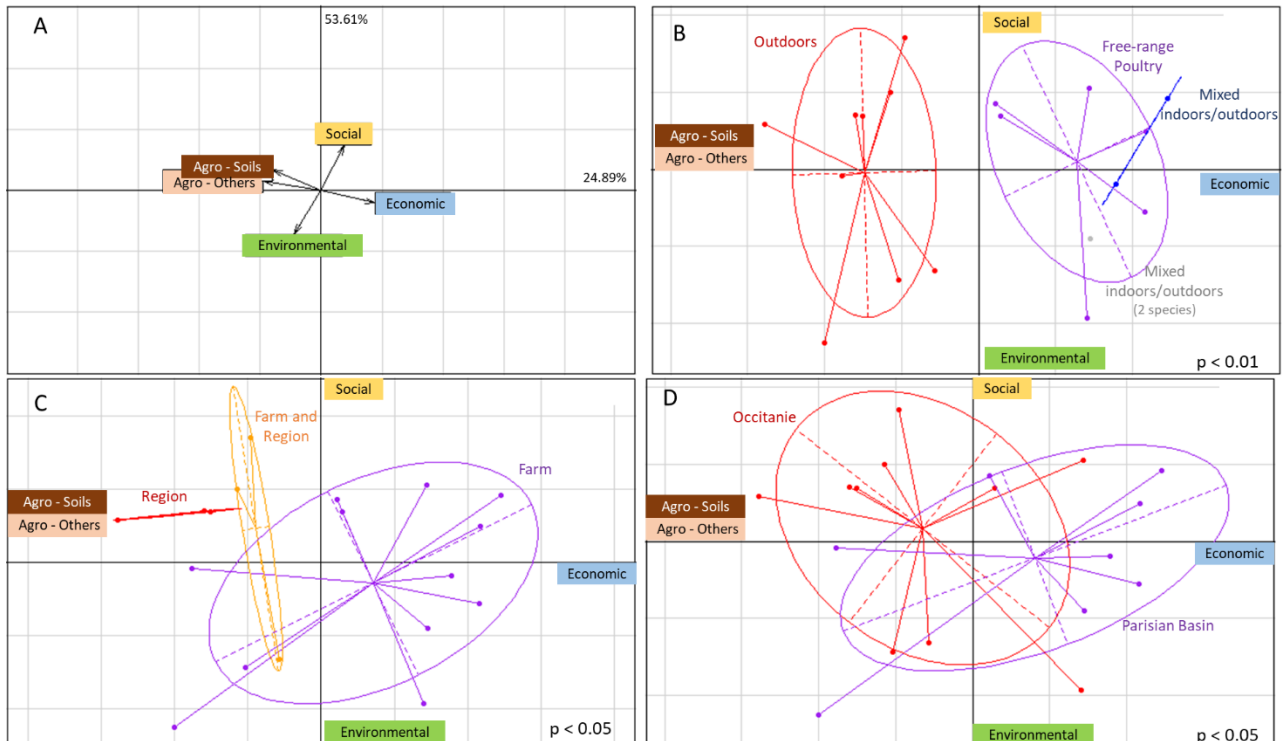


Figure 23: (A) Factorial map of the motivations for reintegrating livestock, by category, with projections of farmers' rankings as a function of (B) livestock housing, (C) the main level of livestock reintroduction and (D) the region (D). Agro: Agronomic



The projection of farmers' rankings on the factorial map showed that, in our sample, **farmers with outdoor livestock systems** (n=7) **favoured mostly agronomic** (soils and others) **motivations**, whereas **farmers with at least partly indoor systems** (e.g. free-range poultry, mixed indoors/outdoors for other livestock) (n=11) **tended to select more economic motivations** (Monte Carlo method,  $p < 0.01$ ) (Figure 23B, Supplementary Material 2). The type of housing seemed to determine motivations more than the species of livestock reintegrated (Supplementary Material 2). Farmers with outdoor livestock systems selected soil life as their first motivation (1.5 times as many points attributed and selected by 6/7 farmers compared to 7/11 with other systems), followed by other agronomic, environmental and social motivations. Self-sufficiency was the economic motivation that these farmers selected most (2/7 farmers). Farmers with at least partly indoor livestock systems selected income stabilisation by diversifying production as their first motivation (8/11 farmers vs. 0 with outdoor systems). Improving soil life was the first non-economic motivation that these farmers selected (7/11 farmers).

Farmers who reintegrated livestock at the **regional level** (n=3) had perennial systems (i.e. orchard, vineyard) or grain crops, and favoured mostly **agronomic and social motivations** (Figure 23C, Supplementary Material 2). Farmers who reintegrated livestock at the farm level (n=12, including 10 with grain crop systems, 1 with vegetables and 1 with an orchard) prioritised a wider variety of motivations. The farmer with vegetables (F17) reintegrated laying hens on his farm for mostly economic motivations, whereas the farmer with an orchard (F5) reintegrated sheep for social and agronomic motivations. Farmers who reintegrated livestock at both farm and regional levels (n=3) had grain crops, a vineyard or both, and did it more for agronomic motivations, with either a strong social dimension or a strong environmental dimension.

Farmers in **Occitanie** (n=10) favoured **agronomic motivations** (soils and others) in their rankings more than did farmers in the Parisian Basin (n=8), who favoured economic motivations (Monte Carlo method,  $p < 0.05$ ) (Figure 23D, Supplementary Material 2). In both regions, the main motivation for reintegrating livestock was to improve soil life, but farmers in Occitanie selected more motivations regarding soils than did those in the Parisian Basin, with 2.1 times as many points attributed and 1.8 times as many cards selected (e.g. soil fertility was cited 8 out of 10 times in Occitanie vs. 4 out of 8 times in the Parisian Basin). In the **Parisian Basin**, **economic motivations** were most common, being represented 1.7 times more than in Occitanie. They included increasing and stabilising income by diversifying production, mentioned by 4 and 5 out of 8 farmers, respectively (vs. 3 out of 10 each in Occitanie). This difference between regions may have been related to the **larger percentage of outdoor systems in Occitanie** (80% of the systems vs. 25% in the Parisian Basin) and to other reasons (e.g. greater vulnerability of soils in Occitanie, proximity to a vast wealthy consumption basin in the Parisian Basin, which may provide the opportunity to sell high-quality products at higher prices). For the other factors (i.e. UAA, farmers' age and prior connection to livestock farming), we found no clear evidence of differences in motivation ranking (Supplementary Material 2).

### 3.3. Similar motivations between inductive analysis and motivation card rankings

Overall, **64.1% of the motivations were the same** (46.0%) or **nearly the same** (18.1%) **in the discourse analysis and selection of motivation cards**. The motivation farmers ranked first was always the same (72.2%) or nearly the same (27.8%) as one of the motivations identified through discourse analysis, which indicates that the two methods were consistent and increased the robustness of the results. For the **motivations classified as ambiguous or unclear** (14.5%), the **mismatch appeared low in farmers' rankings** (mean rank was  $8.3 \pm 4.0$  considering all of the cards selected) and did not seem to challenge the robustness of the results. The motivations classified as different (21.4%) were mainly those identified through discourse analysis but not selected in the cards (83%). These motivations included ensuring the farm transmission and increasing personal satisfaction with work, which were not explicitly listed on the cards even though they could have been included with the card "Responding to a desire/preference/belief". Farmers rarely mentioned a motivation without selecting the corresponding card, which could have been due to the instruction to select approximately 10 cards.

In both discourse analysis and motivation card rankings, **agronomic motivations** (in which we included promoting ecosystem services, as they support production), especially those **regarding soils, predominated**, as soils were mentioned by 16/18 farmers in their discourse, and at least 1 soil card was selected by all but 1 farmer. **Improving and stabilising income** was cited by 17/18 farmers in their discourse, consistent with the two most-selected economic motivation cards (7 and 8 farmers, respectively). Similarly, **self-sufficiency** was mentioned by 9 farmers in their discourse and selected by 6 of them in their card rankings. **Strengthening social connections** was the most-selected social motivation in card rankings and was mentioned by 14/18 farmers in their discourse, particularly for connections among farmers. **Personal ethical and moral values** were mentioned as a motivation by 17/18 farmers and may have corresponded to a wide variety of motivation cards (e.g. desire, technical challenge, environmental stewardship, connection to family/traditions), as well as to broad values not included in the cards (e.g. farm transmission, feeding the population). In both discourse analysis and card rankings, keeping the landscape open and decreasing pollution were rarely selected. Farmers did select some environmental cards, but sometimes only because they felt that they needed to select at least one card from each category, despite the instructions to the contrary. The most-selected environmental card was environmental stewardship (8/18), which was consistent with the desire to build an environmentally friendly farming system mentioned by 10 farmers.

## 4. Discussion

### 4.1. Farmers' motivations for reintegrating livestock compared to expected benefits

The farmers' diverse motivations for reintegrating livestock are **consistent with the benefits of crop-livestock integration in the literature**. Crop farmers' main motivation was to **promote ecosystem services**, especially by improving **soil** life and fertility. Improving soil quality is one of the main benefits of mixed systems, especially those based on grazing, due to organic fertilisation from livestock waste and the diversification of crop-pasture rotations to feed the animals (Brewer and Gaudin, 2020; Franzluebbbers, 2005; Soussana and Lemaire, 2014). Crop farmers' **economic motivations** included **increasing and stabilising income** by diversifying production and increasing self-sufficiency. The literature highlights that mixed systems increase economic efficiency and decrease dependence on external inputs, which increases resilience to climate and market events (Bell and Moore, 2012; dos Reis et al., 2021; Ryschawy et al., 2021). **Social motivations** were also a main motivation for reintegrating livestock, including strengthening connections with the local community or following personal ethical and moral values. **The literature has not documented social benefits of mixed systems in detail**. The few studies that mention them focus on the difficulty in identifying and maintaining a partnership between crop and livestock farms (Asai et al., 2018; Julie Ryschawy et al., 2017).

**Farmers rarely mentioned motivations linked to energy consumption or pollution, whereas these impacts are documented in the literature**. Mixed systems help to close carbon and nitrogen cycles, which can decrease nitrate leaching and water pollution (dos Reis et al., 2021; Ryschawy et al., 2021; Veysset et al., 2014). The ranking of motivation cards in the environmental category need to be considered carefully given the **potential selection bias** previously mentioned. Similarly, the farmers rarely mentioned maintaining the landscape as a motivation, whereas the literature indicates that grazing helps keep the landscape open and prevent wildfires (Davies et al., 2016; Rouet-Leduc et al., 2021). This result may have been related to the absence of fallow or communal land that the farmers in our sample could use, or because landscape management is a service that society expects from farmers rather than one that farmers expect (Guillaumin et al., 2008).

### 4.2. Similarities with farmers' motivations for adopting other sustainable practices

Farmers' motivations for reintegrating livestock varied, but most were **consistent with those mentioned in studies of the adoption of sustainable practices**. The main motivation in the present study of **promoting ecosystem services**, especially improving soil quality, was consistent with Casagrande et al. (2016), who studied organic farmers' motivations for adopting conservation agriculture practices. Pergner and Lippert (2023) showed that protecting biodiversity (in the soil and elsewhere) was a motivation for reducing pesticide use, and Paut et al. (2021) mentioned biological control as one motivation for grazing orchards. **Increasing biodiversity** was ranked highly in the present study, but was associated instead with the overall idea of diversifying the farming system to be consistent with farmers' values (Stern and Dietz, 1994), rather than to protect auxiliary insects. Paut

et al. (2021) emphasised **grass management** as one of the main motivations for grazing orchards, and Casagrande et al. (2016) highlighted that farmers were motivated to adopt conservation agriculture practices to improve weed, pest and disease control, which several farmers also mentioned in the present study, although it was not the main motivation for reintegrating livestock.

Farmers mentioned **economic motivations**, such as increasing and stabilising income or decreasing production costs, which is consistent with motivations for adopting other sustainable practices, such as converting to organic farming, adopting conservation agriculture practices in organic farming, reducing pesticide use or grazing orchards (Bouttes et al., 2019; Casagrande et al., 2016; Paut et al., 2021; Pergner and Lippert, 2023). Farmers' motivations for reintegrating livestock to **increase self-sufficiency and resilience** to volatile market prices were also mentioned by Bouttes et al. (2019) at a time when organic product prices were high and stable. Bouttes et al. (2019) mentioned **social motivations** as a main influence for farmers to convert to organic farming, as farmers were looking to stimulate **learning**, which can be related to the desire to undertake a technical challenge, which was identified as a motivation for livestock reintegration in the present study. Bouttes et al. (2019) also mentioned developing group dynamics and an open exchange of experiences, which is consistent with the desire to **strengthen connections with the local community** and create social connections in the present study. Bouttes et al. (2019) and Duval et al. (2021) highlighted that farmers adopted sustainable practices to increase **work satisfaction**, which was related to farmers' personal ethical and moral values in the present study. Maintaining or increasing the value of the farm in a perspective of heritage and **transmission** was also a motivation for livestock reintegration, which was related to other motivations in a long-term strategy, such as improving soil quality. Caring about future generations, both within the farmers' families and beyond, was also a motivation for reducing pesticide use (Pergner and Lippert, 2023) or adopting other sustainable practices (Greiner and Gregg, 2011; Ingram et al., 2013; Schoonhoven and Runhaar, 2018).

**Protecting the environment** and being a good steward of the land (Stern and Dietz, 1994) are often strong motivations for adopting sustainable practices, such as soil conservation techniques, reducing pesticide use or grazing orchards, which increases nutrient cycling (Bakker et al., 2021; Chèze et al., 2020; Paut et al., 2021; Reimer and Prokopy, 2012). As mentioned, farmers in the present study mentioned few motivations related to water and air pollution or energy consumption. However, farmers mentioned **environmental values**, either directly during the interview, through the environmental card "Environmental stewardship" or to explain their selection of the social card "Responding to a desire/preference/belief", or indirectly by referring to sustainable practices that they wanted to uphold. Reducing health risks for farmers and consumers is a main motivation for reducing pesticide use (Chèze et al., 2020; Pergner and Lippert, 2023). None of the farmers we interviewed mentioned health concerns, likely because given the current state of knowledge, the relationship between livestock reintegration and farmer health and food safety is more difficult to make.

Recent studies focused on mapping farmers' motivations and clustering them into farmers' profiles for adopting sustainable practices (e.g. investment-minded farmers, farmers focused on their quality of

life) (Lalani et al., 2021; Tessier et al., 2021). In our work, farmers mentioned several motivations in their discourse, but they always belonged to at least three dimensions (among agronomy, economy, social and environment) and farmers almost never mentioned feedback loops between them. Identifying farmers' profiles of motivations for reintegrating livestock by studying those interlinkages could be a future research question. Many studies of farmers' motivations focused on elements that facilitate or hinder farmers' adoption of sustainable practices, such as a farmer's profile (e.g. age, level of education, experience with the practices) (Damalas, 2021; Prokopy et al., 2015; Yoder et al., 2019); economic and social costs of implementing changes on the farm (Chèze et al., 2020); or the lack of inspiring examples (Bakker et al., 2021; Hammond et al., 2017), knowledge or an adapted sociotechnical system (Gaitán-Cremaschi et al., 2022; Mamine and Farès, 2020; Spangler et al., 2022). These elements were not considered in depth in the present study, as they influence farmers' motivations for reintegrating livestock in relation to their behavioural control rather than to their attitudes towards the practice. We found no clear influence of farmers' profile age or prior connection to livestock farming on their motivations for reintegrating livestock, perhaps due to the small sample size and the fact that these elements would influence the adoption of a practice rather than the motivations for performing it. As it is important to consider motivations for, but also obstacles to and mechanisms for developing crop-livestock integration, **these elements will be analysed in future studies**. Similarly, given our small sample size, the influence of farms' characteristics (organic or conventional, type of crop or livestock reintegrated) on farmers' motivations for reintegrating livestock could be further analysed.

#### 4.3. A mixed method for completeness and robustness of the results

We developed a **mixed method to summarise motivations for reintegrating livestock by combining qualitative inductive discourse analysis with quantitative analysis of farmers' rankings of motivation cards** (DeCuir-Gunby, 2008; Greene et al., 2005). Inductive content analysis is a powerful tool for identifying emerging themes in farmers' responses (i.e. motivations anchored in farmers' realities) (Elo and Kyngäs, 2008). However, farmers' motivations cannot be ranked based on discourse analysis alone because i) it is difficult to determine which motivation is the most important to a farmer, and ii) farmers may not mention the same motivations. Although we counted the number of farmers who mentioned each motivation in their discourse, it is difficult to distinguish whether a farmer did not mention a motivation because it was irrelevant to him/her or because it did not occur to him/her at the time. Offering farmers the same panel of cards and asking them to select and rank those they found relevant was one way to rank their motivations. The selection and ranking phase can enrich the responses by recalling forgotten motivations or deepening subjects that had been mentioned briefly (i.e. triangulation for completeness (Hussein, 2009)). It also allowed differences in the motivations that farmers prioritised to be identified as a function of their farming system, although the small sample size only allowed trends to be identified (Salembier et al., 2021). In addition to **expanding the variety of motivations and ranking them**, combining these two methods **increased the robustness** of the results by comparing the motivations identified through discourse analysis and the number of farmers

who mentioned them to the ranks of cards (i.e. triangulation for confirmation (Hussein, 2009)). Discussing differences between results of the two methods with the farmers and asking them to explain their choices in more detail (e.g. economic motivations mentioned in the discourse but selected rarely in card rankings) would further increase the completeness and robustness of our results.

## 5. Conclusion

Following **innovation-tracking principles**, we **identified and ranked a wide variety of crop farmers' motivations for reintegrating livestock** in two region of France. To do so, we developed an original **mixed method** to combine inductive discourse analysis of farmers' motivations for adopting a sustainable practice with their selection and ranking of predefined cards based on the benefits of this practice found in the literature. In the current context of increasing prices for energy, feed and nitrogen fertilisers, livestock reintegration seems an appropriate lifeline for crop farmers. Understanding the diversity of crop farmers' motivations for reintegrating livestock is **the first step in developing this innovative sustainable practice under favourable conditions**. It could help decision-makers provide recommendations that encourage it, by communicating the benefits of these systems in relation to farmers' objectives and/or by developing payments for the ecosystem services provided by livestock reintegration. Elements other than farmers' motivations should be considered, such as the **conditions that facilitate or hinder livestock reintegration**.

## 6. Acknowledgements

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## 7. Supplementary material for chapter 1

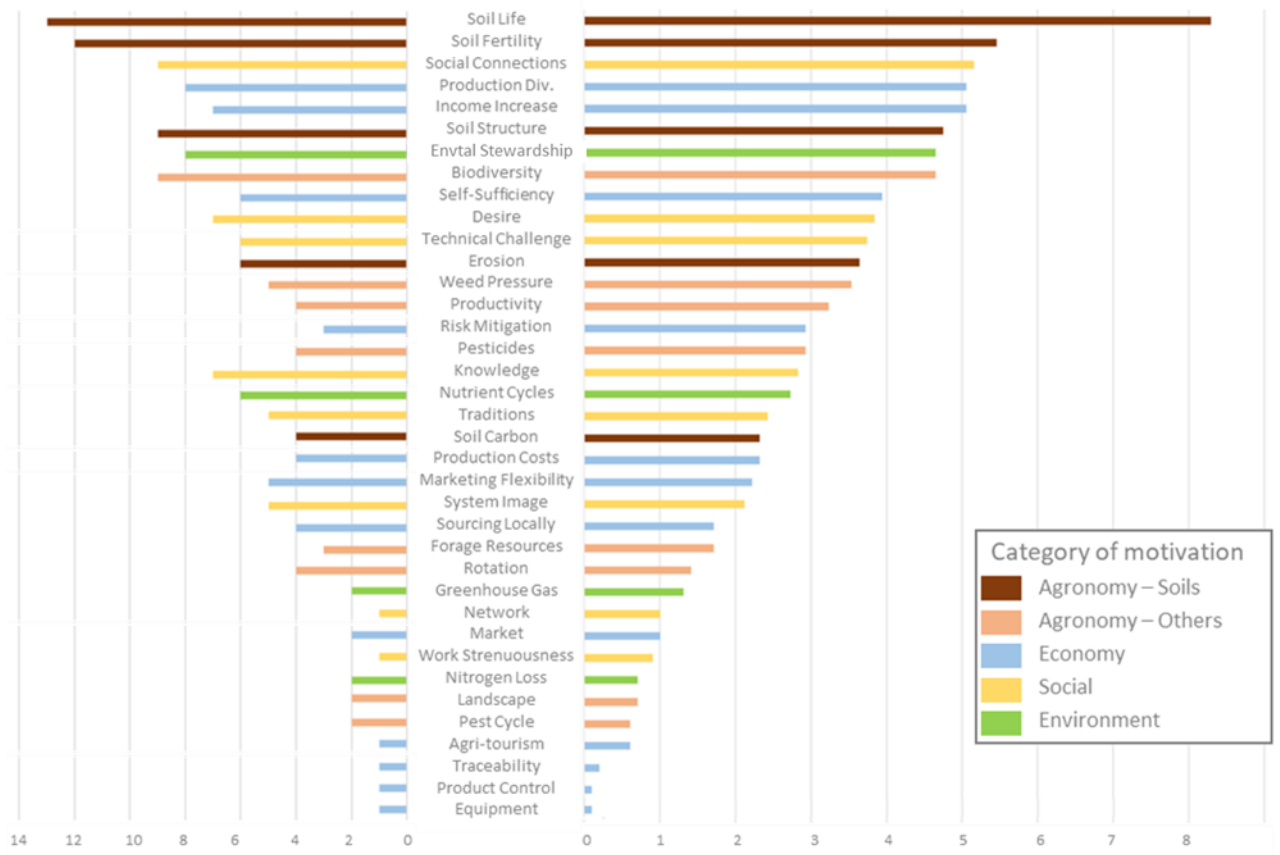
### 7.1. Supplementary Material 1

Points attributed and number of times each motivation card offered to farmers was selected (table and histogram). Div.: Diversification, Envta: Environmental

Category		Motivation card	Points attributed to the motivation card (% of total points attributed)	Number of farmers who selected the motivation card (/18)
Agronomic	Soils	Improving soil fertility/organic matter content	5.5	12
		Improving soil structure	4.8	9
		Promoting carbon storage in the soil	2.3	5
		Promoting erosion control	3.6	7
		Improving soil life (biomass and microbial activity)	8.3	13
	Others	Reducing all types of pesticides/mechanical weeding	2.9	5
		Reducing weed pressure	3.5	5
		Breaking pest, weed and disease cycles	0.6	3
		Promoting biodiversity	4.7	9
		Increasing productivity per ha	3.2	4
		Optimising forage resources	1.7	4
		Diversifying and extending crop rotations	1.4	4
		Maintaining the landscape of the region	0.7	4
Environmental	Decreasing greenhouse gas emissions	1.3	2	
	Closing nutrient cycles (nitrogen, phosphorus, potassium)	2.7	8	
	Decreasing nitrogen loss/water pollution	0.7	3	
	Improving environmental stewardship	4.7	8	
Economic	Ensuring a market for specific products	1.0	2	
	Sharing equipment	0.1	1	
	Reducing production costs	2.3	6	
	Stabilising prices despite climate and market uncertainties	2.9	3	
	Stabilising income by diversifying production	5.1	8	
	Becoming more self-sufficient	3.9	6	
	Increasing income	5.1	7	
	Sourcing inputs locally	1.7	5	
	Ensuring a more flexible marketing method	2.2	5	
	Ensuring better control of the products	0.1	2	
	Improving the traceability of purchased products	0.2	2	
	Promoting agri-tourism	0.6	4	
Social	Improving the image of the production system	2.1	7	
	Creating social connections, solidarity and mutual aid	5.2	12	
	Acquiring and sharing new knowledge	2.8	8	
	Developing networks	1.0	2	
	Connecting to family history/traditions	2.4	5	
	Responding to a desire/preference/belief	3.8	7	
	Responding to the desire for a technical challenge	3.7	7	
	Decreasing the amount of strenuous work	0.9	1	

Number of times selected

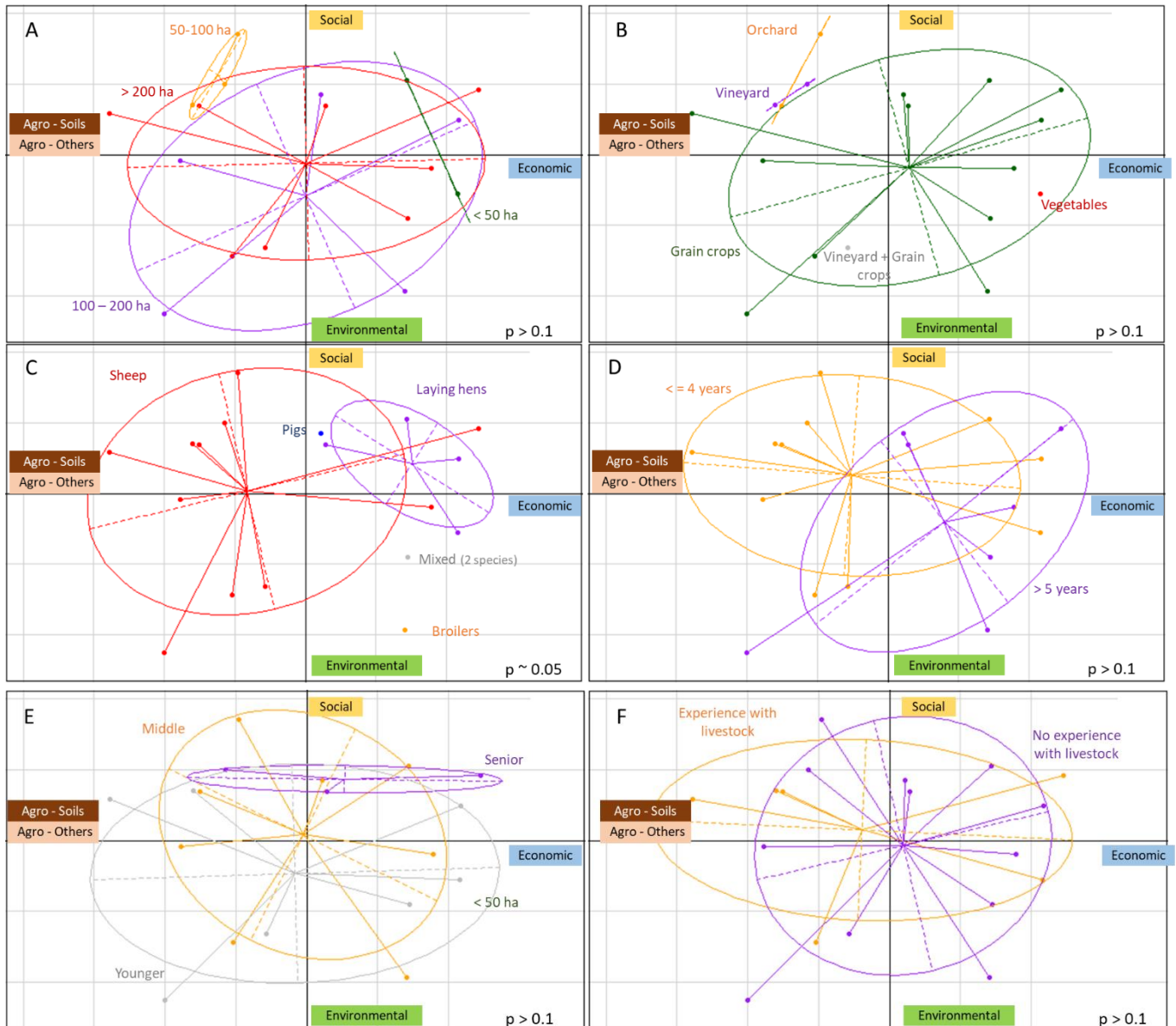
% of points attributed





## 7.2. Supplementary Material 2

Projections of farmers' rankings on the factorial map of the motivations for reintegrating livestock classified by category according to the UAA (A), crops (B), livestock (C), years reintegrated (D), farmers' age (E) and farmers' previous connection to livestock farming (F). Agro: Agronomic





## Conclusion of Chapter 1

In chapter 1, I contributed to produce knowledge on livestock reintegration through **studying in depth farmers' motivations** (Figure 24). I relied on individual interviews to show that farmers' motivations to reintegrate livestock were **very diverse**, and covered **agronomic, economic, social and environmental dimensions**. The three main motivations I identified for reintegrating livestock were **following personal values, promoting ecosystem services and increasing and stabilising income**.

I contributed to improve the innovation-tracking framework through providing a **mixed method to inventory and rank farmers' motivations** to reintegrate livestock. Such method could be applied to other agroecological innovations.

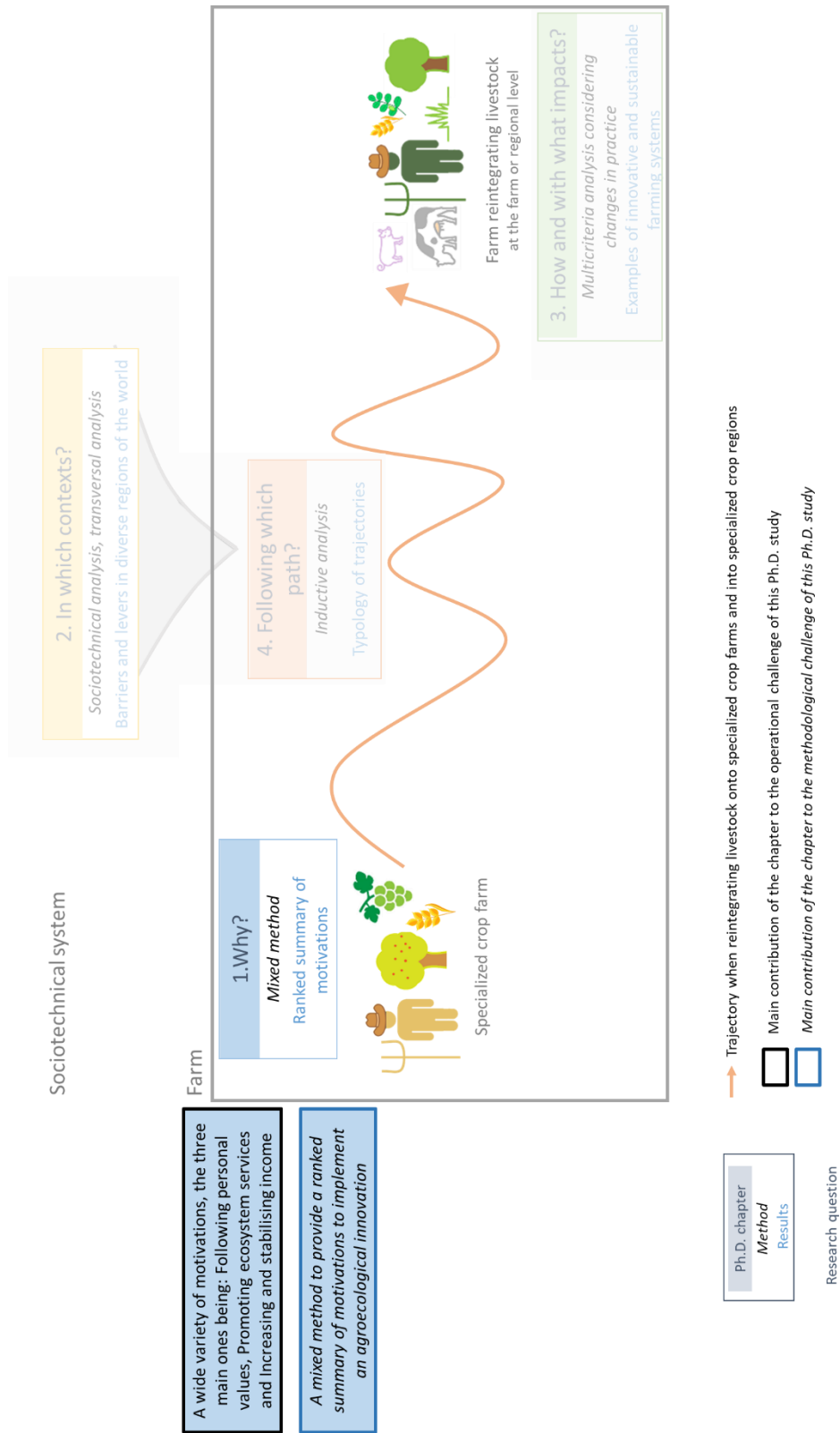


Figure 24 : Positioning Ph.D. study chapters along the trajectory that farmers follow to reintegrate livestock onto specialized crop farms and into specialized crop regions: main results of Chapter 1 on farmers' motivations. Operational challenge of this Ph.D. study: producing knowledge on why, in which contexts, how and with what impacts farmers reintegrate livestock into specialized crop farms and regions. Methodological challenge of this Ph.D. study: improving the innovation-tracking framework by studying at multiple levels the determinants that lead to agroecological innovations and assessing their performances objectively.



## Episode 1: Diversifying the farm production to undertake technical challenges: from crop tests to the idea of reintegrating sheep

Since my father retired, I began trying one or two new things... When he was here, he wanted to stay careful, I mean, converting to organic had been a big step for him already, a big change in his habits... in what he had always known, in a way. So, he did not want to take big risks, to change his way of doing things beyond what was necessary. Me, I'm more... I don't know, I like to try new things. I know there are risks, but I'm like that, if I do have an idea, I need to see where it can go. My wife, she knows, she does not even try to dissuade me now, she tells me "why are you asking me my opinion ? No matter what I say, you will do it anyway, so please don't even ask !". She's not wrong...

So yes, I tried a bunch of stuff. I tried new crops, summer cereals, that we did not grow before, millet and sorghum. I tried chickpeas and lentils as well, it worked pretty well, so I tried to intercrop lentils and spring wheat, well, I'll never do it again, I was so disappointed, I got almost nothing, maybe it was bad luck, I don't know... But no, this is not for me. I grew cover crops also, now, I've been doing that for 5 years, something like that. After harvest, it covers the soil during winter, it's good for soil life. I was using a mix of oat and vetch, so with the legume, it brings nitrogen.

But, I needed to mow it twice, sometimes even three times during winter depending on the year, and ... I don't know, it took time, it meant going in the field with the tractor many times, which was not that good for the soil, and ... well, I was thinking to myself, maybe, you know, with sheep... if I had sheep ... they could make a good use of the cover crop for sure, convert it into human food, and it would save me time, money... And the sheep manure, it would be good for my soil, maybe help me reduce my organic manure input, because, it's not easy to find in the region ! Plus, I liked sheep. They reminded me of my grandfather, of Eastern celebrations we had here. To me, it made sense, in the end, to have animals on the farm again. It was bucking the trend, but I liked it ! It seemed obvious to me we should never have abandoned this diversified farm we had, like a small ecosystem, with all crops and animals interacting together... No matter policies nor market, we should not have stopped farming like that. Yet, well, that was a thing, to think about having sheep. But, me, I was not a livestock farmer !









Chapter 2: Sociotechnical barriers to and levers for reintegrating livestock onto specialized crop farms and into specialized crop regions

## Preface of Chapter 2

*Farmers' motivations are one of the key determinants leading to change in practices. Besides this psycho-cognitive determinant at the individual level, other determinants also condition the possibility to reintegrate livestock.*

In particular, farms are embedded within a **broader sociotechnical context** (Boulestreau et al., 2021; Casagrande et al., 2024; Ryschawy et al., 2021), that **facilitates or hinders** the emergence and scaling up of agroecological innovations such as livestock reintegration. Building a comprehensive analysis of livestock reintegration requires studying such sociotechnical context. It encompasses documenting what were the **sociotechnical barriers** farmers faced when reintegrating livestock, and **how they managed to overcome them** (Box 6). **Involving actors besides farmers** is needed to understand in depth such sociotechnical contexts.

In chapter 2, I widened my analysis from French farmers to address the **sociotechnical system level**. I studied in depth the **sociotechnical barriers and levers** to such reintegration, through a transversal analysis in three regions where livestock was being reintegrated under diverse sociotechnical contexts: eastern Scotland, south-western France and northern California. Through interviews with key actors of the sociotechnical system surrounding livestock reintegration, I addressed my second research question: **What are the sociotechnical barriers and levers for reintegrating livestock into specialized crop farms and regions?**

Previous studies on innovation-tracking initiatives very seldom addressed innovations occurring beyond the farm level (Box 7). In addition, the impact of the sociotechnical context on the emergence of innovations on farms has often been overlooked (Boulestreau et al., 2022; Salembier et al., 2021). The innovation tracking framework could be **broadened to consider innovations beyond the farm level** (e.g. partnerships between farmers). It could also be improved **by being combined with methods to further consider the sociotechnical barriers and levers** to agroecological innovations that call for involving actors besides farmers.

Studying the sociotechnical barriers and levers to reintegrating livestock would allow supporting the **scaling up** of livestock reintegration, if livestock reintegration is found to be sustainable.

*This chapter takes the form of a researcher paper, currently under revision to be submitted to Land Use Policy.*

Meunier, C., Martin, G., Fenster, T.L.D., Gaudin, A.C.M., Grillot, M., Lecole, P., Topp, C.F.E., Walker, R.L., Watson, C.A., Williams, S.R., Ryschawy, J. (n.d.). Barriers and levers for reintegrating livestock into crop farms and regions – A transversal analysis in three countries. [Under revision, to be submitted to Land Use Policy].

*(Contrary to the rest of this Ph.D. manuscript, this paper was written in American English)*

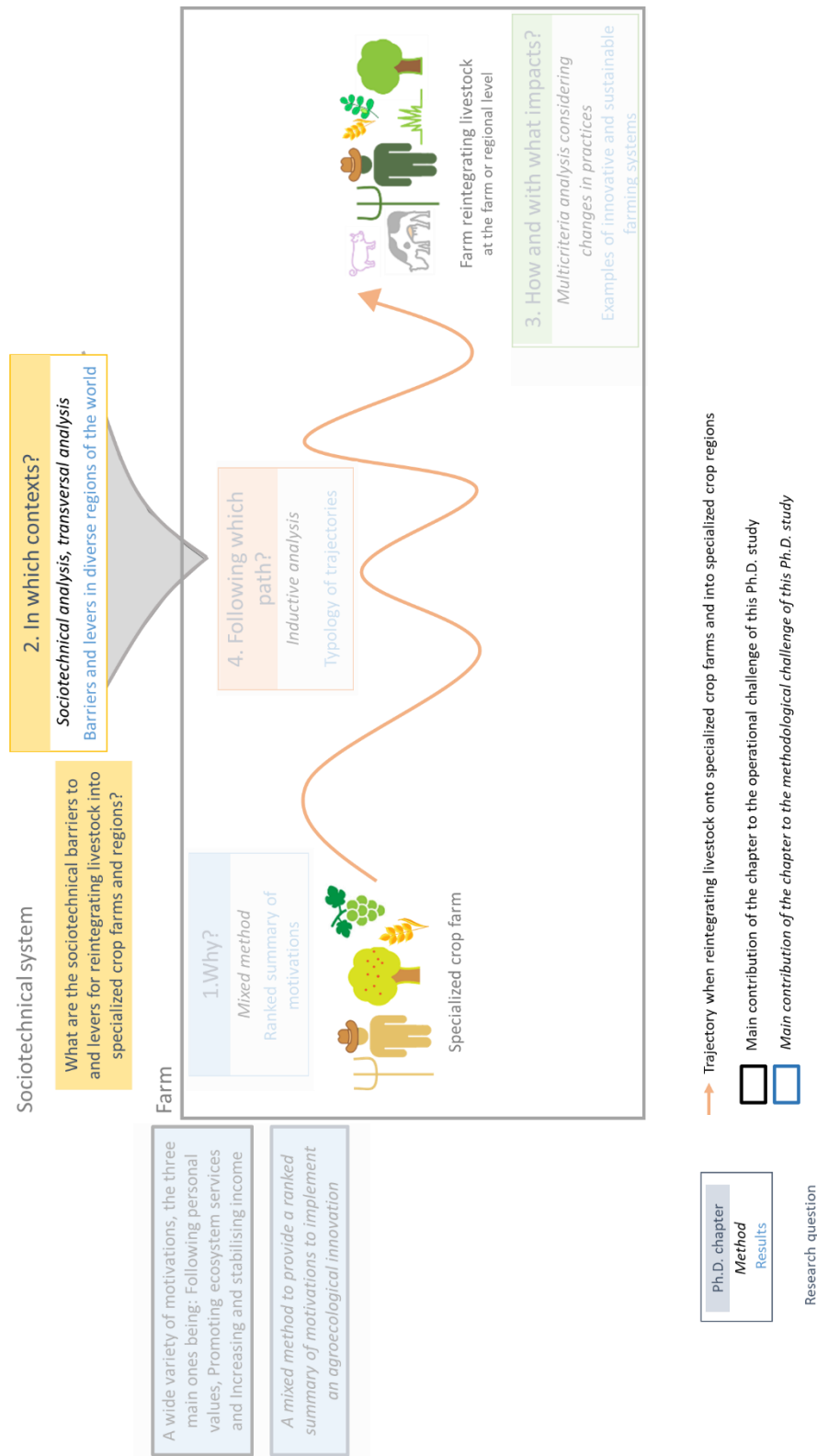


Figure 25 : Positioning Ph.D. study chapters along the trajectory that farmers follow to reintegrate livestock onto specialized crop farms and into specialized crop regions: main focus of Chapter 2 on sociotechnical barriers and levers. Operational challenge of this Ph.D. study: producing knowledge on why, in which contexts, how and with what impacts farmers reintegrate livestock into specialized crop farms and regions. Methodological challenge of this Ph.D. study: improving the innovation-tracking framework by studying at multiple levels the determinants that lead to agroecological innovations and assessing their performances objectively.

# Barriers and levers for reintegrating livestock into crop farms and regions – A transversal analysis in three countries

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## Abstract

High-input specialized farming systems where crop and livestock production are disconnected leads to negative environmental impacts. However, a few pioneering farmers are intentionally reintegrating livestock into crop farms in several regions, but this has rarely been examined by research to date.

We analyzed the sociotechnical barriers and levers to reintegrating livestock into specialized crop farms and regions through a transversal analysis in three regions with diverse sociotechnical systems: Southwestern France, Northern California, and Eastern Scotland.

Building on the multilevel perspective framework, we carried out 32 semi-structured interviews with key actors of the sociotechnical systems surrounding livestock reintegration in the three regions, i.e. farmers, technical advisors, researchers-teachers and public policy experts. We analysed these interviews inductively to characterize the barriers and levers to reintegrating livestock, studying the differences between regions.

We showed that livestock have been reintegrated into various farming systems. These systems were designed to limit learnings needed for starting livestock production, additional workforce and capital investments. Livestock reintegration was associated with other niches (organic farming, regenerative farming), and implemented by farmers who already had innovative systems, previous links to livestock production, and who shared motivations such as developing ecosystem services. The main barriers for expanding livestock reintegration were limited knowledge regarding how to reintegrate livestock and which benefits to expect, lack of specific subsidies for these systems or premium outlets for the products, environmental and animal-welfare-related pressures on livestock (especially in Scotland)

and specific regulations constraining farming practices, e.g. the timing of grazing. The main factors favouring livestock reintegration were innovation-oriented initiatives linking researchers, farmers and governmental actors, cultural heritage on mixed farming, increased fertilizer prices and new government incentives for agroecological practices indirectly favouring livestock reintegration.

We showed that collective action is required to overcome the barriers associated with reintegrating livestock into specialized crop farms and regions.

## Keywords

Multi-Level Perspective, Integrated crop livestock systems, Innovation, Agroecology

### 1. Introduction

Over the past few decades, the trend towards agricultural **specialization**, driven in part by agricultural public policies and markets, has spatially **disconnected crop and livestock farming systems** across the world. While **integrated crop livestock systems (ICLS)** were fairly common until the 1960s, they are now **uncommon in the Global North**, occupying less than 10% of the agricultural area and number of farms in most of Europe and the United States (Garrett et al., 2020). Further, they are generally implemented **in areas where biophysical conditions limit intensive crop or livestock production**, or in regions with cultural specificities (e.g. Amish communities in the U.S.) (Garrett et al., 2020). This decoupling of crop and livestock production has had major impacts on farming systems and **negative environmental externalities**. **At the farm level**, due to the lack of market opportunities for livestock feed, the share of forage legumes in crop sequences has decreased to the profit of cereals (Ballot et al., 2022; Schott et al., 2010), thereby reducing the provision of ecosystem services provided by legumes (e.g. nitrogen supply) and increasing reliance on external inputs. Crop livestock disconnection also applies at the **regional level**, with specialized crop regions dependent on imported nutrients (Harchaoui and Chatzimpiros, 2018). Conversely specialized livestock regions import large quantities of animal feed and generate excessive amounts of manure which leads to storage, disposal and pollution problems (Lassaletta et al., 2009; Peterson et al., 2020). In spite of these acknowledged impacts, **input-intensive segregated crop and livestock systems continue to be developed** (Garrett et al., 2020).

However, **pioneering farmers around the world are reintegrating** (i.e. intentionally organising the return of) **livestock** onto crop farms and into crop regions, looking for promoting ecosystem services, improving and stabilising income and following personal ethical and moral values (Meunier et al., 2024). These systems **can contribute to decreasing negative environmental externalities by reconnecting crops and livestock production** through reintegrating animals at the farm (e.g. rearing livestock on the farm) or regional level (e.g. partnership between a crop farmer and livestock farmer, with the former hosting the latter's livestock for a specific period, for example to graze a winter cover crop) (Moraine et al., 2014). Despite the potential advantages of these systems for sustainable farming, **livestock reintegration is rare and understudied**. Previous studies have focused on the decline of ICLS, the conditions required to maintain ICLS, and the drivers for reconnecting crop and livestock enterprises in regions where both production systems still coexist (Asai et al., 2018; Garrett et al., 2020;

Martin et al., 2016; Marc Moraine et al., 2017b). To date, no study has examined the barriers and levers associated with reintegrating livestock into specialized crop farms or regions.

Our objective was to **characterize the sociotechnical barriers and levers for reintegrating livestock** into crop farms and regions. We used **transversal analysis** across **three case-study regions**, representing a **gradient degree of disconnection between crop and livestock farms**, i.e. whether some livestock farms are still present, and if so, how geographically segregated they are from crop farms. These study's three regions were, by increasing order of disconnection between crop and livestock farms, Eastern Scotland, Southwestern France, and Northern California (Figure 26). We use the word 'crops' in its broadest sense, including grain crops, orchards, vineyards and vegetables.



Figure 26: Examples of a diversity of systems in which livestock was reintegrated in the three case studies: sheep grazing kale in Eastern Scotland, sheep grazing into vineyard in Southwestern France and cattle grazing into residues of watermelons for seed production in Northern California. Credits: C. A. Watson, C. Meunier.

## 2. Methods

### 2.1. Conceptual Framework

The emergence, rejection, or mainstreaming of an innovation, such as livestock reintegration, is impacted by the functioning of **sociotechnical systems**, i.e. a network of actors sharing common practices, knowledge, technologies and formal or informal rules (Casagrande et al., 2023). Following Gaitán-Cremaschi et al. (2019) and Garrett et al. (2020), we adapted the **multilevel perspective (MLP)** from Geels (2011) to classify **barriers and levers to mainstreaming livestock reintegration** into specialized crop farms and regions. The MLP explains sociotechnical transitions such as the mainstreaming of livestock reintegration according to three interacting levels:

1. The **landscape**, that includes all external trends influencing the whole agricultural system (e.g. globalization, climate change, agricultural policies).
2. The **agricultural regime**, defined as the dominant mode of farming, in our case, specialized crop or livestock farming.
3. The **niches**, defined as spaces where innovative activities take place and where protection is offered from regime rules (Ojiem et al., 2006). In line with El Bilali (2019), we call reintegrating

livestock a “niche” as it is a novel farming system, with no specific network developed for now (Elzen et al., 2012; Weituschat et al., 2023).

The regime evolves according to landscape trends (pull factors), and to grassroots/bottom-up innovative movements emerging from niches (push factors). Both pull and push factors create windows of opportunity for niches to emerge and mainstream (Wigboldus et al., 2016).

## 2.2. Case studies

### 2.2.1. Case study regions

We relied on our **academic network** to identify three case-study regions where a few crop farmers have reintegrated livestock: Eastern Scotland, Southwestern France and Northern California (counties of Colusa, Glenn, Solano, Sutter and Yolo) (Table 6). We chose these three regions for their diversity regarding:

- The **relative importance of agricultural production in the country**, as well as the **degree of disconnection between crop and livestock farms** in the region:
  - In Scotland, 80% of the land is agricultural, of which over 90% is classified as “Less-Favoured Area” and is used for livestock grazing (Scottish Agricultural Census, 2023, 2019). **Livestock production is thus deeply rooted in Scotland**, forming a part of its national landscape, and is mainly comprised of meat sheep and cattle production. The main area where the pedoclimatic conditions allow for crops to be grown is located in a narrow strip of land along the eastern coast of Scotland. Eastern Scotland is mostly dedicated to cereal production for the whisky industry and livestock feed (Scottish Agricultural Census, 2023), and is in close proximity to the livestock producing regions. Due to this **spatial repartition**, this is the one of the three case-study regions with the **lowest level of disconnection** between crop and livestock farms.
  - In France, 49% of the land is agricultural, with some regions reaching higher proportions (e.g. 70% in the Southwest). In Southwestern France, **specialized crop farms are dominant** (67% of farms), and their proportion keeps increasing at the expense of mixed farms and specialized livestock farms that represent 81% of the farms that ceased operation between 2010 and 2020 (16% and 65% respectively) (AGRESTE, 2020). Due to the region’s history with livestock farming, **some services** (e.g. veterinarians, slaughterhouses) **are still present in the region, even though their numbers are decreasing**.
  - In California, only 23% of the land is dedicated to agricultural production. In Northern California **intensive specialized crop production on large farms** (average utilized agricultural area (UAA): 175 ha, compared to 70 ha in France and 45 ha in Scotland) **and livestock production coexist, but rarely interact** (USDA, 2017). The main crops produced are almonds and pistachios, vines, and industrial vegetables (e.g. tomatoes for canneries). The primary forms of livestock are dairy and beef cattle, and broilers (California Department of Food and Agriculture, 2022). It is the one of our three case-study regions with **the highest level of disconnection between crop and livestock production**.



- The **potential impact of climate change on agricultural production** as potential driver of reintegration in the study's regions:
  - In Eastern Scotland, wet, cold, and windy climate conditions restrict the range of possible crops, even though climate change may offer some new opportunities.
  - In Southwestern France, droughts have become a major concern for farmers in recent years. To preserve water resources, public actors regularly enforce strong constraints on irrigation during the summer months.
  - In Northern California, climate change is a significant concern. Wildfires occur yearly, while drought, the over allocation of surface water, and over pumping of groundwater drive water scarcity issues.
  
- The **agricultural policies and subsidy regimes**:
  - In Eastern Scotland, up until BREXIT in 2020, farmers received regular subsidy payments from the European Common Agricultural Policy (CAP). At the time of the interview (early 2023) there was no doubt that farming would continue to be subsidized but the **details of the new agricultural policy remained undefined**.
  - In Southwestern France, farmers still get those **CAP subsidies**, which are partly coupled to their production, and partly linked to the implementation of specific practices.
  - In Northern California, farmers **do not receive regular public subsidies** and rely on crop insurance policies to protect them from climate and market risks. However, farmers can apply for grants incentivizing investments in soil health, reducing on-farm climate emissions, and improving resource use efficiency.
  
- The **share of organic production and direct processing and selling**:
  - In Southwestern France, **organic farming is more developed** than in the other case study regions, with 30% of the farms being certified organic (Agence Bio, 2020), compared to 2% in Scotland (Scottish Government, 2018), and 10% in California (CDFA, 2022; USDA, 2023) (figures expressed at the country and state level for Scotland and California).
  - Organic conversion of at least part of the farm and **direct marketing are also more common in France** (over 10% and 20% of farms, respectively) (AGRESTE, 2020) than in Scotland and California (figures expressed at the country level).

Table 6: Case-study regions description. UAA: Utilized Agricultural Area

Case study region by disconnection gradient	Eastern Scotland	Southwestern France	Northern California
Share of the / state where the region is included dedicated to agricultural production	80%	49%	23%
Region total UAA (ha)	570 000 ha	450 000 ha	850 000 ha
Average UAA of farms (ha) in the region	45	70	175
Dominant crops in the region	Cereals for whisky industry and oilseed rape	Cereals and oilseeds, vineyards	Orchard (almonds and pistachios), vineyards, vegetables (tomatoes, carrots, lettuce)
Current type of livestock reintegrated in the region	Meat sheep, poultry with premium, a few pigs	Meat sheep, poultry	Sheep and goat for grazing, beef cattle
Share of farms certified organic in the region	2%	30%	10%
Share of farms practicing on-farm processing / direct selling in the region	Very rare	10% / 20%	Very rare
Region exposition to climate change	Occasional droughts, Mostly suffering from wet and cold weather conditions limiting the range of crops grown	Droughts and cuts to irrigation	Annual droughts, intensively irrigated cropping systems, wildfires
Policy support	Regular subsidies and specific subsidies for sustainable practices	Regular subsidies and specific subsidies for sustainable practices	No regular subsidies, some grants for sustainable practices
References	(Scottish Agricultural Census, 2023, 2019; Scottish Government, 2018)	(Agence Bio, 2020; AGRESTE, 2020)	(CDFA, 2022; USDA, 2023)

### 2.2.2. Case-study actors

To identify the **main barriers and levers to reintegrating livestock in each region**, we relied on **local actors' perceptions**. Following Magne and Quénon (2021) and Weituschat et al. (2023), we did not aim for statistical representativeness, but instead we **sampled across a wide diversity of actors** from the sociotechnical system to improve our understanding and **build an inventory of those barriers and levers**. We first relied on researchers from our network studying integrated crop livestock systems in the three regions to define the categories of actors we needed to interview. In the three regions, researchers recommended interviews of actors from the production system (i.e. **farmers** who reintegrated livestock), advising system (i.e. **technical advisors** working with this type of farming systems) and actors from the “macro” level (i.e. **specialists of public policies, researchers**). For each category of actors identified, we asked researchers to identify potential interviewees, i.e. one or two representative farmers for each type of production system (e.g. reintegrating livestock at the farm or regional level, with diverse animal species reintegrated into diverse crops) and one actor for each other category.

We emailed or telephoned the identified actors to verify they were willing and felt at ease with answering our questions. Next, we organized a meeting, preferably on the farm or at the company building, otherwise via virtual meeting. The first actors interviewed helped us identify other actors that might be interested in being interviewed, which increased the size of our sample through **snowball sampling** (Biernacki and Waldorf, 1981). In the end, we interviewed 13 actors in Eastern Scotland (Sc), 8 in Southwestern France (Fr) and 11 in Northern California (Ca) (Figure 27). In total, we interviewed 18 crop farmers (Cf) who reintegrated livestock, 2 livestock farmers (Lf) involved in partnerships / contract grazing in California, 3 technical advisors (Adv), 2 researchers-teachers (Rs) and 7 public policy specialists (Pol). In Eastern Scotland, we interviewed a comparatively high number of public policy specialists because the period during which the interview took place corresponded to the post BREXIT situation, with agricultural policy still being actively discussed. Informal discussions completed our understanding of the sociotechnical context, but were not included in the counting of the number of actors interviewed.

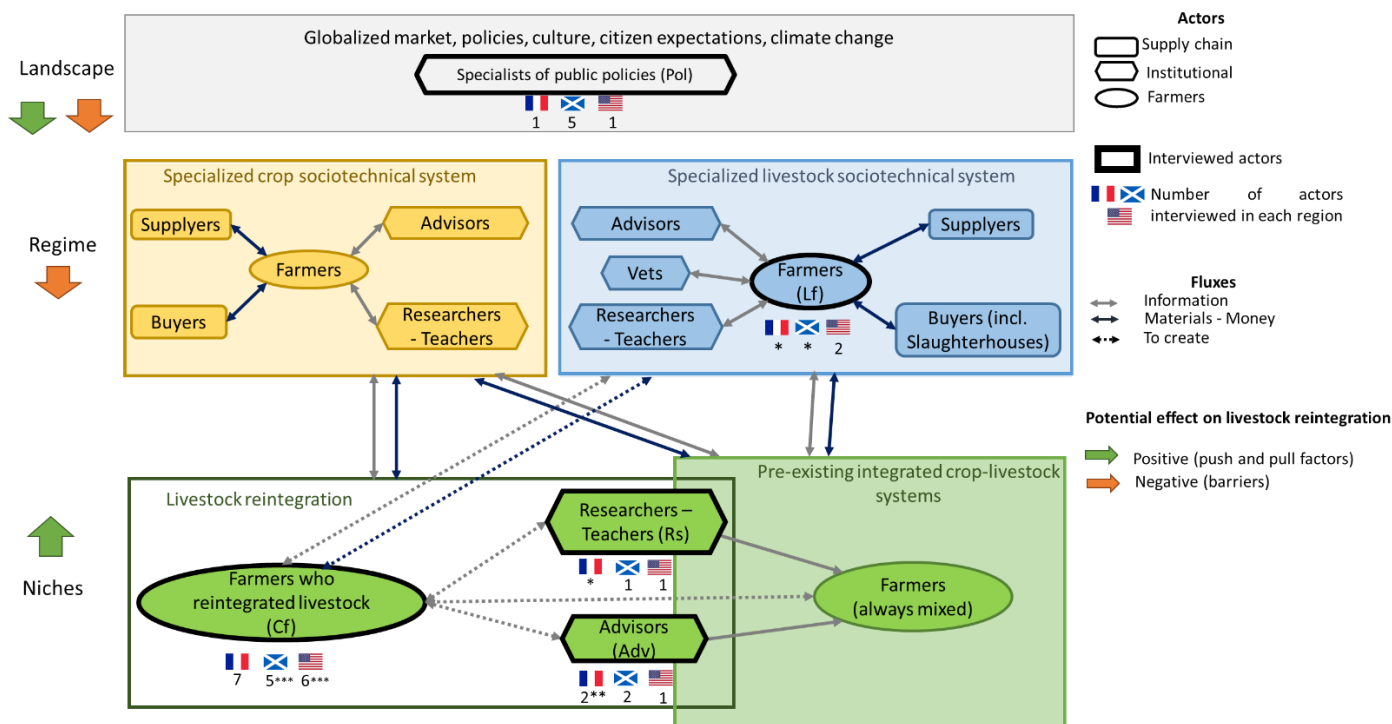


Figure 27: Interrelations between actors from the sociotechnical systems surrounding livestock reintegration and actors interviewed in the 3 regions. \*: only informal interviews. \*\*: interviews from Moojen et al. (2023). \*\*\*: including 2 farmers who already had cattle and reintegrated other livestock, or for which livestock reintegration was done before the farmer took over the farm (see Table 7).

### 2.3. Data collection

The **32 semi-structured interviews** were conducted from December 2021 to September 2023 by one researcher (C.M.) sometimes accompanied by M.G. or members of the local research team. All interviews were conducted in the actors' mother tongue, i.e. either French or English, and thereafter translated when needed. We designed an interview guide that was very similar for all actor categories, including general questions on the mission and funding sources of the actor's institution and the **history of livestock farming and ICLS in the area**. Some questions also covered the **place occupied by systems reintegrating livestock** (or, if not specifically considered, by ICLS) **in the preoccupation of the organization**, and its **evolution** over the last years. For the farmers, we added questions related to the **structure of their farm** and a **description of their system reintegrating livestock**. Core questions of the interview had a specific focus on **barriers and levers to livestock reintegration and how the actor contributed to them**. The main questions asked were: 1.) "What would you say eases / slows down livestock reintegration in your area?" ; 2.) "What could you do or have you already tried to do to help overcome these barriers ? What could other people do?". Follow-up questions were also asked to ensure the interview was targeting barriers and levers at all levels of the MLP, including e.g. for the regime level, whether actors identified a lack of knowledge or outlet for the products that was slowing down livestock reintegration ; for the landscape level, whether livestock reintegration was promoted by public policies ; and for the niche level, whether actors identified difficulties to build partnerships between crop and livestock farmers. Interviews ended with questions asking actor's perception of the evolution of livestock reintegration in the area over the next 10 years.

## 2.4. Data analysis

To identify the main barriers and levers for reintegrating livestock, we listened to the interview recordings and transcribed the corresponding parts. We performed **inductive content analysis** to identify the barriers and levers to reintegrating livestock that emerged from actors' discourses in each region (Elo and Kyngäs, 2008). We systematically collated actors' responses (i.e. the corresponding idea(s) mentioned), their identifiers (e.g. CfCa1 corresponding to crop farmer #1 from Northern California) and a related quote extracted from the transcription. We coded the responses by assembling them into categories and subcategories of similar ideas emerging during the process, and grouped them into the three levels of the MLP (niche, regime and landscape). For instance, *"There is not any science to back [reintegrating livestock], it's just farmers"* (CfCa5) and *"There's a couple of problems, I'd say, or barriers. One is that there's still a lack of scientific understanding about the actual climate benefits or environmental benefits of [reintegrating livestock]"* (PolCa) were grouped under the subcategory "Lack of knowledge", which was a barrier linked to the regime level identified in Northern California (i.e. due to historical specialized farming). We readjusted the categories according to the new ideas emerging from actors' responses as the coding progressed. To increase the robustness of the subcategories of barriers and levers identified, the coding was made by one researcher (CM), and double-checked by two others separately (GM and JR). Results for each category and subcategory were illustrated by pseudonymised quotes. **We collated and compared all the barriers and levers identified** by at least one actor at the niche, regime and landscape levels **in the three regions**. Finally, we organized a meeting with a subset of actors we interviewed in the three regions to collect their feedback on our analysis.

### 3. Results and Discussion

#### 3.1. Description of the regime of specialized farming and how it impedes reintegrating livestock

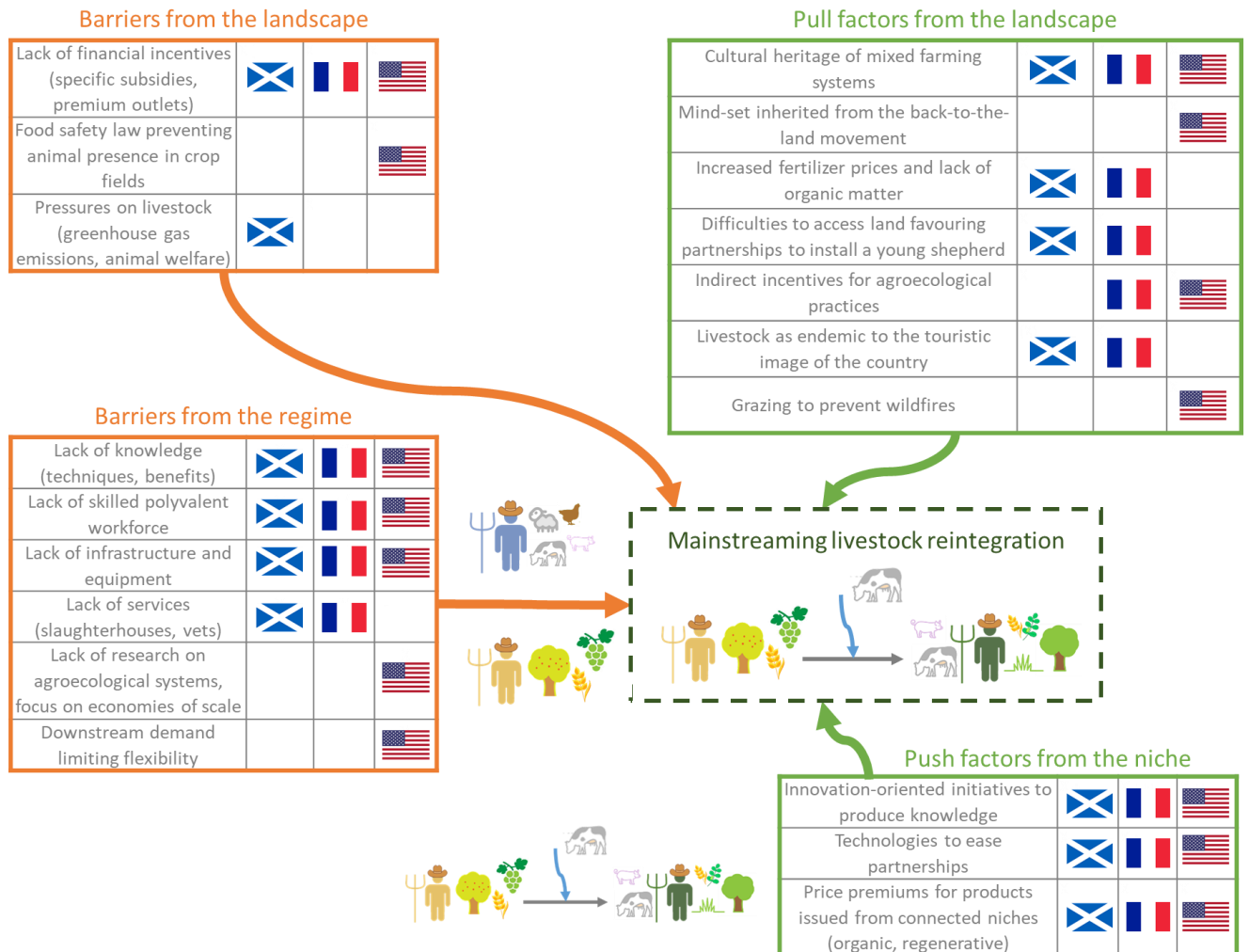


Figure 28: Main barriers and levers to livestock reintegration in Eastern Scotland, Southwestern France, and Northern California. A flag from the region's country means the factor was mentioned by actors of this region.

The **regime of specialized farming in place was similar in the three regions**, with sociotechnical systems specialized for either crop or livestock production hindering the reintegration of livestock, especially due to a lack of knowledge, infrastructure, skilled workforce, services related to livestock in specialized crop regions, research on agroecological systems and downstream demand limiting flexibility (Figure 28).

The first barrier identified by all the actors in the three regions was the **lack of knowledge at all levels of the value-chain**. "There is not any science to back this, it's just farmers" (CfCa5). Many actors, while familiar with ICLS, declined our invitation to interview mentioning they did not have any specific

knowledge regarding livestock reintegration. Further, actors often began their interview by mentioning they were unsure about being ‘the right’ person to talk about that the subject, highlighting the novelty and niche nature of livestock reintegration. **Farmers lacked knowledge regarding the techniques** for reintegrating livestock, which sometimes led them to fear crop damage by the animals, consistent with Niles et al. (2018). Additionally, farmers struggled with the cost of **increasing the complexity of their system** (Asai et al., 2018) **and uncertainties of the potential benefits**, as emphasized in the following quote of a researcher relating what a farmer told him: “[Farmer thought] ‘I’m complicating the system, why do I need to complicate the system?’” (RsSc). Such knowledge-related barriers are **consistent with previous studies** on the expansion of innovative practices, for instance ICLS (Cortner et al., 2019; Garrett et al., 2020; Ryschawy et al., 2021), or crop diversification (Mamine and Farès, 2020; Meynard et al., 2018); even though the severe lack of specific knowledge makes it **even more true regarding reintegrating livestock**.

Actors also mentioned the **lack of a skilled workforce** in Southwestern France and Northern California, a barrier often mentioned for ICLS (Cortner et al., 2019; Garrett et al., 2020; Gil et al., 2016; Ryschawy et al., 2013): “I think that would be a barrier, people that are skilled and knowledgeable about actually managing, just managing sheep and goat.” (LfCa2). This was more nuanced in Eastern Scotland with the spatial proximity between crop and livestock farms making it easier to partner with competent livestock managers.

Similarly, actors mentioned the **lack of suitable infrastructure and equipment** for livestock on crop farms in all three regions, even though fencing infrastructure was more prevalent in Eastern Scotland than in Northern California and Southwestern France: “We did not have a barn, we did not have the knowledge of having sheep, we just assumed they would be out there the whole time” (CfCa3). This was also mentioned in previous ICLS studies (Asai et al., 2018; Gil et al., 2016; Ryschawy et al., 2013), as well as studies on scaling up of other agroecological practices (Magrini et al., 2016; Mamine and Farès, 2020).

Specialization across the entire value chain has resulted in a **lack of essential services related to livestock** in regions primarily dedicated to specialized crops, particularly regarding **farm veterinarians** and **slaughterhouses**. This issue has been notably highlighted in Southwestern France, where stakeholders identified a significant decrease of these services. A similar concern was raised in Eastern Scotland, where the diminishing number of slaughterhouses and veterinarians was perceived as a hindrance, though this challenge extended beyond livestock reintegration: “There are real problems in Britain as a whole to access slaughterhouses.” (CfSc1). In Northern California, slaughterhouses are present, but they generally require the actors to deliver a large number of animals at once, forcing farmers to manage large homogeneous flocks, which can be incompatible with small flock sizes often associated with livestock reintegration at the farm level, especially over the first years. Rather, veterinarians were identified as providing critical connections between crop and livestock researchers in Northern California: “We do have veterinarians, and they connect people, they really have a crucial role in research (...) They are like doctors in linking people to one another (...), and they centralize (...).”

(RsCa) Northern Californians also mentioned the **lack of research on innovative agroecological systems** (i.e. reintegrating livestock) as a barrier, with research on sustainable agriculture focusing on increasing efficiencies of specialized farms through economy of scale: *“The motto is ‘the bigger, the most sustainable’, in dairy farming, because you can capture methane, effluents, transform them into compost at a large scale, and so you manage to create a system that is zero net energy (...) and to do that, you need to have 10,000 cows. And the moto I’m hearing (...) every time I’m going to a meeting where some people are working on animals, is ‘economies of scale’. And then, here we are, with ‘we need [a few cute] sheep to graze’, well, the guys are looking at us, like, really...”* (RsCa). Economies of scale pursued by downstream actors were also identified as leading to geographical concentration of livestock production (Roguet et al., 2015), and hindering other innovative practices such as crop diversification, as minor crops are produced in small volumes (Meynard et al., 2018).

In Northern California, the researcher-teacher and advisor also identified other barriers to livestock reintegration induced by **downstream demands**. Farmers feared that buyers would reject their products due to potential contamination risks by food pathogens if they had had animals in their system: *“Some people would recognize that [...] the company [they are] selling to is not gonna be ok with [having had animals in the crop].”* (AdvCa). Farmers also have to deal with agroindustry predefining planting and harvest dates to meet their supply chain needs. This restricts the flexibility needed to graze cover crops: *“When you have a contract with a cannery, the cannery says ‘we plant on April 28<sup>th</sup>’, you plant on April 28<sup>th</sup>’, ‘to harvest on July 17<sup>th</sup>’, you harvest on July 17<sup>th</sup>. And so, if you have cover crops, it rained a bit before, you did not bring your sheep, (...) you do not have the flexibility you need, so this is a lock-in.”* (RsCa).

### 3.2. Description of the niche: Reintegrating livestock under diverse forms

#### 3.2.1. Characteristics of the farms reintegrating livestock at the farm or regional level

Reintegrating livestock was **uncommon in the three regions**, even though it was more developed in Eastern Scotland where crop and livestock farms are less disconnected. It happened in a **large diversity of systems** regarding crops, livestock reintegrated and form of reintegration (i.e. at the farm or regional level through partnerships).

Reintegrating livestock was associated with **all crop types** in Southwestern France (i.e. vineyard, orchard, grain crops) (Figure 26, Table 6, Table 7). In Eastern Scotland, livestock reintegration primarily occurred in grain cropping systems, the country main type of cropping system, through grazing cover crops or winter cereals at an early phenological stage. Livestock reintegration could also be associated with the introduction of fodder crops (e.g. kale, stubble turnips) in the crop sequence. In Northern California, livestock reintegration was linked to perennial production systems (i.e. orchards, vineyards, and alfalfa) (Brewer et al., 2023; Fenster et al., 2021) or industrial crop residues (e.g. tomatoes for canneries, watermelons for seed production of seedless hybrids). Previous studies have also documented reconnections between crop and livestock production in a range of systems (e.g. cover



crop, orchard or vineyard grazing, mostly through partnerships) (Franzuebbers and Stuedemann, 2014; Paut et al., 2021; Ryschawy et al., 2021).

There was a **diversity of livestock species** reintegrated across the three regions (i.e. cattle, sheep, goats, pigs and poultry) (Figure 26, Table 6, Table 7), with outdoor meat sheep being the most prevalent. In Southwestern France and Eastern Scotland, monogastrics were also reintegrated on grain crop farms. These were indoor systems deeply embedded in the value chain. For this model, all feed and other inputs were bought and delivered regularly to the farm and the eggs were collected on the farm by agrifood companies, with regular payments at pre-established prices. In contrast, in Northern California farmers did not reintegrate livestock through this type of system because it could not compete economically with large industrial production units already present in the area. Both outdoor meat sheep and monogastrics deeply embedded in the value chain were selected by farmers as systems in which to reintegrate livestock since they required limited additional workers and knowledge to start breeding which are key barriers to developing ICLS (Cortner et al., 2019; Garrett et al., 2020; Ryschawy et al., 2021): *“[The sheep] take care of themselves alone [...] I can sometimes spend a week without wondering what they’re doing”* (CfFr3) ; *“Laying hens, it’s the kind of livestock that requires the less labour.”* (CfFr5). However, some farmers in Southwestern France mentioned the difficulty in finding hardy breeds suited for outdoor systems: *“All we can find now is sheep used to indoor, it’s normal [...] and so animals are not adapted to my system.”* (CfFr1). Outdoor systems were also perceived as less risky by limiting the investments needed to reintegrate livestock on the farm, another barrier identified for ICLS (dos Reis et al., 2021; Gil et al., 2016; Ryschawy et al., 2019). To control costs, indoor systems embedded in the value chain are designed to fit predefined selling prices and pre-calculated return on investment: *“A technical advisor [from the buying company] came to explain me what would happen [if I decided to build a laying hen building], and honestly, when I saw the economic predictions, I said ‘well, I’ll do it’”* (CfFr5).

Livestock reintegration was happening at **both the farm and regional level** in the three regions. even though on-farm reintegration was identified by the actors as less frequent in Eastern Scotland and Northern California : *“Very few people have both crops and livestock [...], it’s not a way of diversifying production people think about, like ‘I am going to buy some sheep’, it’s not something that happens, in general (...)”* (RsCa). This predominance of livestock reintegration at the regional level is not reflected in the sample of farmers interviewed for this study, as our aim was to capture the diversity of systems in which livestock could be reintegrated rather than their relative importance.

### 3.2.2. Specific questions raised when reintegrating livestock at the regional level

For livestock **reintegration at the regional level**, where livestock are temporarily hosted on a crop farm, e.g. to graze crop fields, **specific questions** arose, such as the **identification of the right partner**, the **monetarization of the partnership**, the **attractiveness of the crop farm** for the livestock farmer (e.g. availability of sufficient fodder resource) and the **distance** between the crop and the livestock farm.

In case of a partnership, the barriers hindering livestock reintegration identified above for reintegrating livestock at the farm level (lack of knowledge, additional workload, lack of skilled workers and infrastructure) are partially resolved (Asai et al., 2018; Martin et al., 2016; Ryschawy et al., 2021). Yet actors from the three regions mentioned **difficulty in identifying a partner** when they have no connection to the livestock sociotechnical system. Further, **different mindsets** between crop and livestock farmers can lead to dialogue difficulties and lack of trust hindering the formation of successful partnerships (Asai et al., 2018; Julie Ryschawy et al., 2017; Ryschawy et al., 2019): *“We tried with 4 different shepherds, who came and grazed here, [...] But, yeah, it was hard to work in symbiosis (...) Philosophically, I would love to have livestock farmers who see things the way I’m seeing things, but that, it is asking a lot...”* (CfFr7). When livestock farmers are in short supply, crop farmers mentioned that even when they found the ‘right’ partner, they faced competition from neighbouring farms who saw the success of the system and wanted to replicate it on their own farm: *“It’s always the same with the neighbours, they say we’re crazy, and then, when they see the sheep, when they see it is working, they come and see the shepherd to ask him if he can bring the sheep to their place. I warned the shepherd two or three times, I told him, we have an interest in having you graze here, it is not for you to go to the neighbours!”* (CfFr7).

Livestock reintegration at the regional level is often **valued according to the crop and livestock farmers’ perceptions of the service provided**. In Southwestern France, partnerships are almost always considered as a **win-win situation** (Bonaudo et al., 2014; Ryschawy et al., 2019), and rarely involve payment for services which can be penalized by the rural law (Lecadre, 2016). In Eastern Scotland and Northern California, grazing is almost always **monetarized** due to the negative perception of cooperation mentioned by some actors: *“Scottish farmers are not really good at collaborating, they like to be independent.”* (PolSc2). However, this **remuneration vary depending on the context**. In Eastern Scotland, livestock farmers often have to pay crop farmers to access forage resource to feed their livestock: *“[The amount paid by the livestock farmer is] very much specific to cases. It might be, for the area, it might be a general of 50pences/head/week, something said like that. But some farmers, the more technical ones, would be more specific, ‘I know my sheep require this amount of kilos of dry matter, what it is worth’, and they will say it like that, so it ranges quite a lot.”* (AdvSc2). In contrast, in Northern California, *“Usually the [crop] farmer is paying the [grazing] contractor but I’ve heard about situations when they just figure it’s a wash and the animals are putting on enough weight to compensate the services being done and no money is exchanged, and also of few cases of the [crop] farmer being paid for the forage”* (AdvCa). Some **contract grazers** base their business model selling the grazing service to crop farmers, especially on farms producing high value perennial crops like winegrapes. In these systems reintegrating livestock provides a marketing opportunity to promote the sustainability of their operation and market their product (Niles et al., 2018; Ryschawy et al., 2021): *“Vineyards are having that experience here, they’re using it as a marketing benefit. And you know, I’ve heard that some vineyards, try to have the sheep close to the tasting room when people are there.”* (AdvCa).

In the three regions, actors highlighted **key farm features** that could improve the reintegration of livestock at the regional level. Actors mentioned that the UAA of the farm, and especially the **amount of fodder accessible to livestock**, had to be sufficient to interest a livestock farmer and compensate for their transportation costs. It was particularly true in Northern California where livestock farmers often have large flocks: *"I've heard one group sort of say like 'oh you know, get together with your neighbours, if you got a 120 acres I can make it work, if it's less than that, it's gonna be difficult, I need to be able to move the sheep up the road like...'"* (AdvCa). However, in this region, sufficient fodder resources on very large farms may be less compatible with reintegrating livestock, as these are often highly mechanized: *"The biggest hinderance is many people use a lot more equipment in a more intensive way in their orchard than we do. So like having... It's just (...) to have the chicken pens in there, [it would not be compatible with mechanization] (...). I think that'd be the biggest problem."* (CfCa2). In Southwestern France actors also identified **distance** between the crop and livestock farms as an important factor for partnerships (Asai et al., 2018; Martin et al., 2016; Julie Ryschawy et al., 2017): *"Being far away can make it harder, even if shepherds are professional, because sometimes, it's when you have problems, when you have a sheep or cow running away, the guy needs to be close by, he needs to be able to react quickly."* (CfFr4). It was less the case in Eastern Scotland due to spatial proximity of crop and livestock farms. In Northern California the importance of the proximity between grazing operations and crop farms was dependent on the contract grazer. In the three regions, actors also mentioned the need for a place to hold the animals if the need arose to temporarily remove them from the crop field (e.g. after weather events, for a mechanical intervention in the plot, during a specific stage of the crop growth cycle). Such a facility also decreased crop farmers' fear of potential animal damage to the crop or crop field: *"If it rains during a week in the plot, we do not bring the sheep there. Because, well, are you preserving soil structure ? No. So, if it happens, you need a way out. For me, it's the hilltops, because they are unproductive anyway. So I leave a bit of grass there, and if there's a problem, well, they go there."* (CfFr1).

### 3.2.3. Profiles of farmers reintegrating livestock

In the three regions, actors mentioned some **common traits of crop farmers reintegrating livestock**. First, regardless of their age, the farmers were already implementing an **innovative system**: *"And I would say most of [reintegrating livestock] is happening among how I would ... refer to them as early adopters, the farmers that are already kind of on the edge of innovation within their fields, and are typically, you know, very interested in the science, they're interested in trying new things ..."* (AdvCa). This was **consistent with other studies** on adoption of agroecological practices (Kernecker et al., 2021). Farmers reintegrating livestock often had a **pre-existing link to livestock farming**, either through familial experience, through agricultural education, or even through exchanges with livestock farmers: *"I grew up on a pig farm. My dad had sheep and I was not fond of sheep."* (CfSc4). Farmers reintegrating livestock also **shared motivations** such as promoting ecosystem services (especially regarding soils), increasing income, and improving social connections with the community (e.g. through improving their system's image) (Meunier et al., 2024). This was **consistent** with motivations highlighted for crop

livestock integration (Paut et al., 2021; Ryschawy et al., 2021) or adoption of other agroecological practices (Bouttes et al., 2019; Casagrande et al., 2016). In Eastern Scotland, economic motivations appeared to be more important for crop farmers due to the additional income livestock reintegration could represent: *"For the arable farmers, it is a source of income and not having a detrimental impact on their cereals"* (RsSc).

#### 3.2.4. *Other niche systems linked to reintegrating livestock*

In the three regions, reintegrating livestock was **linked to other niche agroecological systems**, i.e. **organic and regenerative farming**, in which actors considered livestock reintegration as a key component to improve soil quality and enhance the delivery of ecosystem services. In Southwestern France, actors mentioned that reintegrating livestock was mostly linked with organic farming, which is consistent with our sample of 7/7 farmers being organic or in conversion: *"In organic farming, some crop farmers are thinking about creating a livestock enterprise to produce manure."* (AdvFr2). In Eastern Scotland and Northern California actors emphasized livestock reintegration in link with regenerative farming. While what constitutes a regenerative system was not completely clear and had somewhat different definitions in the two regions, actors in both regions saw soil quality as being a key component of regenerative farming: *"We are into this new type of farming that people call regenerative agriculture so we are regenerative, we say we are (...) I'm a sceptic of regenerative branding because it has no definition right now"* (CfCa2). These **links between ICLS and organic or regenerative systems have rarely been mentioned** in studies on ICLS to date, beyond Fenster et al. (2021a) who identified animals as an important tool for a Californian farm to implement regenerative principles (Fenster et al., 2021a).

Table 7: Profiles of the interviewed farmers reintegrating livestock in the 3 regions. Younger: less than 35 years old; Middle: between 35 and 55 years old, Senior: over 55 years old.

Identifier	Country	Production mode	UAA (ha)	Crops	Livestock	Number of animals	Form of reintegration	Year in which animals were reintegrated on the farm	Gender	Age
CfCa1	CA	Organic	8	Vegetables and pasture	Sheep, Dairy Cows, Duck, Chicken	5 cows, 25 sheep, a few chicken and duck	Farm	2019	Male	Senior
CfCa2	CA	Organic	3	Highly diversified fruit orchard	Laying hens	60	Regional	Before he took over the farm	Male	Middle
CfCa3	CA	Organic	101	Almond, mandarins, rice	Sheep	50-60 ewes + 15 baby doll sheep	Farm	2011	Male and Female	Middle
CfCa4	CA	Organic	6	Almond orchard	Sheep	50 sheep	Regional	2015	Male	Middle
CfCa5	CA	Organic	566	Tomatoes for processing, seed watermelons, alfalfa, squash, white corn, grain, cover crop	Sheep	Hosts, up to 6000 sheep	Regional	2019	Male	Younger
CfCa6	CA	Mixed organic and conventional	1214	Rice, fresh vegetables and orchard	Sheep, Goats and Cattle	75 cows + sheep and goats	Farm	Always had cattle, 2022 as year working together	Male	Younger
CfFr1	FR	Organic	200 (of which 40 in pasture) + mountain pasture	Grain crops	Meat sheep	200 ewes + 45 other sheep	Farm and Regional	2018	Male	Middle
CfFr2	FR	Converting to organic	30 (+ 30 in grain crops)	Vineyard	Meat sheep	120 ewes	Regional	2020	Male	Younger
CfFr3	FR	Organic	80	Orchard	Meat sheep	12 ewes + 1 ram	Farm	2018	Male	Middle

CfFr4	FR	Organic	45 in plums (+ 230 in grain crops)	Orchard	Meat sheep	Hosted ewes	Regional	2020	Male	Middle
CfFr5	FR	Organic	29 (of which 5 in permanent pasture)	Grain crops	Laying hens	6000 laying hens	Farm	2020	Male	Middle
CfFr6	FR	Organic	130 (of which 10 in pasture)	Grain crops	Broilers (+ renting a field to a neighbour to graze cattle)	2 × 8000 broilers	Farm (+Regional)	2013	Male	Middle
CfFr7	FR	Organic	2000, of which 80 in vineyards and 100 in pasture	Vineyard, Grain crops	Meat sheep	1000 ewes	Farm and Regional	2018	Male	Younger
CfSc1	SC	Conventional	750 ha arable + 300 ha pasture + 350 ha woodland	Grain crops	Cattle, Sheep	500 cattle + 800 sheep hosted	Mixed farm from the beginning, contracting for sheep		Male	Middle
CfSc2	SC	Conventional	650	Grain crops	Sheep (+ cattle)		Regional	2016	Male	Senior
CfSc3	SC	Conventional	146	Grain crops, kale, stubble turnips	Turkeys	3500	Farm	2012	Male	Younger
CfSc4	SC	Conventional	180 ha + 80 ha trees	Grain crops	Pigs + sheep	1100 pigs (fattening only) (*4 / an) ; hosting 100 sheep grazing	Farm and Regional	2016	Male	Younger
CfSc5	SC	Conventional	80	Grain crops and pumpkins	Cattle and sheep	60 suckler cows, 1300 sheep	Mixed farm from the beginning		Male	Middle

### 3.3. Landscape level barriers to reintegrating livestock

The main **barriers from the landscape** identified by actors as hindering reintegrating livestock are the **lack of specific valorization** for those systems and the products that come from them ; **specific regulation** of the presence of animals into crop fields and **environmental and societal pressures** on livestock (Figure 28).

Actors mentioned the **lack of specific financial incentives** as a barrier to reintegrating livestock in the three regions. **Public policy subsidies or grant programs do not specifically target reintegrating livestock** into crop farms or regions, nor ICLS (Garrett et al., 2017; Garrett et al., 2020) : *"There's not a lot of financial programs that help take away the risk factors for farmers to try [reintegrating livestock], like if they try it and it fails, they're losing their whole season or their whole crop, or if their animals run away or they die, knowing that there's like maybe some financial protection to try it and see how it works, I think [it would really help] for farmers to want to even just try it."* (PolCa). Also, **specific premiums for products coming from farms where livestock have been reintegrated are rare**, if not inexistent, as there is **no specific consumer recognition** for the role of this practice in enhancing quality and/or environmental benefits. This lack of specific marketing channels has **already been identified for products of ICLS** (Cortner et al., 2019; Gil et al., 2016; Julie Ryschawy et al., 2017) and other agroecological practices (e.g. crop diversification (Meynard et al., 2018), cereal-legume intercrops (Mamine and Farès, 2020)).

In Northern California, almost all the actors mentioned the **Food Safety Modernisation Act (FSMA)** as a barrier to reintegrating livestock, consistently with previous studies (Garrett et al., 2020; Niles et al., 2018). This law encourages following the National Organic Program (NOP) guidance which states there must be a 90-120 day window (depending whether the parts of the crop that are harvested are in direct contact with soil or not) between raw manure application (either through spreading or having animals in the field) and harvest to avoid risk of crop contamination with food borne pathogens from animal faeces (USDA - AMS - NOP, 2011). This complicates livestock reintegration, because **farmers need another area to hold their animals during this period**: *"One of the biggest problem with having sheep in the orchard is the food safety law that requires moving sheep out of the orchard 90 days before harvest even though the nuts we harvest never touch the ground."* (CfCa3). This is a major reason explaining livestock reintegration being more prevalent in vineyards in California, as grapes are not in contact with the soil and the fermentation process kills potential food borne pathogens. This regulation suffers being **misunderstood by farmers, but also by other actors**. They argue that the presence of wild animals in the crop fields also leads to contamination risks, and that the delay before harvest should not apply in case of a harvesting process involving no contact between the fruits harvested and the soil. This regulation has no equivalent in France or in Scotland.

**Environmental and animal-welfare-related pressures** on livestock were also mentioned as barriers to reintegrating livestock. The ambitious Scottish Government target of greenhouse gas reductions (NET Zero by 2045) (Scottish Government, 2023) and environmental activist movements were mentioned as barriers by the majority of Scottish public policy actors (3 out of 5) : *"If you're trying to put livestock*

*into arable units, what you're in danger of doing is ... pushing greenhouse gas emissions up. So, you've got one little group over here which is environmentalist and they say, we need to get greenhouse gas emissions under control, and the only way to do that is getting rid of every single animal there is in Scotland. So why are you encouraging animals over here?"* (PolSc5). The **rise of veganism and animal welfare movements** were also mentioned by few actors as potentially slowing down livestock reintegration in Eastern Scotland. In Edinburgh, regional authorities have decided to remove meat from school and hospital meals: *"In Edinburgh, everything is going to be plant-based, which is awful (...) There's never been a worst time to be a farmer than right now. Ever. [...] Because of all the public moving against. If you're a vegetable farmer then you're probably OK but if you're [a livestock farmer] you need to be pretty careful."* (CfSc5). In Northern California and Southwestern France, pressures for greenhouse gas reduction or veganism were not mentioned as barriers, despite the presence of carbon neutrality targets. Societal pressure regarding animal welfare was oriented towards intensive livestock farming systems (concentrated animal feeding operations) in Northern California. Barriers associated with environmental movements were **not mentioned by previous studies** on integrated crop livestock systems. To advocate for maintaining some presence of livestock farming in spite of this societal pressure, some recent studies are focusing on defining the sustainable quantity of meat consumed to achieve agroenvironmental targets (Billen et al., 2024; Cué Rio et al., 2022) while emphasizing societal roles of livestock farming beyond food production (Herzon et al., 2023).

#### 3.4. Push factors from the niche to mainstream reintegrating livestock

The main **push factors from the niche** contributing to favour reintegrating livestock according to interviewed actors are **innovation-oriented initiatives to communicate on those systems, technologies and contract templates easing partnerships**, and **price premiums for products coming from other niche systems** highly connected to livestock reintegration (Figure 28).

Actors mentioned some **innovation-oriented initiatives**, mostly from associations and advisors, to **promote the creation of partnerships between crop and livestock farmers**, as well as reconnecting crop and livestock enterprises on mixed farms. This presented an encouraging avenue for crop farmers to reintegrate livestock if the benefits of this reconnection are acknowledged more widely. Outreach efforts to facilitate the reintegration of livestock were reported in the three regions. These efforts were most widely developed in Eastern Scotland, followed by Northern California, and Southwestern France. Examples of these outreach events were: field days on winter cover crop grazing in Southwestern France, field days on grazing winter cereals at an early phenological stage in Eastern Scotland, and field days on grazing in orchards and vineyards in Northern California. A **participatory programme** involving Scottish **farmers, advisors and members of the government**, aimed at improving the productivity, profitability and sustainability of Scottish farms was mentioned by 7 of 13 actors (farmers, public policy specialists, researchers/advisors) as a **key push factor towards livestock reintegration**: *"Historically, having some sort of demonstration farm (...) as a means of showing what is possible is also another way of encouraging [reintegrating livestock]."* (PolSc2) During the last campaign, one of the initiatives



from the applicant farms that was selected for three years' funding by the government was a crop farmer reintegrating livestock on the farm through a partnership with a livestock farmer. With regards to livestock reintegration, **this program aided knowledge production, and the dissemination of useful information**, as well as **network building** : "*We had government people come here to see us, the head of agriculture in Scotland came, because of what we were doing, he spent an afternoon there [...] so there's a good opportunity of sharing the knowledge with the people that make the decisions. This is really important!*" (CfSc2). **Involving a wide range of actors**, especially end-users, at all stages of the development of innovative practices has been identified as a key driver of adoption, as documented through many examples of action research and living labs (Hossain et al., 2019; Meynard et al., 2023; Toffolini et al., 2023).

Regarding reintegrating livestock at the **regional level**, some actors (mostly advisors) mentioned **online apps** in the three regions (MatchGraze in California, Carbon Dating in Scotland, Mon Berger Local in France), as a **tool to help facilitate partnerships** among crop and livestock farmers through easing partner identification and matching offer and demand. However, none of the farmers interviewed for this study mentioned these apps. Other technologies were also mentioned in Eastern Scotland as a way to ease the management of livestock (e.g. virtual fencing): "*Optimistically, I'd like to see more cooperation. Technology is gonna help. Not just to bringing farmers together, but also like, fencing, making things more mobile and easier, user-friendly, with tracking, with collars and things like that, that might help, virtual fencing, you know you can move your stock from 30 miles away quite easily...*" (AdvSc1). Similarly, **online social networks** were identified as a way to **help building trust** between crop and livestock farmers in Eastern Scotland and a means to resolve problems remotely. Online social networks were not mentioned in Southwestern France or Northern California, though farmers do use WhatsApp groups. In the three regions, actors also mentioned **pre-existing contract templates** to facilitate partnerships between crop and livestock farmers (Asai et al., 2018; Martin et al., 2016).

**Price premiums** for products **issued from niches that are closely connected to reintegrating livestock** (e.g. organic farming in France, regenerative farming in Scotland and California, label Regen Organic in California (ROA, 2024)) may assist the development of those niches, and, in the end, contribute to favouring reintegrating livestock. This is consistent with the idea that the **development of marketing channels may ease the implementation of an innovative practice** (Magrini et al., 2016; Mamine and Farès, 2020; Meynard et al., 2018). Beyond the development of specific marketing channels, farmers can also add value to their niche system products by **direct selling**, on farms or farmers' markets (mostly in France, little in California) or online (Scotland, California) (Cortner et al., 2019; Garrett et al., 2020). This allow them to advocate for the higher quality of their products and the story of how they are produced, thereby leading to consumers willing to pay a premium: "*The grain we grow on the farm, we feed to the turkeys as well which is quite nice, the customers really love that, everything that they eat, the oat barley and wheat, it's produced on the farm just on the field next where they are so... They like that.*" (CfSc3)

### 3.5. Pull factors from the landscape to mainstream reintegrating livestock

The main **pull factors from the landscape** facilitating livestock reintegration identified by actors are **cultural heritage**, mainly of mixed farming, **increased fertilizer prices** and **lack of organic amendments, difficulties in accessing land, incentives from the government** for practices that may indirectly favour livestock reintegration, **link between livestock production and tourist image** of the country and **need to prevent wildfire** (Figure 28)

In the three regions, actors widely mentioned the **cultural heritage of mixed farming systems** as a factor that could aid livestock reintegration: *“Historically, [livestock] has been there, mixed farming was the norm in the past... You go to a big arable farm, you find a building where the livestock used to be, so the concept is not completely dead.”* (AdvSc2). This is **consistent** with Garrett et al. (2020) which identified the persistence of mixed farms within the dominant regime as a potential driver for recoupling crop and livestock production. In Northern California, the researcher also identified the **mind-set inherited from the back-the-land movement** (1960’s and 1970’s) (Roy Reed, 1975) as a factor that could help reinspire livestock reintegration : *“It started here, in California, with the hippie movement in the 70’s (...) It’s really when people began saying ‘we’re going to farm in a different way, we are going to go back to what we did before the second world war.”* (RsCa).

In Southwestern France and Eastern Scotland, actors also mentioned **increased fertilizer prices and a lack of organic amendments** associated with organic matter accrual as a driver for reintegrating livestock, which facilitates on farm manure production, **in line** with Asai et al. (2018), Garrett et al. (2020) and Ryschawy et al. (2019): *“But now that inorganic fertilizer prices have gone very very high, I would expect many arable farmers would be looking to having livestock grazing on their farm, what benefits they may actually bring to them and how it can actually reduce the costs.”* (PolSc2). In Northern California, the interviewed actors did not identify reintegrating livestock as driven by a lack of organic amendments: *“We don’t have any problem with compost, have you seen how much of it we have ? [...] We have off soil dairy and chicken industries, we collect all the effluents (...) [we] have tons of compost to sell.”* (RsCa). This might though be nuanced in other counties of Northern California.

In Southwestern France and Eastern Scotland, actors identified that **difficulties in accessing land** favours livestock reintegration through partnerships involving sheep grazing. These partnerships **help get a young shepherd started**, without having to buy land, and instead only needing capital to buy animals and mobile fencing : *“It’s always satisfying to think that we can install young farmers with us, and help them earn a living (...). Our land is ‘useless’ for 6 months a year, it helps [shepherd] having free grass, earn a living, do their business, and not having to deal with the problem of the land ! Because, now, the land is really expensive, even we can’t buy any, it’s too expensive!”* (CfFr7). This factor **has not been identified in previous studies** involving crop and livestock reconnection (Garrett et al., 2020; Niles et al., 2018).

In the three regions, **indirect incentives from the government** were identified by actors as ways to favour reintegrating livestock. In France, **subsidies favouring the development of fodder crops, cover crops and inter-row grassing may favour reintegrating livestock** as a way to manage and terminate

those crops. New conditionality measures from the CAP2023 include the obligation to grow winter cover crops to access CAP subsidies (Ministère de l'agriculture et de la souveraineté alimentaire, 2023). Additional subsidies are also accessible through inter-row grassing in perennial systems, or by growing a fodder legume crop to feed a livestock farmers' animals. In Scotland, agricultural policies following BREXIT were still under development at the time of the interview, but actors mentioned their **hope for more conditionality measures**, especially regarding nature-based climate solutions that may favour reintegrating livestock: *"The new funding will be, if you want to receive anything you have to do a carbon audit."* (AdvSc2). In California, some **grants from the government**, such as the Healthy Soils Program, are **promoting soil health practices**, which can contribute to promoting livestock reintegration (CDFA, 2024). However, those grants are for a wide variety of practices (e.g. spreading compost), at the price of a heavy administrative burden: *"Sometimes it's not worth it, it's just too hard a pressure, like 'oh we took a picture but it's not geo-located', 'we took a picture of the tractor but we did not take a picture of way we...' like, argh!"* (CfCa3). These grants are **currently mostly utilized by large farms to spread compost on**, rather than by farmers reintegrating livestock. Incentivizing agroecological practices through **taxes on pollution** generated or **payments for ecosystem services** were also identified as levers that might favour reconnecting crop and livestock production (Garrett et al., 2017; Veysset et al., 2014), as well as other agroecological practices (Mamine and Farès, 2020).

Actors mentioned livestock as being **endemic to the tourist image of the country** in Scotland (and to a lesser extent in France), which could favour reintegrating livestock: *"People associate Scottish farming with sheep and beef [...] so I would say it's historic and culturally it is very important."* (PolSc4). In Northern California, the government rather promoted reintegrating livestock as a way to **prevent wildfires**, as mentioned by Ryschawy et al. (2021): *"Most of my work is residential housing and it's grazing for fire prevention."* (LfCa2).

#### 4. Conclusion

This research demonstrated for the first time that, across regions, farmers **face numerous barriers to reintegrating livestock**, with the main barrier being the **lack of specific knowledge** on how to implement the practice on their farms and what benefits to expect from it. Though the barriers identified for reintegrating livestock are generally **similar** (sometimes stronger due to the enhanced novelty of reintegration) **to those that have been documented for maintaining ICLS, limited actions** at the market and policy level **have been taken** to minimize these barriers so far. This forces farmers to figure out, adapt, and experiment with reintegration on their own and in their communities of practice.

To address these barriers, we argue that first, **collective action needs to be taken** to fill in the knowledge gaps surrounding livestock reintegration. This should be done through multidisciplinary approaches and research action, e.g. via participative design of research studies or systems reintegrating livestock, field days and farmers' training. Simultaneously, **the benefits of livestock reintegration need to be clearly communicated** to associated industries, consumers, and policy makers. Increasing market demand and incentives for products associated with livestock reintegration

may help drive premiums for such products, working to reduce another barrier to livestock reintegration (e.g. by the creation of a specific label as well as arrangements of the value chain). Communicating on the benefits of livestock reintegration could also sustain the government's initiatives to promote specific research programs to develop more knowledge, as well as subsidies or payment for ecosystem services

## 5. Acknowledgements and Funding

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## Conclusion of Chapter 2

In chapter 2, I contributed to produce knowledge on livestock reintegration through studying **how the sociotechnical context facilitates or hinders the emergence and scaling up of such reintegration** (Figure 29). I found that there are **numerous sociotechnical barriers** to livestock reintegration, most of which are **similar between regions of the world despite differences in sociotechnical contexts**. Those barriers are close to those documented for ICLS but are more difficult to overcome. I particularly identified the **lack of knowledge, specific subsidies and premium outlets** and the **increasing environmental pressures** as barriers hindering livestock reintegration. I also identified **collective actions** involving several actors of the sociotechnical system as a key lever to favour the scaling up of livestock reintegration, e.g. innovation-oriented initiatives connecting researchers, farmers and policy-makers.

I **broadened the innovation-tracking framework** to consider innovations beyond the farm level (i.e. livestock reintegration at the regional level). I also improved such framework by providing a **method to combine on-farm innovation tracking and broader analysis of the sociotechnical system** in which it is embedded more systematically. Such method could be used for other agroecological innovations.

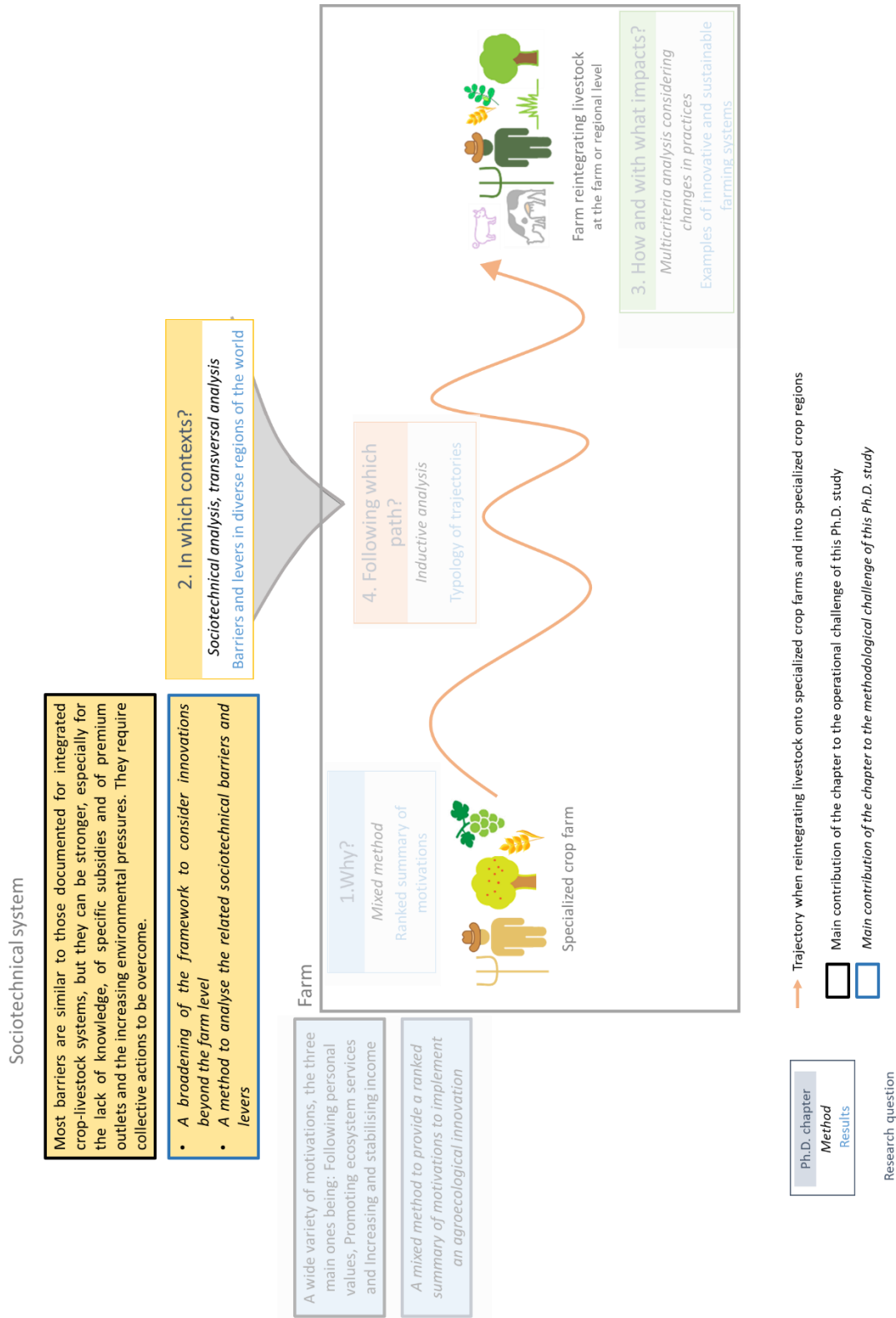


Figure 29 : Positioning Ph.D. study chapters along the trajectory that farmers follow to reintegrate livestock onto specialized crop farms and into specialized crop regions: main results of Chapter 2 on sociotechnical barriers and levers. Operational challenge of this Ph.D. study: producing knowledge on why, in which contexts, how and with what impacts farmers reintegrate livestock into specialized crop farms and regions. Methodological challenge of this Ph.D. study: improving the innovation-tracking framework by studying at multiple levels the determinants that lead to agroecological innovations and assessing their performances objectively.



## Episode 2: Reintegrating sheep through a partnership: a cakewalk ?

Having sheep on my cover crops. I kept this idea in mind for a few years. It is very rare that I stay with an idea for such a long time before actually trying it, I usually take the plunge almost immediately. But this time, it was very different. I mean, of course I liked sheep, well, in fact I liked what I remembered of my grandfathers' sheep, but I had never actually managed any sheep, or any animal, beyond my daughters' cat that she had left at home when she left home to go to the university ! I had so many questions in mind! How many sheep could I feed with my cover crops ? What would they eat the rest of the year ? Where would they go when it rains and they can not stay in the fields without trampling ? If they were ill, would I be able to see that ? Where could I find a vet to heal them when needed ? And then, there would be lambs, what would I do with them ? Plus, there was no slaughterhouse nearby, I did not know who to sell my meat to, and I had no time to manage all of this... So, beyond the idea, it seemed impossible to actually do it.

And then ... One day, 4 years ago, I was watching a television report on farming in the 20<sup>th</sup> century, and it struck me. At that time, shepherds from the mountain, they did bring their sheep into the plains during the winter. Why not do the same ? It would solve so many problems !

So I began looking for a shepherd. It was hard, because I did not know any. The ones I found, they had indoor ewes, they were not interested in that type of idea, they did not want to bother I think, or they thought I was mad. Those in the mountains, in the Pyrenees, they were too far away, they could not come to watch the ewes every day or even every two days ... And then, I found Marie ! She had just settled as a shepherdess, somewhere between my home town and the Pyrenees, and she was looking for land to let her sheep graze. It was my chance ! I offered her to come and have her sheep graze on my cover crops. She came to visit the farm, we drank a coffee, and she agreed. We decided she would come in November, for a first try. And, it was on track.









## Chapter 3: Changes in farming practices after reintegrating livestock onto specialized crop farms and related agroenvironmental impacts

## Preface of Chapter 3

*When farmers have the motivation for reintegrating livestock and have managed to overcome the sociotechnical barriers to it, they can begin to reintegrate livestock onto specialized crop farms and into specialized crop regions.*

Such reintegration can imply **various changes in practices** according to farmers' initial farming systems, their motivations and sociotechnical contexts, and generate **diverse agroenvironmental impacts** (Godinot et al., 2024; Ryschawy et al., 2012). Studying such impacts is key to determine to which extent livestock reintegration can improve crop farms' sustainability, and **whether its scaling up should be supported**.

Thus, in chapter 3, I re-focused on the farm level and on French farms to characterize **changes in practices** after reintegrating livestock onto specialized crop farms, and **assess their environmental impacts** (Figure 30, Box 6). I relied on farmers' interviews to address my third research question: **What changes in farming practices are related to reintegrating livestock onto specialized crop farms and to what agroenvironmental impacts do they lead?**

I hereby contributed to **address one of the main sociotechnical barriers identified for livestock reintegration** in Chapter 2, i.e. the lack of knowledge on how to reintegrate livestock and what benefits to expect (Figure 30, arrow B). To ensure providing knowledge that aligned with farmers' needs, I **assessed these changes in practices in relation to farmers' motivations** identified in Chapter 1 (Figure 30, arrow A).

Most published works on innovation-tracking initiatives focused on assessing an innovation through farmers' self-assessment (Box 7), and have rarely completed it with an objective assessment (Salembier et al., 2016; Verret et al., 2020b). The innovation-tracking framework could be improved by further combining it with **methods to objectively assess agroecological innovations**.

Studying the changes in practices after reintegrating livestock and assessing their agroenvironmental impacts is needed to **determine whether livestock reintegration should be supported and under which form**. It would also help promote its scaling up through **communicating on its actual benefits** to all actors of the sociotechnical system (e.g. favouring its adoption by farmers, its promotion by policy makers, its image to consumers).

*This chapter takes the form of a researcher paper, submitted to Agricultural Systems in September 2024.*

Meunier, C., Ryschawy, J., Martin, G. (n.d.). Reintegrating livestock onto crop farms: a step towards sustainability? [submitted to Agricultural Systems in September 2024]

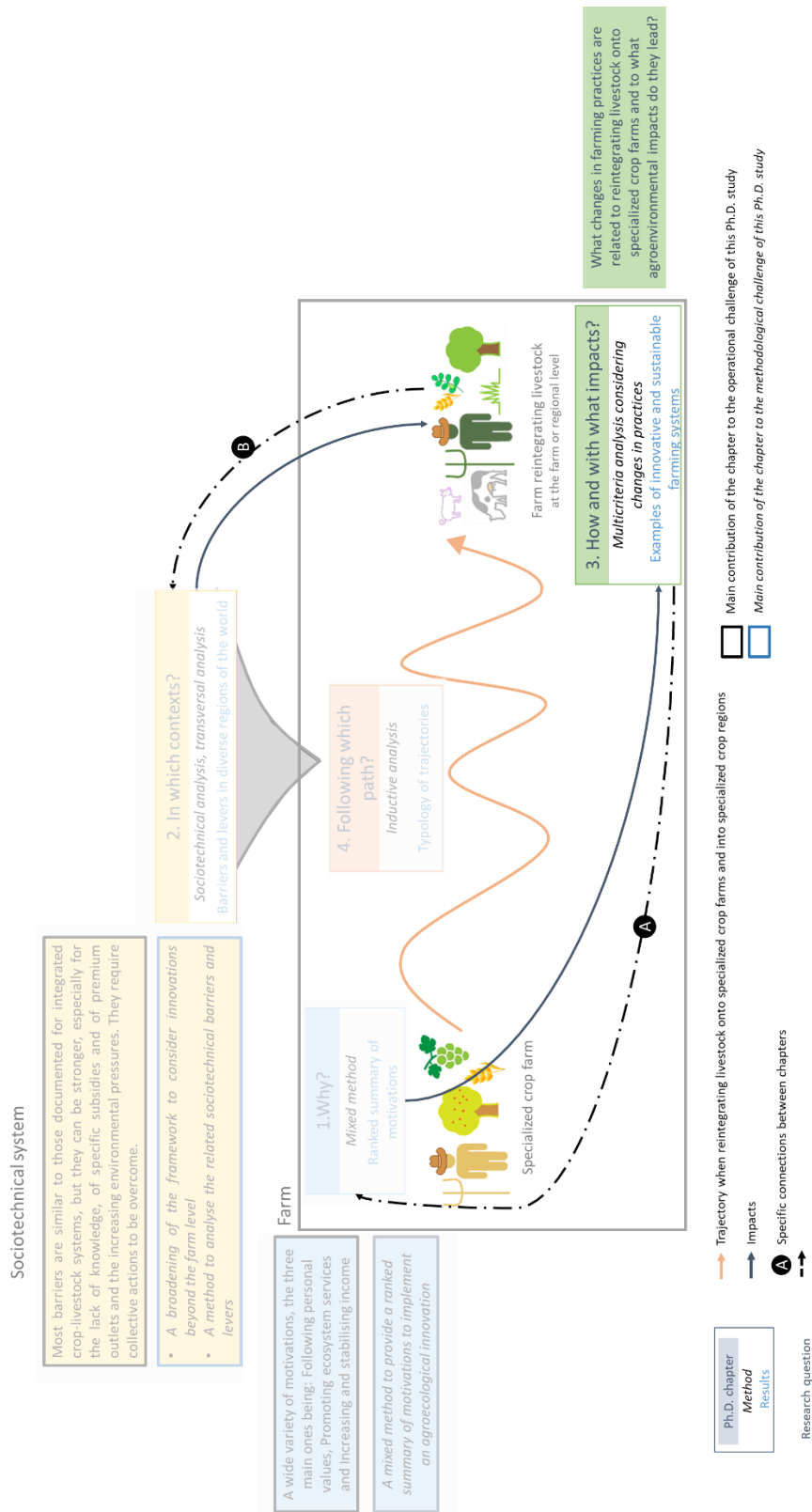


Figure 30 : Positioning Ph.D. work chapters along the journey followed by farmers toward reintegrating livestock onto specialized crop farms and into specialized crop regions: main focus of Chapter 3 on changes in farming practices and related agroenvironmental impacts. Operational challenge of this Ph.D. study: producing knowledge on why, in which contexts, how and with what impacts farmers reintegrate livestock into specialized crop farms and regions. Methodological challenge of this Ph.D. study: improving the innovation-tracking framework by studying at multiple levels the determinants that lead to agroecological innovations and assessing their performances objectively.

# Reintegrating livestock onto crop farms: a step towards sustainability?

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## Abstract

### CONTEXT

In Europe, the ever-increasing disconnection between crop and livestock production generates major environmental externalities. Opposing this trend, a few pioneering farmers have reintegrated (i.e. intentionally organized the return of) livestock onto crop farms. While often depicted as sustainable, these systems have rarely been researched.

### OBJECTIVE

We aimed at characterizing changes in farming practices related to reintegrating livestock on crop farms and at estimating their agroenvironmental impacts.

### METHODS

Using innovation-tracking principles, we identified 15 crop farmers who had reintegrated livestock in farming systems that differed in production mode, farm size, crop and livestock species, and the type and duration of reintegration. We interviewed these farmers to characterize how their farming practices changed after reintegrating livestock. We then estimated impacts of their changes in farming practices after reintegrating livestock on nitrogen surplus, direct and indirect energy consumption and greenhouse gas emissions (including compensation through carbon storage) at the farm level on a yearly basis.

### RESULTS AND CONCLUSIONS

Reintegrating livestock increased mean ( $\pm 1$  standard deviation) farm-level nitrogen surplus ( $+ 16 \pm 27$  kg N/ha/year), energy consumption ( $+ 6\,837 \pm 14\,430$  MJ/ha/year) and greenhouse gas emissions ( $+ 0.93 \pm 1.75$  t CO<sub>2</sub> eq/ha/year), especially when reintegrating poultry ( $+43 \pm 32$  kg N/ha/year,  $+21\,047 \pm 18\,710$  MJ/ha/year and  $+2.46 \pm 2.31$  t CO<sub>2</sub> eq/ha/year, respectively), as the overall aim was to increase farm economic performance (Figure 31). Interactions between crop and livestock production remained limited. The systems that reintegrated poultry relied on large amounts of feed input and did not decrease the amount of fertilizers purchased once chicken manure became available. Reintegrating sheep was associated with lower environmental impacts, with nearly no change in farm nitrogen surplus ( $+2 \pm 9$  kg N/ha/year), decreased energy consumption ( $-268 \pm 198$  MJ/ha/year) due to grazing cover crops or between orchard/vineyard rows and nearly no impact on greenhouse gas

emissions ( $+0.08 \pm 0.13$  t CO<sub>2</sub> eq/ha/year) due to decreased mechanized operations and conversion of cropland into permanent or temporary pasture, which mitigated livestock-related emissions.

## SIGNIFICANCE

This study is the first to estimate environmental impacts of farming-practice changes after reintegrating livestock onto specialized crop farms. We assert that reintegrating livestock helps promote farm agroenvironmental sustainability only if farmers subsequently change practices to maximize interactions between crops and livestock (e.g. adjusting fertilization strategies, introducing legume-dense pastures into crop rotations to feed livestock). This study provides insights into benefits of reintegrating livestock and examples of subsequent adaptations of the cropping system that are needed. It thus supports communication to farmers and policy makers to sustain scaling up of agroecological pathways to reintegrate livestock.

## Graphical abstract

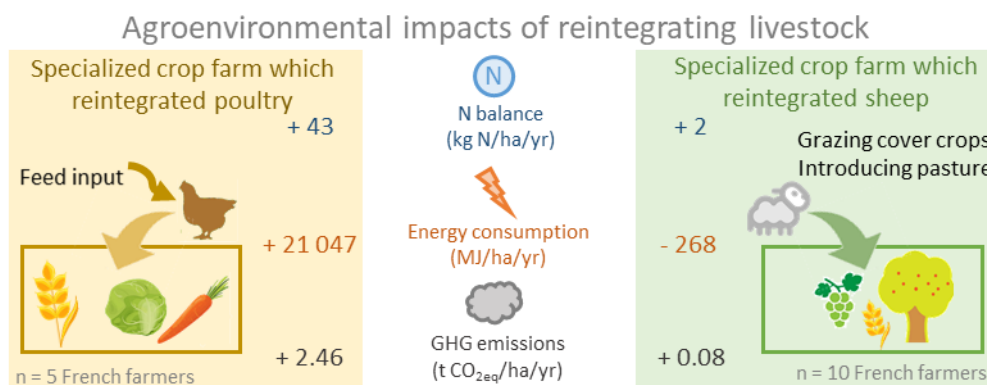


Figure 31 : Graphical abstract of Chapter 3 on changes in farming practices after reintegrating livestock and their agroenvironmental impacts

## Highlights

- Specialisation of crop or livestock production generates high environmental externalities.
- A few pioneer farmers reintegrated livestock onto crop farms and into crop regions.
- Livestock reintegration can improve the agroenvironmental sustainability of farms.
- To do so, reintegrating livestock needs to come up with subsequent farming-practice changes.
- Otherwise, reintegrating livestock generates high environmental impacts.

## Keywords

Sustainability, crop-livestock integration, resilience, agroenvironmental assessment, farming practices



## 1. Introduction

In Europe and particularly in France, public policies and market orientations since the 1950s have pushed farms and agricultural regions into **specialization**, leading to a **decoupling of crop and livestock production**. Such specialized farms and regions contribute greatly to **the environmental impacts generated by agricultural production** (e.g. disturbance of biogeochemical flows, water pollution, biodiversity loss, climate change) (Campbell et al., 2017). The lack of animals to make use of pastures as feed on specialized crop farms and in specialized crop regions drove the **decrease in pastures in crop rotations** (Ballot et al., 2022; Schott et al., 2010), thereby **depriving farms of the ecosystem services** which animals and/or pastures can provide, such as **nitrogen supply** from legume nitrogen fixation and manure; **soil quality improvement** due to manure application to and carbon storage under pasture (Franzluebbers et al., 2014); and **biodiversity promotion** and **biological pest and weed control** through permanent crops that can be grazed, diversified crop rotations and heterogeneous landscape mosaics (Bretagnolle et al., 2011)). To compensate for this lack of ecosystem services, specialized crop farms and regions **relied increasingly on direct and indirect energy inputs** (Harchaoui and Chatzimpiros, 2018) and **imported nutrients** (Lemaire et al., 2014). Conversely, specialized livestock farms and regions import **massive amounts of animal feed** and generate **excessive amounts of manure**, which leads to storage, disposal and pollution problems (Lassaletta et al., 2009; Peterson et al., 2020). Specialization of farms and regions thus **challenges the agroenvironmental dimension of their sustainability**.

Studies have highlighted **integrated crop livestock systems (ICLS)** as a **promising way to increase the sustainability of agricultural production** (Mosnier et al., 2022; Ryschawy et al., 2012; Sekaran et al., 2021). This is especially true for **strong interactions between crops and livestock**, such as for ICLS which include pastures in rotations with crops and recycle livestock manure on the farm for crop and pasture fertilization, which helps improve soil structure, fertility and microbial activity; control erosion; decrease nitrate leaching and increase nutrient self-sufficiency (Brewer and Gaudin, 2020; Franzluebbers, 2005; Hendrickson et al., 2008; Veysset et al., 2014). Similarly, ICLS which include grazing of cover crops or cereals at early developmental stages can help improve pest and weed control, decrease energy consumption and mitigate greenhouse gas emissions (Brewer and Gaudin, 2020; dos Reis et al., 2021; Niles et al., 2018)). Despite these environmental benefits, **ICLS have continued to decrease in France** (from 19% of French farms in 1988 to 12% in 2020), while specialized crop farms have increased (from 37% in 1988 to 52% in 2020), and specialized livestock farms have decreased (from 44% in 1988 to 36% in 2020) (AGRESTE, 2020).

**Opposing this trend of specialization and decreasing livestock numbers**, a few **pioneering farmers in France have reintegrated** (i.e. intentionally organized the return of) **livestock**, either at the farm level (e.g. rearing livestock on the farm) or regional level (e.g. partnership between a crop farmer and livestock farmer, with the former hosting the latter's livestock for a specific period, for example to graze a winter cover crop). Unlike ICLS, which have been studied widely in recent years (Baker et al.,

2023; Paut et al., 2021; Sekaran et al., 2021), livestock reintegration and its environmental impacts have been **rarely studied to date** (Ryschawy et al., 2021; Schut et al., 2021). While increasing the supply of ecosystem services (especially soil quality improvement and biodiversity promotion) has been identified as one of the main motivations which drive farmers to reintegrate livestock, the **actual benefits of reintegration remain highly uncertain**, as do the **best management practices** necessary to obtain them (Dumont et al., 2019; Meunier et al., 2024). This **overall lack of knowledge**, combined with **societal pressure** to decrease environmental impacts of livestock production, were identified as main sociotechnical barriers to scaling up this innovative practice (Thornton, 2010). Thus, there is a need to determine the extent to which reintegrating livestock can improve the agroenvironmental dimension of crop farm sustainability (as advocated by researchers and desired by farmers).

Against this background, this study aimed to **characterize farming-practice changes related to livestock reintegration and estimate their agroenvironmental impacts** to develop knowledge on livestock reintegration and support policy recommendations about **whether scaling up of this practice should be supported**, depending upon the benefits identified.

## 2. Methods

### 2.1. Sample description

We conducted 15 **interviews with farmers** who had reintegrated livestock onto specialized crop farms to characterize their farming-practice changes and environmental impacts of these changes.

#### 2.1.1. Principles of farm identification

We used **innovation-tracking principles** (Salembier et al., 2021) to explore and describe a **wide range of farming-practice changes** after reintegrating livestock and **estimate a range of related agroenvironmental impacts**. We considered reintegrating livestock as an **innovative practice**, as it opposes the trends of specialization and decreasing livestock numbers in France (AGRESTE, 2020; Garrett et al., 2020). As the objective was to **encompass a wide range of farming systems**, individuals were chosen for their diversity more than for their representativeness (Paut et al., 2021; Salembier et al., 2021, 2016; Verret et al., 2020b). Reintegrating livestock is a **niche innovation** (Geels, 2011) implemented on few pioneer farms in France. Using an **exploratory approach**, we thus decided to target farms which produced any type of crop and had reintegrated any type of livestock, in organic or conventional systems, on the farm or through a partnership. We focused on two French regions where livestock is being reintegrated: the Occitanie region, where livestock production and related services remain present (on mixed crop-livestock or specialized livestock farms), although their number is decreasing, and the Parisian Basin, where cash-crop farms have dominated for decades (AGRESTE, 2020). We included only farms on which livestock had been reintegrated for at least 1 year before the interview date to ensure that we could collect feedback about impacts of reintegrating livestock on the farming system.

#### 2.1.2. Farm identification

Like in most cases of innovation tracking, farms on which livestock had been reintegrated were **difficult to identify** (Salembier et al., 2021). There is no public database of such farms, which have been studied

little to date. We thus relied on **farm advisors** from our network (i.e. Chambers of Agriculture and Organic Farmer Associations in both regions, as well as the organization Agrof'île, which promotes living soils and agroforestry in the Parisian Basin) to identify farms on which livestock had been reintegrated. We telephoned the farmers identified to determine whether they met the criteria: having reintegrated livestock on a specialized crop farm for at least 1 year and being willing to participate. We collected general information on the farm and scheduled a meeting to conduct the interview. The first few interviews allowed us to increase the sample size through **snowball sampling**.

### 2.1.3. Farm characteristics

We interviewed 15 farmers, whose farms differed in production mode, utilized agricultural area (UAA), the crops and livestock produced, and the type and duration of livestock reintegration (Table 8). Most farms in the sample were certified organic (10 + 1 in conversion). The sample included a **wide range of farm sizes** (5-2000 ha UAA) and **number of animals reintegrated** (e.g. from 200 laying hens to 1 200 ewes plus 15 000 fattening lambs), **four types of crops** (i.e. grain crops (10), fruits (3), vineyards (2) and vegetables (1)), and **two types of livestock reintegrated** (i.e. poultry, either laying hens (4) or broilers (1) and sheep (for meat (9) or wool (1))). Poultry were always reintegrated on the farm itself in free-range systems (5), while sheep were reintegrated on the farm (5), through a partnership (4) or both (1), and in fully outdoor systems, except for 1 farm, which had a fully indoor on-farm system for fattening lambs. The duration of livestock reintegration (i.e. years between livestock reintegration and the interview) varied greatly (2-25 years), but the overall trend was **recent** for most farms (mean of 6.6 years and median of 5 years).

## 2.2. Data analysis

### 2.2.1. Indicators and calculation methods chosen

We considered indicators and ways to assess them that were i) **sensitive to changes in practices** after reintegrating livestock; ii) **aligned with the main advantages attributed to ICLS** in the literature (as the most similar documented practice, to compare to this study's results) (Ryschawy et al., 2012; Schut et al., 2021; Sekaran et al., 2021); iii) **aligned with farmers' initial motivations** for having reintegrated livestock (Meunier et al., 2024); iv) and **easily transmissible and explainable to farmers** and v) required relatively **little time or energy from farmers to provide the necessary data** (e.g. relying on their changes in practices rather than additional measurements).

We selected **three agroenvironmental indicators** extensively used in the literature: **nitrogen surplus**, **energy consumption** (including direct and indirect energy) and **greenhouse gas emissions** (including the compensation provided by carbon storage). We calculated them using equations and coefficients from IDEA4 (*Indicateurs de Durabilité des Exploitations Agricoles* in French, i.e. Indicators of Farm Sustainability) (Zahm et al., 2019; 2023), a recognized method for assessing the sustainability of farms, which can be applied to multiple farm types, including various crops (annual and/or perennial) and/or livestock species. For coefficients that IDEA4 did not have, we used other sources from the scientific or grey literature (Table 9) (Constant et al., 2019; CUMA Ouest, n.d.; ITAVI, 2008; ITAVI and CEPSCO, 2010). As we aimed specifically at assessing farming-practice changes after reintegrating livestock, we

focused on **assessing the changes in these indicators before and after reintegrating livestock**. Like Zahm et al. (2019), we calculated all indicators at the **farm gate on a yearly basis**. To assess the changes in indicators before and after reintegrating livestock, we thus considered the following:

- i) For nitrogen surplus (kg N/ha/year), the changes in farm nitrogen input (i.e. synthetic and organic fertilizers, animal feed and live animals), output (i.e. crop and animal products, nitrogen volatilized from animal manure and fertilizer spreading) and storage under permanent pasture, considered as nitrogen not released into the environment.
- ii) For energy consumption (MJ/ha/year), the changes in direct (i.e. electricity and fuel) and indirect (i.e. imported animal feed and synthetic and organic fertilizers (excluding manure)) energy consumption.
- iii) For greenhouse gas emissions (t CO<sub>2</sub> eq/ha/year), the changes in emissions related to mechanized operations (CO<sub>2</sub>), electricity (CO<sub>2</sub>), inputs of synthetic and organic fertilizers (excluding manure) and animal feed (CO<sub>2</sub>), animal presence (CH<sub>4</sub>, N<sub>2</sub>O) and mechanized spreading of synthetic and organic (including manure) fertilizers (excluding manure at grazing) (N<sub>2</sub>O); and of carbon storage by converting cropland into permanent or temporary pasture or by planting trees and hedgerows.

Results for each farm were expressed per ha of UAA to facilitate comparison and consider the relative importance of livestock reintegration as a function farm size. For farms which reintegrated livestock on the farm, we estimated impacts of farming-practice changes on both the cropping system (changes in inputs, crops, and outputs) and on the newly created livestock system (additional inputs and outputs related to livestock) (Figure 32). For farms which reintegrated livestock through a partnership (always sheep), we estimated only the impacts of farming-practice changes on the cropping system. Consequently, we considered the reintegrated sheep as “mowers” and did not include their greenhouse gas emissions or products, as we assumed that they were related to the livestock farm, and not to the crop farm which temporarily hosted them.

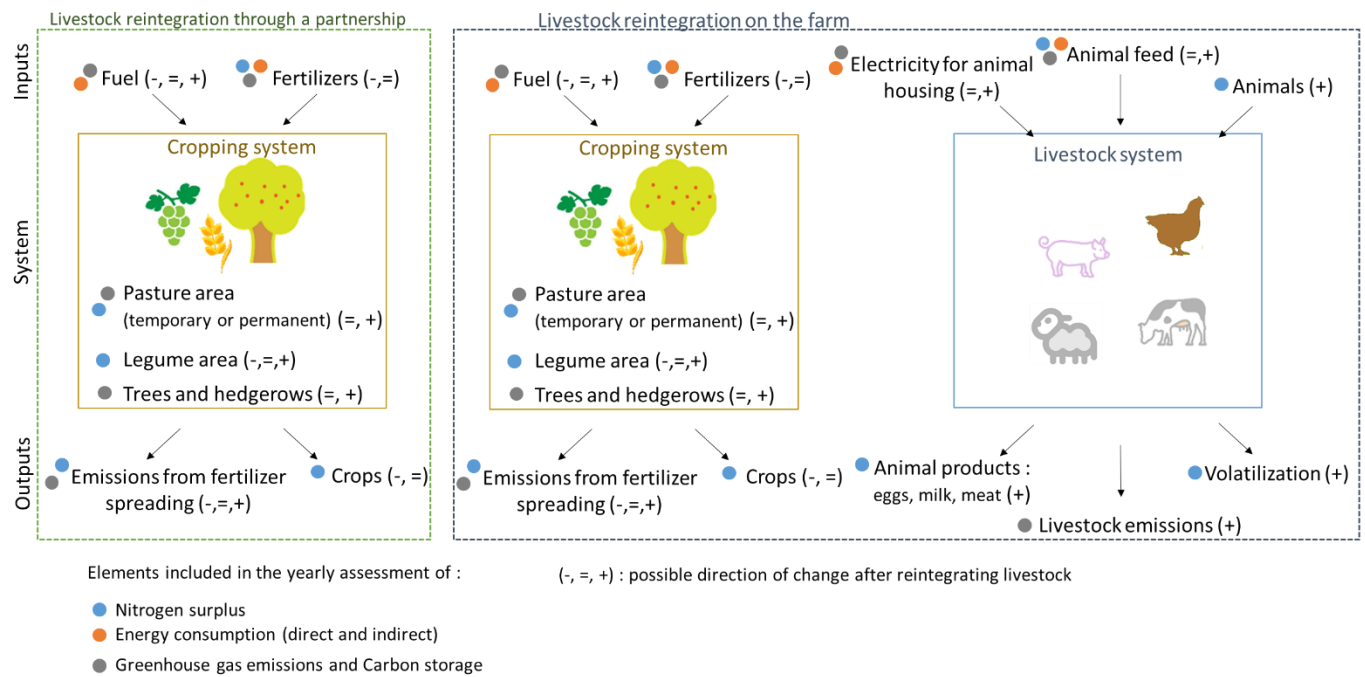


Figure 32: System boundaries, indicators and variables considered when estimating environmental impacts of reintegrating livestock onto specialized crop farms through a partnership (left) or on the farm (right).

### 2.2.2. Data collection

Previous interviews with farmers in the sample had allowed us to identify their motivations for reintegrating livestock (Meunier et al., 2024), sociotechnical barriers they faced and levers they found to overcome them, and to obtain detailed descriptions of their cropping and livestock systems. We conducted **supplemental interviews** to collect the data needed to estimate the changes in farm nitrogen surplus, energy consumption and greenhouse gas emissions after reintegrating livestock. These interviews aimed at i) **identifying farming-practice changes related specifically to reintegrating livestock** (i.e. distinguishing them from other farming-practice changes that may have happened simultaneously but were not related to reintegrating livestock) and ii) **quantifying how these changes changed farm inputs, outputs, the cropping system or the newly created livestock system** (Table 9). Interviews were conducted in person for the first round and by telephone for supplemental interviews, the latter of which lasted 30-60 min and were performed from late 2023 to early 2024. The study procedure followed INRAE (2020) guidelines. Interviewees did not belong to particularly vulnerable groups. We explained the purpose of the interview to them and how we would use the data they furnished, and they provided informed oral consent before the interview began. They were also informed that they could skip questions. The data were pseudonymized before processing following European Commission (2020) guidelines.

### 2.2.3. Data analysis

We compared the changes in nitrogen surplus, energy consumption and greenhouse gas emissions per ha on the farms in the sample after reintegrating livestock. We calculated descriptive statistics for all farms and per group of farms which had similar characteristics for livestock reintegration (e.g. livestock species reintegrated, type of adaptation made to the cropping system after reintegrating livestock (R

Core Team, 2018)). We compared the relative changes in the indicators to standard values per ha for reference specialized French crop farms which produced the same type of crops (i.e. farms that did not reintegrate livestock). To ensure that the equations and assumptions used to calculate these indicators were similar to those in the present study, we obtained reference farms data from WEB-IDEA (INRAE, 2023; Zahm et al., 2019; 2023), a platform which compiles sustainability assessments of farms performed using IDEA4, and compared them to literature data when available (Anglade, 2015).

Table 8: Characteristics of the sample's 15 farms in the Occitanie (O) or Parisian Basin (PB) regions. UAA: utilized agricultural area. Conversion means from conventional to organic farming. Younger: less than 35 years old; Middle: between 35 and 55 years old, Senior: over 55 years old.

Farm	Region	Production mode	Crops considered in crop-livestock interaction	Other crops on the farm	Livestock	Level of reintegration	UAA in 2023 (ha)	Number of animals owned in 2023	Number of animals hosted in 2023 (and hosting duration)	Outdoors / Indoors	Fertilizers used before livestock reintegration	Gender	Age
F1	O	Conversion	Vineyard	Grain crops	Meat sheep	Partnership	58	0	140 (5 months)	Fully outdoors	No	Male	Younger
F2	O	Organic	Vineyard, orchard		Meat sheep	Farm and Partnership	100	50	270 (5 months)	Fully outdoors	Yes	Male	Senior and his younger son
F3	O	Organic	Orchard	Grain crops	Meat sheep	Partnership	275	0	350 (8 months) + 200 (4 months)	Fully outdoors	Yes	Male	Middle
F4	O	Organic	Orchard	Grain crops, asparagus	Meat sheep	Farm	80	20	-	Fully outdoors	Yes	Male	Middle
F5	O	Organic	Grain crops	-	Meat sheep	Farm	200	396	-	Fully outdoors	No	Male	Middle
F6	O	Organic	Grain crops	-	Broilers	Farm	130	16 000	-	Free range	Yes	Male	Middle
F7	O	Organic	Grain crops	-	Laying hens	Farm	102	10 000	-	Free range	No	Male	Senior
F8	O	Organic	Grain crops	-	Laying hens	Farm	29	6 000	-	Free range	Yes	Male	Middle
F9	PB	Organic	Grain crops	-	Wool sheep	Farm	165	40	-	Fully outdoors	Yes	Male	Younger

F10	PB	Organic	Grain crops	-	Meat sheep	Farm	144	50	-	Fully outdoors	No	Male	Middle
F11	PB	Conventional	Grain crops	-	Fattening lambs	Farm	500	15 000	-	Fully indoors	Yes	Male	Senior
F12	PB	Conventional	Grain crops	-	Laying hens	Farm	160	8 000	-	Free range	Yes	Male	Younger
F13	PB	Organic	Vegetables	-	Laying hens	Farm	5	200	-	Free range	Yes	Male	Younger
F14	O	Conventional	Grain crops	-	Meat sheep	Partnership	127	0	500 (1 month) + 350 (3.5 months)	Fully outdoors	Yes	Male	Middle
F15	O	Conventional	Grain crops	-	Meat sheep	Partnership	130	0	240 (4 months)	Fully outdoors	Yes	Male	Senior

Note : Conversion means from conventional to organic farming.



Table 9: Variables considered to estimate changes in farm nitrogen (N) surplus, energy consumption and greenhouse gas (GHG) emissions and carbon storage. Asterisks identify variables considered only for livestock reintegration on the farm.

Indicator	Indicator component and source	Variables considered
N surplus  (N input – N output – N storage)	N input (A)	Synthetic and organic fertilizers
		Animal feed*
		Live animals*
	N output (A)	Crop products
		Animal products*
		NH <sub>3</sub> and N <sub>2</sub> O emissions from animal manure*
		N <sub>2</sub> O emissions from mechanized spreading of fertilizer
N storage (A)	Additional N storage under permanent pasture	
Energy consumption  (direct + indirect energy consumption)	Direct (B-C)	Electricity*
		Fuel
	Indirect (A)	Synthetic and organic fertilizers (excluding manure)
		Animal feed*
GHG emissions and carbon storage	GHG emissions (A)	Mechanization (CO <sub>2</sub> )
		Electricity* (CO <sub>2</sub> )
		Synthetic and organic fertilizers (excluding manure) (CO <sub>2</sub> )
		Animal feed* (CO <sub>2</sub> )
		Animal presence* (CH <sub>4</sub> , N <sub>2</sub> O)
		Mechanized spreading of synthetic and organic (including manure) fertilizers (excluding manure at grazing) (N <sub>2</sub> O)
	Carbon storage (D)	Conversion of cropland into pastureland (temporary or permanent)
		Hedgerows and trees planted

Note: A refers to Zahm et al. (2019, 2023). B refers to Zahm et al. (2019, 2023), supplemented by farmers' estimates of electricity consumption for poultry buildings and confirmed by ITAVI (2008). C refers to Zahm et al. (2019, 2023), supplemented by Constant et al. (2019), CUMA Ouest (n.d.). D refers to Zahm et al. (2019, 2023), supplemented by ITAVI and CEPSCO (2010).

### 3. Results

Overall, **reintegrating livestock increased nitrogen surplus, energy consumption and greenhouse gas emissions** (Table 10). Their mean increases were relatively **large** compared to the mean values for reference specialized crop farms which produced the same type of crop as farms in the sample, especially for energy consumption and greenhouse gas emissions. For example, reintegrating livestock of any kind was associated with a mean increase of + 6 837 MJ/ha in energy consumption, while reference grain crop farms consumed 13 425 MJ/ha and reference vineyard, orchard and vegetable farms consumed 21 480 MJ/ha. Nonetheless, **impacts varied greatly among farms** (e.g. standard deviation of 14 430 MJ/ha and a range of -603 to + 51 687 MJ/ha for energy consumption) **depending on the main features of livestock reintegration**, especially the livestock species (Table S1).

Table 10: Overall impacts (mean  $\pm$  1 standard deviation) of reintegrating livestock on nitrogen surplus, energy consumption and greenhouse gas emissions and carbon storage.

Category	System		Change in nitrogen surplus (kg N/ha)	Change in energy consumption (MJ/ha)	Change in greenhouse gas emissions and carbon storage (t CO <sub>2</sub> eq /ha)		
					Change in greenhouse gas emissions	Change in carbon storage	Difference
Impacts of reintegrating livestock on farms in the sample	All livestock (n = 15)		+ 16 $\pm$ 27	+ 6 837 $\pm$ 14 430	+ 0.93 $\pm$ 1.75	+ 0.09 $\pm$ 0.10	+ 0.83 $\pm$ 1.7
	Poultry	All farms (n = 5)	+ 43 $\pm$ 32	+ 21 047 $\pm$ 18 710	+ 2.46 $\pm$ 2.31	+ 0.16 $\pm$ 0.07	+ 2.62 $\pm$ 2.31
		All farms (n = 10)	2 $\pm$ 9	-268 $\pm$ 198	+ 0.08 $\pm$ 0.13	+ 0.06 $\pm$ 0.10	+ 0.02 $\pm$ 0.08
	Sheep	Farms without subsequent adaptations of cropping systems (n = 4)	0 $\pm$ 1	-206 $\pm$ 150	+ 0.05 $\pm$ 0.08	+ 0.00 $\pm$ 0.00	+ 0.05 $\pm$ 0.08
		Farms with subsequent adaptations of cropping systems (n = 6)	4 $\pm$ 11	-309 $\pm$ 228	+ 0.11 $\pm$ 0.16	+ 0.10 $\pm$ 0.12	+ 0.01 $\pm$ 0.08
Means for reference specialized crop farms producing the same crops as the sample farms (INRAE, 2023; Frédéric Zahm et al., 2019; Zahm et al., 2023)			35 (all crops)	13 425 (grain crops); 21 480 (vineyard, orchard, vegetables)			2.25 (grain crops, vineyard, vegetables); 0.75 (orchard)

### 3.1. Farming-practice changes on farms which reintegrated poultry and their agroenvironmental impacts

**On-farm poultry reintegration** (n = 5, with either grain crops (n = 4) or vegetables (n = 1)) (Table 8) **increased nitrogen surplus, energy consumption and greenhouse gas emissions greatly** compared to mean values for reference specialized crop farms (Table 10, Figure 33, Table S2). In these systems, poultry was usually reintegrated to **ensure economic sustainability** of the farm, and **did not drive subsequent changes in farming practices** (i.e. adaptations of the cropping system), as crop and livestock interactions were limited to spreading chicken manure on some of the cropland. Laying hens and broilers were reintegrated in large numbers (4900  $\pm$  3400 animals per farm per year), and in **close**

**relation with cooperatives** (n = 4), which provided chicks and chicken feed, and collected eggs or broilers. Thus, **none of the farmers used their own crop production to feed poultry**, as they lacked equipment (e.g. to store grain, to grind feed), lacked knowledge on formulating poultry diets and feared a decrease in production if they varied the diets' protein content. These farms produced many eggs per year (56 000 to 2 500 000, with a mean of 1 700 000) and broilers per year (16 000) due to stable outlets (4 to cooperatives, 1 of which already sold vegetables directly to consumers who also requested eggs). These farms' **crop fertilization was rarely adjusted** as a function of the amount of poultry manure produced on the farm (two farmers decreased it slightly, and one applied no fertilizers before reintegrating livestock), due to a lack of knowledge on its nutrient content. Reintegrating poultry was associated with converting a single crop field into pasture (n = 4, the 5<sup>th</sup> farmer having established it on a field which had not been cropped) and to planting hedgerows and trees to encourage poultry to explore the outdoor area (n = 5).

The **strong reliance of these systems on imported animal feed** was far from being compensated for by the occasional and small decrease in the amount of nitrogen fertilizers imported. This pattern drove a **huge increase in nitrogen surplus** (+100 ± 88 kg N/ha) which was decreased only slightly by the output of animal products (+29 ± 28 kg N/ha). These **changes in inputs represented most of the increase in energy consumption** (95% ± 4%) and **greenhouse gas emissions** (80% ± 8%) after on-farm poultry reintegration. Electricity for poultry buildings represented only 5% ± 4% of the increase in energy consumption. Similarly, emissions from live animals represented 18% ± 6% of the increase in greenhouse gas emissions. Increased carbon storage (+ 0.16 ± 0.07 t CO<sub>2</sub> eq/ha) due to converting a crop field into pasture and planting trees and hedgerows compensated for 30% of emissions from live animals and 6% of total additional emissions after reintegrating livestock.

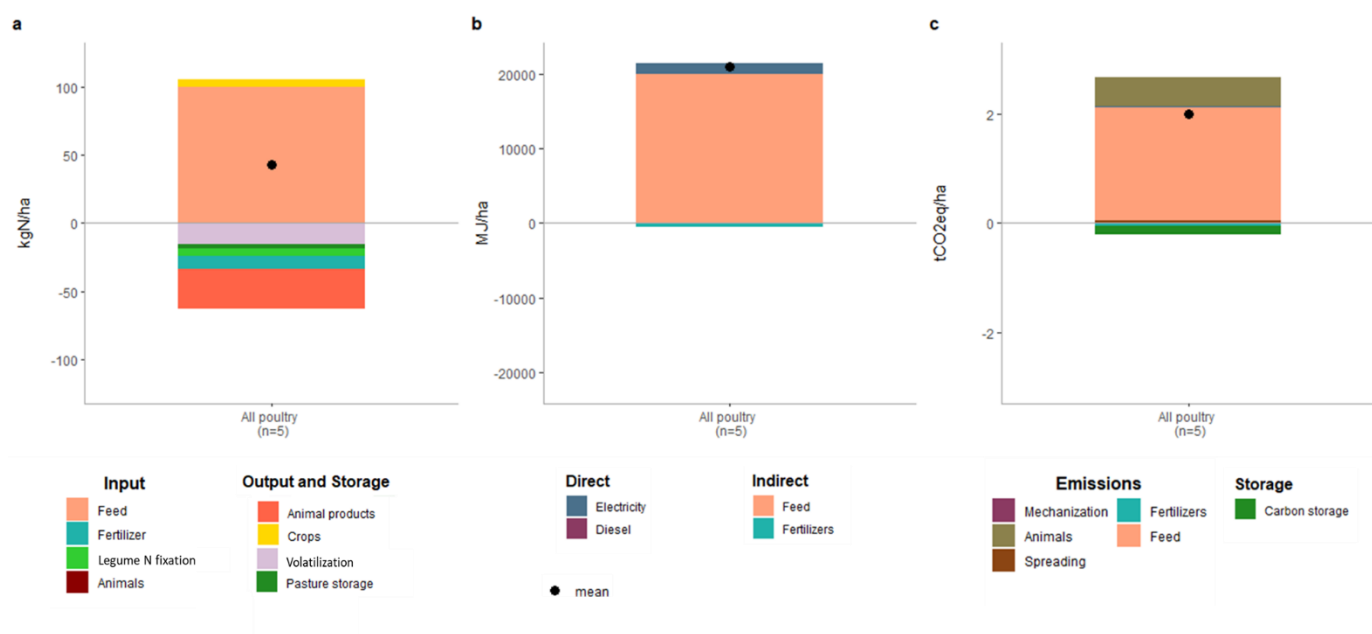


Figure 33: Changes in (a) farm nitrogen surplus, (b) energy consumption and (c) greenhouse gas emissions and carbon storage after reintegrating poultry on farm (n = 5). A positive change can correspond to (a) an increase in inputs or a decrease in outputs or storage, (b) an increase in direct or indirect energy consumption or (c) an increase in emissions or a decrease in carbon storage. A negative change can correspond to (a) a decrease in inputs or an increase in outputs or storage, (b) a decrease in direct or indirect energy consumption or (c) a decrease in emissions or an increase in carbon storage. See Table S1 for details.

### 3.2. Farming-practice changes on farms which reintegrated sheep and their agroenvironmental impacts

**Reintegrating sheep** (n = 10, with grain crops (n = 6), a vineyard (n = 2) or an orchard (n = 2)) (Table 8) resulted in **much lower agroenvironmental impacts** than those of reintegrating poultry, with **nearly no change in nitrogen surplus, additional greenhouse gas emissions compensated for by carbon storage and a decrease in energy consumption** (Table 10, Figure 34, Table S2). These low impacts can be explained by several farming-practice changes implemented when reintegrating sheep.

#### 3.2.1. Sheep reintegration without subsequent adaptations of the cropping system

Four of the 10 farmers had reintegrated sheep for a few years (mean of  $3 \pm 1$  years) but had **not made subsequent adaptations of their cropping system** in response to the presence of sheep. They either owned a few sheep (n = 2, 20-50 sheep throughout the year) or hosted some from a shepherd for a few months each year (n = 3, 140-270 sheep for 4-5 months). When farmers owned the sheep, they **sold few lambs** due to the small flock size and their desire to increase it. Sheep on these four farms were reared in **fully outdoor systems** and **fed only by grazing** between vineyard/orchard rows (n = 3) or cover crops (n = 1), with only one farmer buying minimal amounts of supplemental fodder. As the farmers considered sheep as a **simple way to terminate cover crops** without chemicals or mechanized operations **rather than as an integral component of the system**, they **did not modify the crop rotation** or the composition of their cover crops or vineyard/orchard rows, which were determined in order to

provide benefits for the following crop or perennial crop rather than nutrients for sheep. Farmers **did not adjust their fertilization** to consider the deposition of sheep manure, as they considered it as a bonus that was difficult to quantify (and given that one farmer applied no fertilizers before reintegrating livestock).

This **absence of subsequent farming-practice changes** to the cropping system resulted in **low impacts of reintegrating sheep on farm nitrogen surplus** (mean of  $0.5 \pm 0.6$  kg N/ha, with no change in the nitrogen surplus for the two farms which reintegrated livestock through a partnership, due mainly to nitrogen volatilization from animal manure) (Table 10). **Energy consumption decreased greatly**, as sheep allowed farmers to decrease the amount of fuel consumed to terminate cover crops and mow between rows ( $-206 \pm 149$  MJ/ha), without any increase in electricity, feed or fertilizer consumption. **Greenhouse gas emissions increased slightly** ( $+0.05 \pm 0.08$  t CO<sub>2</sub> eq/ha) due to increased animal emissions that were not compensated for by decreased emissions due to reducing mechanization.

### *3.2.2. Sheep reintegration with subsequent adaptations of the cropping system*

Six of the 10 farmers had reintegrated sheep for a slightly longer time (mean of  $8 \pm 8$  years) and had **subsequently adapted the cropping system** after doing so. They either owned sheep ( $n = 4$ , from 40 to 396 ewes or 15 000 fattening lambs) or hosted some from a shepherd ( $n = 2$ , 200-500 sheep for 4.5-12 months). When farmers owned the sheep, they also **sold lambs or wool**, although only in small amounts, as they had difficulty finding appropriate infrastructure (e.g. slaughterhouses, wool-production industries) and outlets in specialized crop regions and often kept some female lambs to increase the flock size. Sheep on most of these farms were reared in **fully outdoor systems** ( $n = 5$ ), where they were **fed at grazing** with no ( $n = 4$ ) or minimal additional feed input as forage ( $n = 1$ ). On one farm, sheep were reared in a fully indoor system, with nearly all feed produced on the farm (i.e. barley, maize and beetroots) and supplemented with lamb-fattening concentrates ( $n = 1$ ). As sheep were considered an **integral component of the system** which interacted with others and was at least as important as the crops (even for the farms which reintegrated them through a partnership), farmers **adjusted their cropping system accordingly**. They **converted some cropland into permanent or temporary pasture** ( $n = 4$ ) and/or **included more legumes in their cover crops** to make them more nutritious for sheep ( $n = 1$ ). Some farmers **considered the deposition of sheep manure and decreased their input of organic or synthetic fertilizers** accordingly ( $n = 2$ , as two additional farmers applied no fertilizers before reintegrating livestock).

These systemic adaptations of cropping practices **increased nitrogen surplus** moderately after reintegrating sheep ( $+4 \pm 11$  kg N/ha) (Table 10), as changes in input ( $+6$  kg N/ha from animal feed but  $-7$  kg N/ha from fertilizer) nearly equalled those in output ( $-4$  kg N/ha exported as crops, due to feeding them to livestock or converting cropland into pasture, but  $+5$  kg N/ha exported as meat or wool). **Energy consumption decreased greatly** ( $-309 \pm 227$  MJ/ha) after reintegrating sheep and making changes to related practices, such as decreasing the amount of fuel consumed to terminate cover crops or mow between rows and converting cropland into pasture ( $n = 6$ ) ( $-56 \pm 509$  MJ/ha). Fuel consumption decreased more for the five farms that reintegrated sheep with outdoor systems (mean

of  $-251 \pm 197$  MJ/ha), but increased greatly for the indoor system (+920 MJ/ha), mainly due to the need to distribute animal feed and clean the building. For this farm, this increase in direct energy consumption was more than compensated for by the decrease in indirect energy consumption in synthetic fertilizers (-1831 MJ/ha). Reintegrating sheep had **almost no impact on greenhouse gas emissions**, as animal emissions were compensated for by additional carbon storage and a decrease in emissions related to decreased mechanization and fertilizer use ( $+0.01 \pm 0.01$  t CO<sub>2</sub> eq/ha when subtracting changes in carbon storage from those in greenhouse gas emissions). For two of the six farms which reintegrated livestock through a partnership, greenhouse gas emissions decreased due to the decrease in mechanization. For one farm that reintegrated sheep on the farm, the increase in carbon storage due to converting cropland into permanent pasture, planting hedgerows and other systemic adaptations (e.g. decreasing mechanization,) more than compensated for animal emissions.

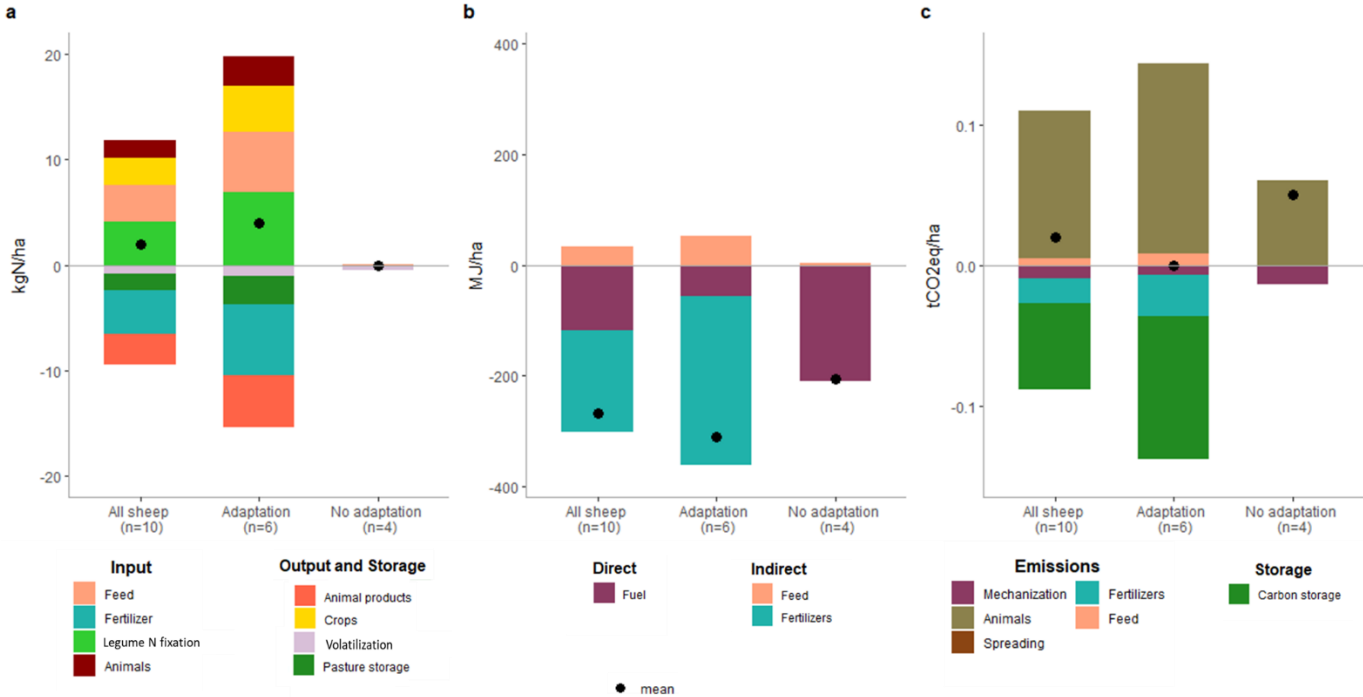


Figure 34: Change in (a) farm nitrogen surplus, (b) energy consumption and (c) greenhouse gas emissions and carbon storage after reintegrating sheep on the farm or through a partnership. A positive change can correspond to (a) an increase in inputs or a decrease in outputs or storage, (b) an increase in direct or indirect energy consumption or (c) an increase in emissions or a decrease in carbon storage. A negative change can correspond to (a) a decrease in inputs or an increase in outputs or storage, (b) a decrease in direct or indirect energy consumption or (c) a decrease in emissions or an increase in carbon storage. See Tables S1 and S2 for details.

## 4. Discussion

### 4.1. Methodological challenges of estimating impacts of reintegrating livestock in innovative farming systems “in the making”

#### 4.1.1. *An original approach to produce knowledge on innovative farming systems*

This study provided, for the first time, a **range of farming-practice changes related to reintegrating livestock and their agroenvironmental impacts** at the farm level. It thus produced knowledge on a variety of farming systems which reintegrated livestock, which have been little documented to date. Its approach has several main strengths.

First, as in studies by Niles et al. (2018) and Paut et al. (2021), the present study built on **data from real-world farming conditions**, which supports the generalization of its results to other farms. Previous studies used instead analytical approaches based on experiments at the field level, on research stations or on commercial farms (Assmann et al., 2014; Lenssen et al., 2013; MacLaren et al., 2019; McKenzie et al., 2016; Peterson et al., 2020); average public data for reference farms in given areas (dos Reis et al., 2021; Dos Reis et al., 2020) or simulation models to estimate impacts of integrating crop and livestock production (Bos and Van De Ven, 1999; de Koeijer et al., 1995; Garnier et al., 2016; M. Moraine et al., 2017; Mosnier et al., 2022; Sneessens et al., 2016). Supplementing the results of these studies with an assessment based on data from real-world farming conditions is essential to encourage farmers to reintegrate livestock onto crop farms and recommend policies which adequately support scaling up of this practice (Passioura, 1996; Salembier et al., 2018).

Second, we studied a **type of innovative farming system that has been little documented to date**, beyond farmers’ motivations, as well as sociotechnical barriers to and levers for implementation (Meunier et al., 2024). Most studies which assessed economic and/or agroenvironmental performances of ICLS **considered farms on which crop and livestock production already existed** (dos Reis et al., 2021; Lantinga et al., 2013; Puech and Stark, 2023; Ryschawy et al., 2012). Other studies estimated **impacts of specific practices**, such as sheep grazing in annual cropping systems (on cover crops and crop stubble (Kumar et al., 2019; Lenssen et al., 2013; MacLaren et al., 2019; McKenzie et al., 2016; Peterson et al., 2020) or between vineyard or orchard rows (Brewer et al., 2023a; Niles et al., 2018; Paut et al., 2021)) or grazing cattle on annual crops (Assmann et al., 2014). ICLS which involve poultry have been documented the least, with only a few studies of grazing poultry in orchards and their potential impacts on pest control (Bosshardt et al., 2022; Paut et al., 2021). The present study is thus original in that it assessed farming-practice changes related to reintegrating livestock and their agroenvironmental impacts onto **a variety of specialized crop farms**.

In the studies cited above, **farming-practice changes indirectly related to reintegrating livestock** (e.g. introducing new crops to rotations, modifying cover crop composition or farm inputs and outputs) **were not analysed specifically**, either because the farms were already mixed or because the focus was on one specific practice and its impacts. However, results of the present study indicate that subsequent farming-practice changes strongly influence the agroenvironmental impacts of reintegrating livestock onto crop farms. Analysing impacts of innovations such as reintegrating livestock, which imply



transformative changes in farming systems (Hill and MacRae, 1996), thus calls for a **systems approach** which includes indirect farming-practice changes. Studying farming-practice changes related to reintegrating livestock and their impacts with a systems approach provides useful insights into the sustainability of these systems, supplementing previous comparisons of performances of specialized vs. mixed farms (Mosnier et al., 2022; Ryschawy et al., 2012).

#### *4.1.2. Unavoidable trade-offs when comparing farmers' expectations and data requirements*

The indicators we calculated provide only either **indirect and partial or no information on some of farmers' main initial motivations** for reintegrating livestock. As documented in Meunier et al., (2024), improving soil quality was the main motivation. It is advocated as one advantage of ICLS, as introducing pasture and recycling livestock manure internally improves soil fertility, structure and life (Brewer et al., 2023b; Brewer and Gaudin, 2020; Franzluebbers et al., 2014). We did not estimate impacts of reintegrating livestock on soil quality due to i) using data that required no physical measurements and ii) the relatively short duration of livestock reintegration, which seemed too short to have influenced soil properties (e.g. soil organic matter content). The study's assessment of farming-practice changes after reintegrating livestock – mainly a decrease in nitrogen fertilizer use, introduction of pasture and cover crops which included legumes and a decrease in mechanized operations – provided only indirect and partial information on potential effects of reintegrating livestock on soil quality and was unable to quantify them. Estimating these impacts would require **long-term monitoring** on research stations or in on-farm experiments, but long-term monitoring has become complex because research is now funded mainly through short-term projects that have to propose new ideas to attempt to receive funding.

**Socio-economic advantages** (e.g. diversifying types of production to increase and stabilize income, increasing farm self-sufficiency and resilience) of ICLS are advocated in the literature (Ryschawy et al., 2019; Veysset et al., 2014) and were often mentioned by farmers as one of their main motivations for reintegrating livestock. We **initially planned to assess these advantages** in this study, but farmers were **reluctant to provide financial documents**. This initial reluctance also led us to decide to collect relatively few data (Ryschawy et al., 2017). Thus, we did not collect data on farm equipment and certain technical management options needed to estimate operational costs and margins. These estimates of agroenvironmental impacts of farming-practice changes after reintegrating livestock will need to be supplemented by future studies (e.g. socio-economic dimensions, long-term impacts on soils).

#### *4.1.3. Challenges of assessing farming systems "in the making"*

This study assessed how reintegrating livestock impacted agroenvironmental performances of specialized crop farms by interviewing farmers in a variety of **farming systems "in the making"** (Toffolini et al., 2019). Its approach capitalizes on innovative experiences without waiting for these farming systems to reach a routine regime. Assessing the performances of diversified farming systems is a challenge in itself (Magne et al., 2024), and comparing the practices and agroenvironmental performances of farms before and after reintegrating livestock raises additional issues.

Livestock reintegration is anchored in a **long-term step-by-step process which relies on trial-and-error** to progressively address sociotechnical barriers against it (Asai et al., 2018; Garrett et al., 2020; Martin et al., 2016). On most farms in the sample, livestock had been reintegrated relatively recently, and the farm's overall functioning had not reached a routine regime. It can be difficult for farmers to describe their farming practices "in the making" (Toffolini et al., 2019) and for researchers to derive reliable data from these recent and ever-changing systems (Magne et al., 2024). This instability is exacerbated by the inter-annual variability in environmental conditions (e.g. droughts) and market prices, which pushes farmers to permanently adapt (Darnhofer, 2021; Darnhofer et al., 2010), and makes it **more difficult to distinguish farming-practice changes related** to annual conditions or **to reintegrating livestock. Monitoring those farms over the long term** would be needed to study their trajectories and determine which adaptations they kept and the impacts of these adaptations (Chantre et al., 2015; Revoyron et al., 2022; Sutherland et al., 2012).

Comparing systems before and after farming-practice changes is also influenced strongly by **the initial state of the system**. It defines the range of possible farming-practice changes and their potential agroenvironmental impacts, thereby constraining the **potential for progress**. For example, some farmers applied no nitrogen fertilizers to crops before reintegrating livestock and thus could not decrease it when considering application of livestock manure. Similarly, in orchards and vineyards which had already sown grass or cover crops between rows before reintegrating livestock, there was no additional compensation for livestock-related greenhouse gas emissions. Thus, **farms which implement agroecological practices already will have less potential for progress** than regime-dominant specialized crop farms when reintegrating livestock and making the necessary farming-practice changes. This calls for assessing farming system states and trajectories, and for considering the system's initial state when interpreting assessment results (Magne et al., 2024).

**Methodological choices made** during assessments (i.e. those discussed previously, plus delineation of system boundaries (Figure 32), the choice and calculation of indicators, farm sampling) **influence assessment results** (Thompson, 2002). Describing the assumptions behind these choices transparently and emphasizing how they influence the results and their domain of validity is essential to produce sound knowledge on innovative farming systems and practices "in the making". In particular, in this work, we decided to rely on IDEA4, a published sustainability assessment method, which provided us with equations and coefficients to assess the selected agroenvironmental indicators (Zahm et al., 2019; 2023). However, the **calculation of nitrogen surplus** in IDEA4 is uncommon when compared to other studies (Quemada et al., 2020), as nitrogen storage under permanent pasture and losses due to volatilization and livestock emissions are usually not externalised from the result. Subtracting nitrogen storage and losses can lead to underestimate the increase of nitrogen surplus linked to reintegrating livestock. Such underestimation remains low, and **does not question our conclusions**, as the above sources of nitrogen storage and emissions account for  $2 \pm 6$  and  $4 \pm 10$  kg N/ha/year respectively, which is quite low. Similarly, we decided to assess **carbon storage** linked with introduction of temporary and permanent pasture on the crop farm as a way to compensate for greenhouse gas emissions. Such assumptions only hold **over a limited time horizon** after which pasture storage capacity decreases

(Baveye et al., 2018; Moinet et al., 2023). This assumption remains consistent with our assessment of the agroenvironmental impacts of reintegrating livestock in **farming systems that are still in the making** (see below section). For farming systems that have reached their routine regime, further adaptations would be needed to go-on compensating for livestock-related emissions.

#### 4.2. Aligning motivations with practices to reintegrate livestock onto crop farms sustainably

Given the many environmental impacts of livestock production (FAO, 2023; Franzluebbers, 2005; Lassaletta et al., 2009), some studies call for changing the current regime of specialized and input-intensive livestock farming (Benoit and Mottet, 2023; Cheng et al., 2022) and even **question whether livestock are necessary in future food systems** (Garnett et al., 2017; Torpman and Rööös, 2024; Van Zanten et al., 2019). At the same time, recent studies have emphasized **environmental benefits of mixed crop-livestock farms** or partnerships between specialized crop farms and specialized livestock farms (Baker et al., 2023; Martin et al., 2016; Ryschawy et al., 2012). These environmental benefits may be decreased if the access to additional resources (e.g. additional outlets for livestock manure) causes farms to intensify their production (Regan et al., 2017).

Against this background, results of the present study indicate that **whether reintegrating livestock onto specialized crop farms is sustainable is not a simple issue**. The environmental impacts of reintegrating any type of livestock on specialized crop farms initially seemed relatively negative (Table 10). More nuance is needed, however, as the conclusion **depends strongly on the farming-practice changes which farmers implement** due (directly and indirectly) to livestock reintegration, which are strongly related to the initial state of the system, the duration of livestock reintegration, the time since farmers began experimenting with reintegration and farmers' individual motivations and constraints.

##### 4.2.1. Poultry reintegration

The large mean increase in nitrogen surplus, energy consumption and greenhouse gas emissions after reintegrating livestock were driven mainly by **poultry systems**. In the farms studied, poultry were reintegrated in **vertically integrated systems that depended strongly on external feed input**, without crop fertilization being adapted to the application of chicken manure. This characteristic amounts to **having two specialized input-intensive types of production on the same farm** rather than to reconnecting crop and livestock production (Moraine et al., 2014). The present study indicated that this type of system **does not seem to be environmentally sustainable**. For the five farmers who reintegrated poultry, the main motivation was not environmental but economic. They never intended to change their farming system beyond what was necessary (e.g. sowing an outside area with grass for poultry) to reach the expected economic results. **When poultry are reintegrated for their agroenvironmental benefits** (e.g. promoting pest and weed control (Bosshardt et al., 2022; Paut et al., 2021), however, **subsequent farming-practice changes and their environmental impacts would differ** greatly. The agroenvironmental impacts of farms which reintegrate poultry more extensively (e.g. a few hens grazing in orchards) or horizontally (e.g. with strong interactions between crops and livestock which cause fertilization strategies to be adjusted as a function of manure application, feeding poultry

grain or co-products produced on the farm to decrease feed-food competition) still need to be assessed to determine whether public policies should promote these systems.

#### 4.2.2. *Sheep reintegration*

The results indicate that **reintegrating sheep tended to have more balanced impacts on the environmental sustainability of farming systems** (Table 10), with small increases in nitrogen surplus and greenhouse gas emissions, but a large decrease in energy consumption, consistent with the advantages highlighted by previous studies (Benoit and Mottet, 2023; IPCC, 2018). However, like with poultry, **reintegrating sheep is not a panacea** (Franzluebbers and Hendrickson, 2024), as the environmental impacts are determined directly by any subsequent farming-practice changes. The study distinguished two ways to reintegrate sheep:

- (i) **without subsequent adaptations** of the cropping system, which considered that sheep replaced chemical or mechanized termination of cover crops (Hill and MacRae, 1996), consistent with results of previous studies (MacLaren et al., 2019; Niles et al., 2018; Paut et al., 2021). In these systems, the livestock-related increase in greenhouse gas emissions was kept small by **small flock sizes** or the **short-term presence** of sheep on the farm, which seemed sufficient to meet farmers' objectives of occasional termination of cover crops. In these four systems, however, sheep were reintegrated recently, and some farmers mentioned their intention to increase sheep presence over the next few years, which would **require additional adaptations of the cropping system** to promote carbon storage and compensate for increases in greenhouse gas emissions (Lazcano et al., 2022).
- (ii) with **subsequent adaptations** of the cropping system. Farmers' motivations included terminating cover crops, but also taking on technical challenges or aligning themselves with a sense of environmental stewardship (Meunier et al., 2024), which drove the subsequent adaptations. As these farmers reintegrated sheep earlier (on average) than others, they could also redesign their farming system progressively (Hill and MacRae, 1996; Sutherland et al., 2016) **to strengthen interactions between crops and livestock**. In addition to the decrease in energy consumption mentioned, these subsequent adaptations of the cropping system influenced the increase in nitrogen surplus at the farm gate, as reported by other studies which compared specialized crop and mixed crop-livestock farms (Mosnier et al., 2022; Ryschawy et al., 2012). Similarly, increased integration of pasture and fodder legumes in crop rotations helped mitigate livestock-related greenhouse gas emissions by increasing carbon storage (Franzluebbers et al., 2014; Hendrickson et al., 2008), which even led to more carbon being stored than emitted in a few systems.

Thus, reintegrating sheep onto specialized crop farms **should be promoted as a way to decrease their environmental impacts if the cropping system is subsequently adapted to maximize interactions between crops and livestock**. The decrease in fuel consumption allowed by grazing would be particularly beneficial in the current context of rising energy prices (EUROSTAT, 2023) and geopolitical

tensions around the use of non-renewable resources (Martin et al., 2023). Sheep grazing can also help improve crop performances (Cicek et al., 2014), due to the rapidly available nitrogen in manure and to decreased pest and disease pressure caused by animal trampling and consumption of pest (e.g. slug) eggs and disease inocula (Dairy Australia, 2019), and produce some human-edible protein on areas that do not compete directly for human food production (Baber et al., 2018; Hennessy, 2021)

## 5. Conclusions

The study highlighted that **the agroenvironmental impacts of reintegrating livestock depend strongly on whether and how farmers subsequently change their farming practices**. Environmental benefits (i.e. large decreases in energy consumption without increasing nitrogen surplus or greenhouse gas emissions) emerge only when livestock reintegration is accompanied by a redesign of the farming system to maximize interactions between crops and livestock. Thus, reintegrating livestock is **clearly not an assured pathway to sustainability**.

Several points can be emphasized to support scaling up of a sustainable way to reintegrate livestock. Expected benefits of livestock reintegration and the need to adapt the cropping system subsequently to maximize interactions between crops and livestock need to be communicated. Examples of trajectories towards sustainable livestock reintegration need to be documented to inspire and reassure farmers. Thus, researchers should continue to research livestock reintegration and estimate its impacts on crop-farm sustainability, especially by including socio-economic dimensions and monitoring farms over the long term. Public policies should support reintegrating livestock only when farming practices are changed systemically, such as by paying farmers to provide ecosystem services or offering insurance to farmers willing to participate but who are particularly averse to potential financial losses.

## 6. Acknowledgements

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## 7. Supplementary Material for chapter 3

**Table S1.** Impacts of reintegrating poultry (n = 5) or sheep (n = 10) on crop-farm nitrogen (N) surplus, energy consumption and greenhouse gas emissions, by variable. SD: standard deviation

Species	Type of system	Indicator	Indicator mean	Indicator SD	Variables per indicator	Type of variable and impact on the indicator	Variable mean	Variable SD	Mean effect of the variable on the indicator		
Poultry	All systems (n = 5)	Change in N surplus	43	± 32	Animals	Input (+)	0	± 0	0		
					Feed	Input (+)	100	± 88	+100		
					Fertilizer	Input (+)	-10	± 18	-10		
					Legume N fixation	Input (+)	-5	± 12	+5		
					Animal products	Output and Storage (-)	29	± 28	-29		
					Crops	Output and Storage (-)	-6	± 9	+6		
					Volatilization	Output and Storage (-)	16	± 14	-16		
					Pasture storage	Output and Storage (-)	3	± 2	-3		
		Change in energy consumption	+21 047	± 18 710	Electricity	Input, Direct energy consumption (+)	1456	± 1714	+1456		
					Fuel	Input, Direct energy consumption (+)	109	± 137	+109		
					Feed	Input, Indirect energy consumption (+)	19 953	± 17 867	+19 953		
					Fertilizers	Input, Indirect energy consumption (+)	-471	± 1052	-471		
		Change in (GHG emissions – carbon storage)	2	± 2.3	Carbon storage	Storage (-)	0.16	± 0.07	-0.16		
					Animals	Output, Gross emissions (+)	0.53	± 0.51	+0.53		
					Electricity	Output, Gross emissions (+)	0.01	± 0.01	+0.01		
					Feed	Output, Gross emissions (+)	2.07	± 1.91	+2.07		
					Fertilizers	Output, Gross emissions (+)	-0.05	± 0.1	-0.05		
					Mechanization, i.e. fuel combustion	Output, Gross emissions (+)	0.01	± 0.01	+0.01		
					Fertilizer spreading	Output, Gross emissions (+)	0.05	± 0.07	+0.05		
		Sheep	All systems (n = 10)	Change in N surplus	+2	± 9	Animals	Input (+)	2	± 5	+2
							Feed	Input (+)	3	± 11	+3
Fertilizer	Input (+)						-4	± 11	-4		
Legume N fixation	Input (+)						4	± 8	+4		
Animal products	Output and Storage (-)						3	± 9	-3		
Crops	Output and Storage (-)						-3	± 7	+3		
Pasture storage	Output and Storage (-)						2	± 4	-2		

				Volatilization	Output and Storage (-)	1	± 1	-1
	Change in energy consumption	-268	± 198	Electricity	Input, Direct energy consumption (+)	0	± 0	0
				Fuel	Input, Direct energy consumption (+)	-117	± 398	-117
				Feed	Input, Indirect energy consumption (+)	33	± 97	+33
				Fertilizers	Input, Indirect energy consumption (+)	-183	± 579	-183
	Change in (GHG emissions – carbon storage)	+0.02	± 0.08	Carbon storage	Storage (-)	0.06	± 0.1	-0.06
				Animals	Output, Gross emissions (+)	0.11	± 0.13	+0.11
				Electricity	Output, Gross emissions (+)	0.00	± 0	0
				Feed	Output, Gross emissions (+)	0.01	± 0.02	+0.01
				Fertilizers	Output, Gross emissions (+)	-0.02	± 0.06	-0.02
				Mechanization, i.e. fuel combustion	Output, Gross emissions (+)	-0.01	± 0.03	-0.01
	Fertilizer spreading	Output, Gross emissions (+)	0.00	± 0.02	+0			

**Table S2.** Impacts of reintegrating sheep with (n = 6) or without (n = 4) making subsequent adaptations on crop-farm nitrogen (N) surplus, energy consumption and greenhouse gas emissions, by variable.

Species	Type of system	Indicator	Indicator mean	Indicator SD	Variables per indicator	Type of variable and impact on the indicator	Variable mean	Variable SD	Mean effect of the variable on the indicator
Sheep	No subsequent adaptation (n = 4)	Change in N surplus	0	± 1	Animals	Input (+)	0	± 0	0
					Feed	Input (+)	0	± 0	0
					Fertilizer	Input (+)	0	± 0	0
					Legume N fixation	Input (+)	0	± 0	0
					Animal products	Output and Storage (-)	0	± 0	0
					Crops	Output and Storage (-)	0	± 0	0
					Volatilization	Output and Storage (-)	0	± 1	0
					Pasture storage	Output and Storage (-)	0	± 0	0
		Change in energy consumption	-206	± 150	Electricity	Input, Direct energy consumption (+)	0	± 0	+0
					Fuel	Input, Direct energy consumption (+)	-209	± 151	-209
					Feed	Input, Indirect energy consumption (+)	3	± 7	+3
					Fertilizers	Input, Indirect energy consumption (+)	0	± 0	+0
		Change in (GHG emissions – carbon storage)	0	± 0.08	Carbon storage	Storage (-)	0.00	± 0	+0
					Animals	Output, Gross emissions (+)	0.06	± 0.07	+0.06
	Electricity				Output, Gross emissions (+)	0.00	± 0	0	
	Feed				Output, Gross emissions (+)	0.00	± 0	0	
	Fertilizers				Output, Gross emissions (+)	0.00	± 0	0	
	Mechanization, i.e. fuel combustion				Output, Gross emissions (+)	-0.01	± 0.01	-0.01	
	Fertilizer spreading	Output, Gross emissions (+)	0.00	± 0	0				
	Adaptation (n=6)	Change in N surplus	4	± 11	Animals	Input (+)	3	± 7	+3
					Feed	Input (+)	6	± 14	+6
					Fertilizer	Input (+)	-7	± 13	-7
					Legume N fixation	Input (+)	7	± 9	+7
					Animal products	Output and Storage (-)	5	± 12	-5
					Crops	Output and Storage (-)	-4	± 8	+4
					Volatilization	Output and Storage (-)	1	± 1	-1
					Pasture storage	Output and Storage (-)	3	± 6	-3
Change in energy consumption		-309	± 228	Electricity	Input, Direct energy consumption (+)	0	± 0	0	
				Fuel	Input, Direct energy consumption (+)	-56	± 510	-56	
				Feed	Input, Indirect energy consumption (+)	52	± 125	+52	
				Fertilizers	Input, Indirect energy consumption (+)	-305	± 748	-305	
		0.00	± 0.08	Carbon storage	Storage (-)	0.10	± 0.12	-0.1	



		Change in (GHG emissions – carbon storage)			Animals	Output, Gross emissions (+)	0.14	± 0.16	+0.14
					Electricity	Output, Gross emissions (+)	0.00	± 0	0
					Feed	Output, Gross emissions (+)	0.01	± 0.02	+0.01
					Fertilizers	Output, Gross emissions (+)	-0.03	± 0.07	-0.03
					Mechanization	Output, Gross emissions (+)	-0.01	± 0.03	-0.01
					Spreading	Output, Gross emissions (+)	0.00	± 0.02	0
					Feed	Input, Indirect energy consumption (+)	3	± 7	+3
					Fertilizers	Input, Indirect energy consumption (+)	0	± 0	+0

## Conclusion of chapter 3

In chapter 3, I contributed to produce knowledge on livestock reintegration through characterizing **changes in farming practices after reintegrating livestock and assessing their agroenvironmental impacts** (Figure 35). I found that the changes in farming practices after livestock reintegration are **very diverse**, and lead to **diverse agroenvironmental impacts**. **Livestock reintegration can improve crop farm sustainability, only if it goes along with subsequent adaptations of the farming system.**

I contributed to improve the innovation-tracking framework by combining it with **a multicriteria assessment method to objectively assess an innovation, in regard of farmers' motivations to implement it**. Such method could be applied to other agroecological innovations with marginal adjustments in the chosen indicators

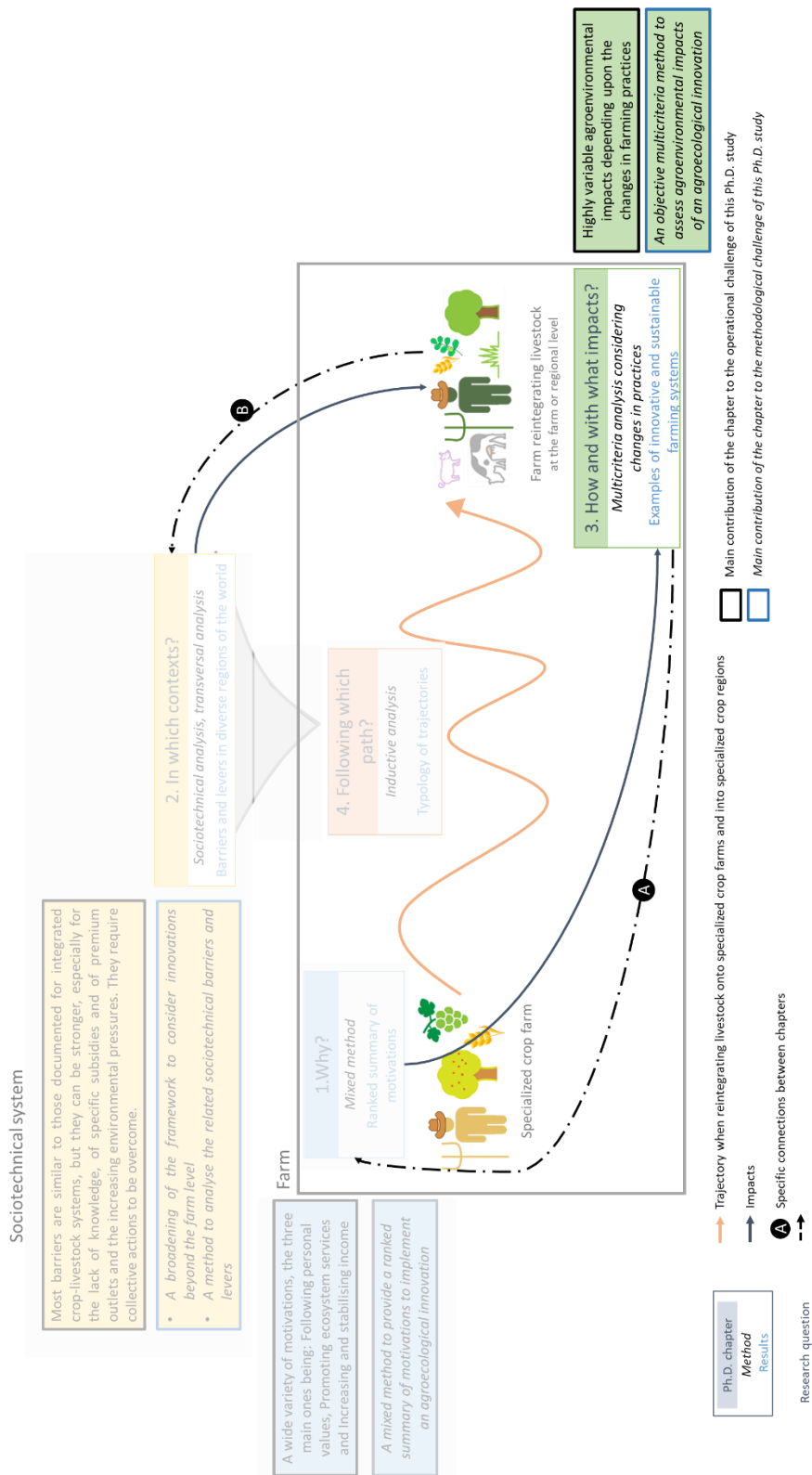


Figure 35 : Positioning Ph.D. work chapters along the journey followed by farmers toward reintegrating livestock onto specialized crop farms and into specialized crop regions: main results of Chapter 3 on changes in farming practices and related agroenvironmental impacts. Operational challenge of this Ph.D. study: producing knowledge on why, in which contexts, how and with what impacts farmers reintegrate livestock into specialized crop farms and regions. Methodological challenge of this Ph.D. study: improving the innovation-tracking framework by studying at multiple levels the determinants that lead to agroecological innovations and assessing their performances objectively.



## Episode 3: A lasting collaboration that leads to deep changes in farming practices

With Marie, we have been collaborating for 3 years now. And everything is going perfectly well. As our partnership was lasting, this year, I made a few adjustments. I adjusted a little the mix I sow in my cover crops. I included more vetch, as she said it was better for ewes, and it's, true they like it better. I also put some clover, as she asked me... and, well, legumes can't make any bad on my soils ! I am waiting to see what it does on my crops. On top of that, I stopped cropping the hills, I returned to something close to what my grandfather did in a way. I left hills go back to natural pasture. I was not making any money out of them anyway, it was rather the opposite, to be honest. So, now, the ewes can graze there as well. Marie is happy, because she says she will be able to bring more sheep next year, and stay longer over the spring. It could also be a safe place to stay for the sheep when it rains too much. This way, they do not trample my crop fields. I did not reduce the amount of organic manure I buy for now. I rather see the sheep manure as a bonus. And, it is not that much... I think. However, the sheep, they did make a difference in the time I spend to manage the cover crop ! I save 2 or 3 cuts in the year. It saves time, but also fuel and money !

Actually, to be honest, with Marie, we had a small argument in the beginning, the first year. Yes, because, a fence fell down, so some of her sheep escaped to my neighbour's field, and grazed the wheat he had sown a few weeks before ! And, as Marie had left for the weekend, I had terrible trouble in bringing her sheep back to my farm. She was not even here to help. I was quite upset, it's true... So I told her it could not happen again! But well, it never did. Now, when she leaves for the weekend, she asks one of her colleagues to replace her in case of problem.

Lately, I have been rethinking about this incident. And actually, his wheat had never grown that well ! So, I am wondering whether I could use sheep to graze my wheat at early stages. I have heard that, in Scotland, all farmers do it, it's up-to-date ! And, the Scottish, they do know much about grazing ! So, yes, this is my new idea, maybe you are going to think "this one, he is really a weirdo", and I have not talked about it to my wife yet. But, if I do not try, I will never know !









Chapter 4: Trajectories followed by farmers when reintegrating livestock onto specialized crop farms and into specialized crop regions, and changes in researchers' stances and practices needed to study them

## Preface of Chapter 4

*Once farmers have reintegrated livestock, reflexive analysis of the trajectory that led them to this current state of the system may help them envision its evolution.*

Livestock reintegration is a **process of change**, and it thus includes an intrinsically **dynamic dimension**. In the first three chapters of my Ph.D. study, I relied on a static approach to characterize farmers' motivations and sociotechnical barriers and on a comparison between snapshots to characterize changes in practices and their agroenvironmental impacts. This approach could be completed by **analysing livestock reintegration over time**, i.e. identifying how farmers' motivations and sociotechnical contexts evolved progressively, how they combined with emerging opportunities, with farmers' resources and observations of the effects of their changes in practices, to progressively lead them, through common steps, to reintegrate livestock (Chantre et al., 2015; Coquil et al., 2014; Revoyron et al., 2022).

Thus, in chapter 4, I aimed at studying the **trajectories** followed by farmers when reintegrating livestock (Figure 36, Box 6). I tried addressing my fourth research question: **What trajectories do farmers follow when reintegrating livestock into specialized crop farms and regions?**

Most published works on innovation-tracking initiatives adopted a static approach, and overlooked farmers' trajectories toward implementing an agroecological innovation. The innovation-tracking framework could be improved by **methods to study in depth such trajectories** (Box 7).

Studying the trajectories followed by farmers when reintegrating livestock would allow supporting the scaling up of livestock reintegration, e.g. through **promoting previous steps in the process of change**.

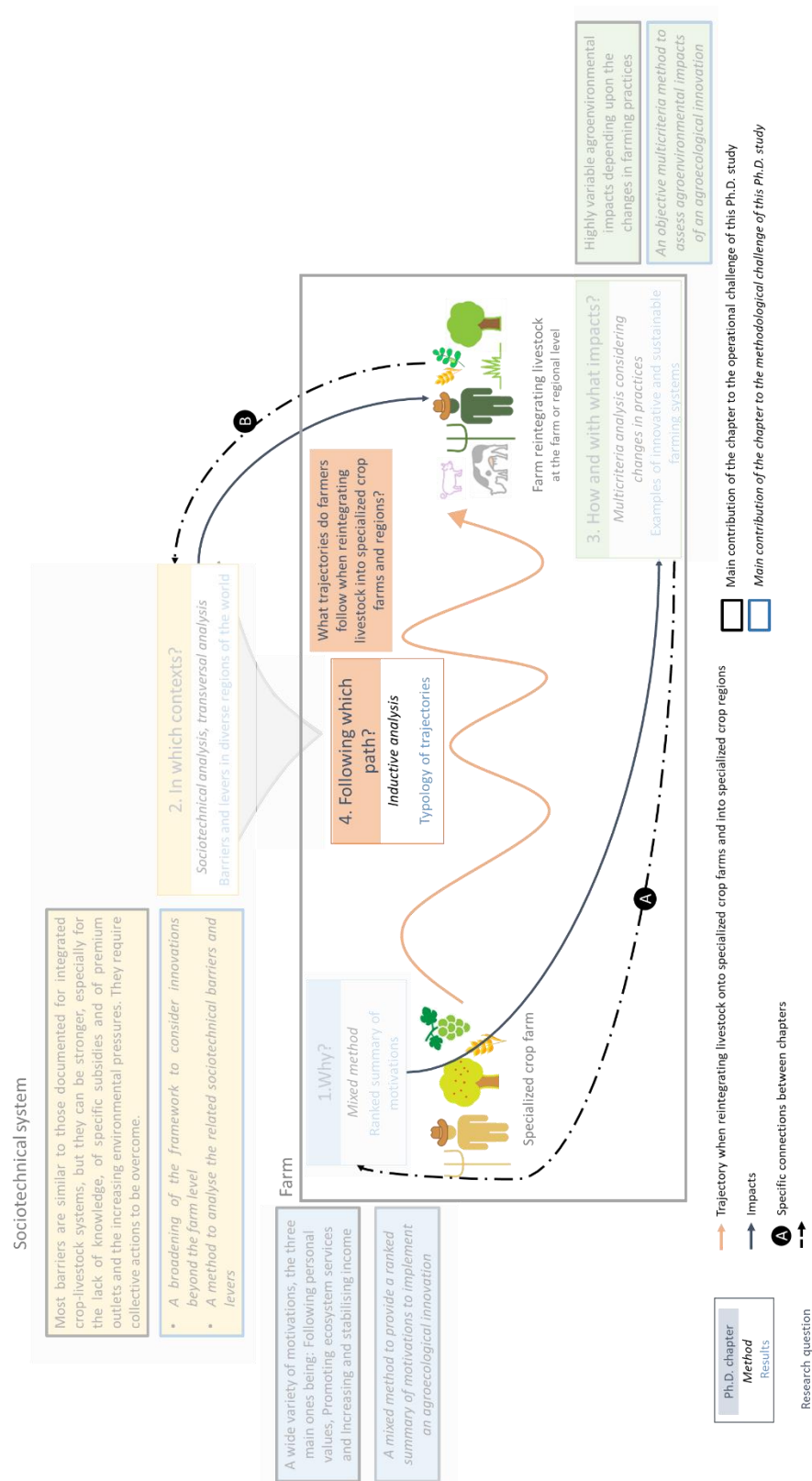


Figure 36 : Positioning Ph.D. work chapters along the journey followed by farmers toward reintegrating livestock onto specialized crop farms and into specialized crop regions: main initial focus of Chapter 4 on farmers' trajectories. Operational challenge of this Ph.D. study: producing knowledge on why, in which contexts, how and with what impacts farmers reintegrate livestock into specialized crop farms and regions. Methodological challenge of this Ph.D. study: improving the innovation-tracking framework by studying at multiple levels the determinants that lead to agroecological innovations and assessing their performances objectively.

## 0.1. Before we start - Some words from the author

*If this Ph.D. study had followed a linear and predetermined path, you would have here found a research paper, in which I would have provided a typology of trajectories followed by farmers towards reintegrating livestock. As always when studying agroecological innovations such as livestock reintegration, this Ph.D. study was full of surprises. Instead of the expected research paper providing a typology of farmers' trajectories toward reintegrating livestock, you will thus find in the next few pages the story of how I failed at fulfilling my initial ambition, and how I converted this failure into an emerging opportunity to reflect more broadly on my research stance and practices.*

*In the next section, I thus very briefly describe the method I used to collect and analyse the data on farmers' trajectories toward reintegrating livestock. I then elaborate a little more on the results I derived from this analysis, to justify why they did not allow addressing my objective.*

## 0.2. Brief overview of the method used to study farmers' trajectories

In this chapter, I aimed at **providing a typology of trajectories** followed by farmers when reintegrating livestock. To do so, I relied on the same data used in chapter 1, i.e. the transcriptions of semi-structured interviews led with 18 French farmers having reintegrated livestock in a wide diversity of farming systems. Precise description of my sample and methods for data collection can be found in Chapter 1, sections 2.1-2.3. The farmer identification codes I use below are the same as the ones used in Chapter 1. During the interview, farmers were asked about the **main events in farm history** that led, more or less directly, to livestock reintegration. This is what allowed me **reconstructing their trajectories**.

In line with Chantre et al. (2015), I **delineated successions of coherence phases**, i.e. periods during which the farming system is considered as stable, leading to reintegrating livestock, and identified the main events triggering the passage from one phase to the other. As in Gosnell et al. (2019), I also identified **“zones of friction and traction”**, i.e. factors that facilitated or hindered the passage from one phase to the other, more or less directly. I divided these factors into three main categories, adapted from the three spheres of transformation defined by Gosnell et al. (2019): i) the “personal sphere”, happening at the farmer level, and corresponding to his/her motivations ; ii) the “practical sphere”, happening at the farm level and encompassing agroenvironmental, economic and social dimensions ; iii) the “political sphere”, encompassing all broader changes like climate change, policies recommendations, and mostly corresponding to the elements included in the landscape level in the Multi-Level Perspective used in Chapter 2 (Geels, 2004).

I **compared the 18 trajectories** followed by farmers toward reintegrating livestock, and **characterized their similarities** regarding the coherence phases occurring before reintegrating livestock and the events that triggered, facilitated or hindered the switch from one phase to the other.

## 0.3. The story of how my results did not allow me to address my objective

Trajectories followed by farmers when reintegrating livestock were **very diverse**, to the point they were **almost all unique**. To illustrate these differences, I present **examples of the main diverging**

**points**, and provide three examples of trajectories on Figure 37, Figure 38, and Figure 39. On those figures, trajectories followed by farmers have been much simplified to make them easily readable. They all represent cases of sheep reintegration in full-time outdoor systems, in organic farming and within the Occitanie region, to emphasize that even when reintegrating the same type of livestock system in the same type of farming system and in the same region, very diverse trajectories can be followed by farmers.

### 0.3.1. Common coherence phases for farms reintegrating livestock?

#### *0.3.1.1. Organic cropping: a previous coherence phase to reintegrating livestock?*

Most of my sample farmers having reintegrated livestock practiced **organic agriculture** at the time of the interview (15/18 being either certified organic or in conversion), consistently with results from chapter 2, in which I found that livestock reintegration and organic farming were two niches that have close connections. However, reintegrating livestock **also happened on conventional farms** (F11, F16, F14). Moreover, the **order of events and time lags** between converting to organic farming and reintegrating livestock **varied a lot**.

Fourteen out of 15 farmers interviewed **first converted to organic farming, and then reintegrated livestock**. Among those farmers, some **reintegrated livestock several years after having converted their specialized crop farms to organic**. The **delay** between conversion to organic cropping and livestock reintegration could be quite **short** (e.g. 3 years for F13, 4 years for F5) or much **longer** (e.g. 26 years for F3, 44 years for F9) (Figure 38, Figure 39). Reintegrating livestock was **seen as a solution** to the observed **decrease in soil fertility** and/or **increased weed pressure** resulting from several years of organic specialized crop production with low levels of inputs and limited soil tillage (e.g. F5, F13). This acknowledgement occurred with more or less delay regarding the initial state of the farming system, in particular the state of the soil before converting to organic cropping. For these farmers, livestock reintegration was thus a **more or less direct or differed consequence of the organic conversion**.

Some farmers **reintegrated livestock concomitantly with converting their farm to organic**. In some cases, reintegrating livestock and converting to organic farming were **the two main parts of a transformation of the farming system**, as farmers just took over the farm, and wanted to implement changes to make the farming system match their personal motivations rapidly (e.g. F12, F17). In other cases, **reintegrating livestock was necessary to design an organic farming system that kept alignment with farmers' motivations**. For instance, F4 previously managed his orchard with limited soil tillage, to match his values of environmental stewardship. When his son settled on the farm and wanted to convert to organic farming, reintegrating grazing sheep to manage grass and weeds in the orchard allowed combining an organic farming system with limited soil tillage. In other cases, **converting to organic farming and reintegrating livestock happened concomitantly but "by chance"**, as the farmer had planned to do both for a few years, and finally managed to meet with a shepherd to create a partnership on the year he converted to organic (e.g. F1).

One farmer in the sample (F18) **converted to organic farming after having reintegrated livestock**, as he saw organic labelling as a way to ease market penetration for his premium livestock products, along with developing his own brand.

Hence, even if organic farming was often associated to reintegrating livestock, **no clear pattern could be found** on the role of organic cropping towards reintegrating livestock.

#### *0.3.1.2. Reintegrating livestock at the regional level, a step before reintegrating livestock at the farm level?*

My sample farmers had reintegrated livestock at the farm level (12), at the regional level (3) or both (3). Reintegrating livestock at the regional level can contribute to addressing some of the sociotechnical barriers to reintegrating livestock, especially regarding farmers' lack of knowledge, outlet for livestock products or equipment (see Chapter 2). **I analysed the extent to which reintegrating livestock at the regional level could be a “first step” for farmers to familiarize with livestock production**, before buying their own animals. This hypothesis was reinforced by a longer average duration since livestock was reintegrated on farms having reintegrated livestock at the farm level ( $7 \pm 6$  years) compared to farms having reintegrated livestock at the regional level ( $3 \pm 2$  years). The reality was yet **not that simple**.

First, **reintegrating livestock at the farm level was sometimes the only choice**. It was the case for **some livestock enterprises**, such as highly-integrated laying hen or broiler production (e.g. F8, F9, F10, F11, F17), or pig fattening (F18). It was also the case **in the Parisian Basin**, where farmers could not find any livestock farmer they could partner with in their region. When livestock could be reintegrated at the farm and/or regional level, i.e. for cases of sheep reintegration in Occitanie (7 farmers), **diverse combinations and order of events were found between reintegrating livestock at the farm and/or regional level**.

F5 **reintegrated sheep at the farm level without having looked for any partnership before** (Figure 39). In this case, the farmer received subsequent help from members of his family who were livestock farmers, and saw partnering with someone else as a constraint rather than as an opportunity given his particular situation.

F2 and F3 **first considered reintegrating livestock at the regional level**, but difficulties in identifying an interested livestock farmer and in finding the right livestock farmer to maintain partnership in the long term led them **to combine reintegrating livestock at the farm and regional level** (Figure 38). They went on trying to find the right partner, and finally bought some sheep to ensure benefiting from the related agroenvironmental advantages throughout the year and regardless potential conflicts that may occur with their partner. For F2 and F3, **reintegrating livestock at the farm level can be seen as a consequence of failures** when trying to reintegrate livestock at the regional level. F1 never experienced particular difficulties in his partnership, and kept up with livestock reintegration at the regional level. He mentioned he may, one day, reintegrate sheep on the farm as well to benefit from

sheep grazing yearlong, but would not stop his partnership, from which he was fully satisfied. In his case, reintegrating livestock at the farm level could be seen as **a continuation of reintegrating livestock at the regional level.**

F4 and F7 never considered reintegrating sheep at the farm level, and said they never would. F4 experienced the same difficulties as F2 and F3, but kept looking for the right partner during more than 6 years, as he felt he did not have the desire nor the capacity to manage sheep himself. F7 never really had particular will to have animals on his farm, and rather partnered with a livestock farmer to benefit from specific CAP subsidies. In both cases, **reintegrating livestock at the regional level was not a step toward reintegrating livestock at the farm level.**

Finally, F6 first reintegrated pigs at the farm level, before stopping because it was not consistent with his values regarding potential feed-food competition. A few years after, he reintegrated sheep through a partnership, for which he bought part of the animals to ease the settling of the shepherd (Figure 37). Again a few years after, a conflict ended this partnership, and the farmer was left with the sheep he had bought. He first hired someone to manage the livestock, and when the hired shepherd left, he eventually ended up managing the sheep himself. As he did not have sufficient feed for the animals on his farm, he partnered with specialized crop farmers from his neighbourhood, and contributed to make them reintegrate livestock at the regional level. In this case, **reintegrating livestock at the farm level was somehow an unintended follow-up of having reintegrated livestock at the regional level.**

Here again, **no clear pattern could be identified** on the role of reintegrating livestock at the regional level towards reintegrating livestock at the farm level.

### 0.3.2. Similar trigger events and related adaptations of the farming system when reintegrating livestock?

Changes in the farming system were **triggered by an economic crisis** on eight out of my 18 sample farms. This crisis led **either to conversion to organic farming** (e.g. F2, F7, F8, F15) (Figure 38) or **to reintegrating livestock**, for farms that were already certified organic (e.g. F6) or for farms that remained conventional (e.g. F11, F14, F18). For the 10 remaining farms, reintegrating livestock was **not directly linked to an economic crisis.**

Similarly, **modifications in the farm workers** often triggered changes in the farming system. Farmer establishment or settlement of their son or wife either led to convert to organic farming (e.g. F1, F4, F5) (Figure 39) or to reintegrating livestock (e.g. F8, F9, F17). An encounter with a key person, such as an interested shepherd or a technician from a cooperative of highly-integrated poultry production could as well trigger livestock reintegration (e.g. F2, F6, F7, F9) (Figure 37, Figure 38). Here again, **for some farms, no such event happened** (e.g. F13).

On some farms, it was sometimes **hard to identify the event that triggered livestock reintegration**, which rather seemed to emerge from the reassembling of some elements that were already there (Figure 39).

Thus, **diverse events** contributed to **trigger** direct or indirect **changes toward reintegrating livestock**, and **farmers had different reactions** to similar events. This diversity made it **difficult to identify similar trigger events** in the trajectories leading farmers to reintegrate livestock.



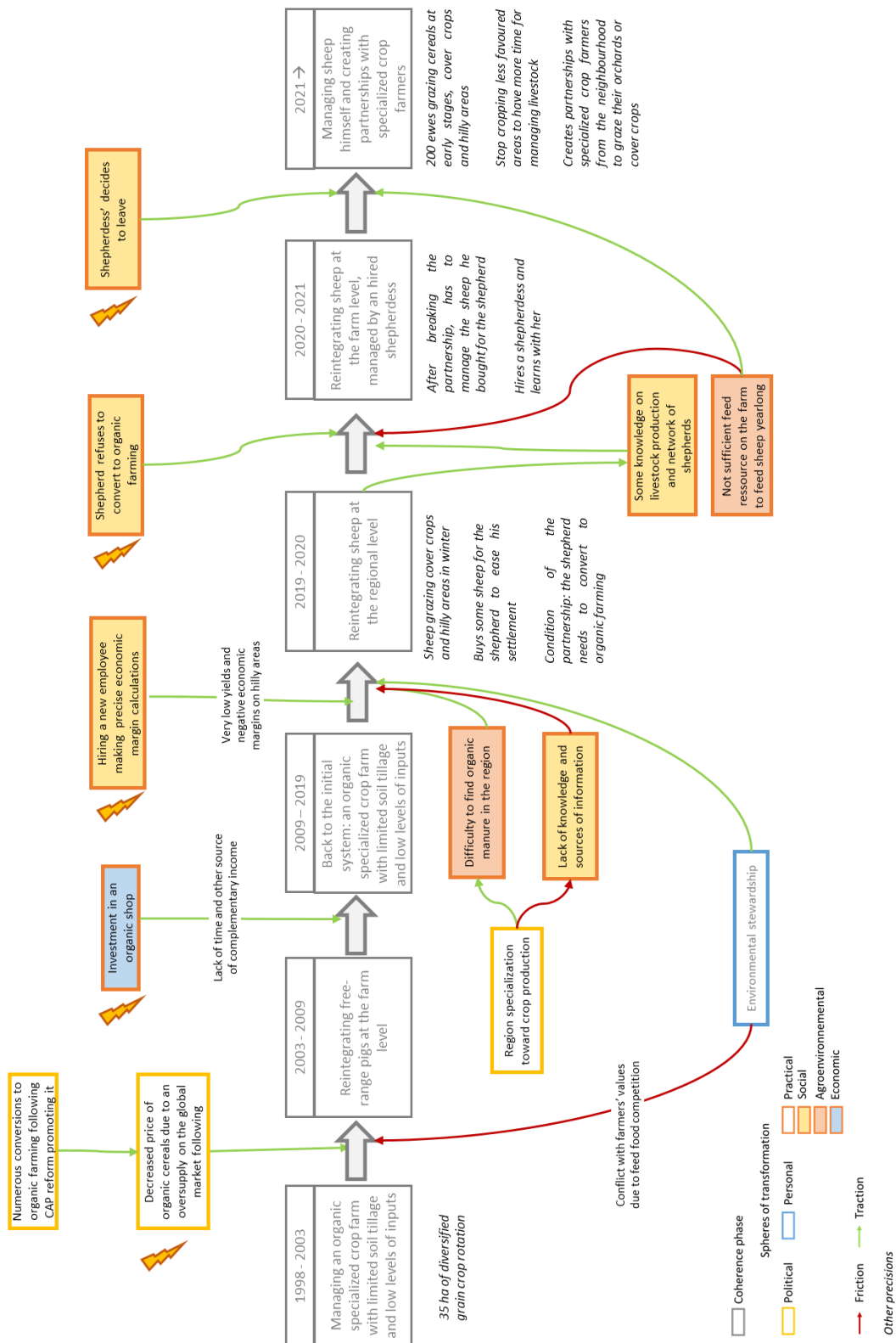


Figure 37 : Example of the trajectory followed by the farmer F6 when reintegrating livestock

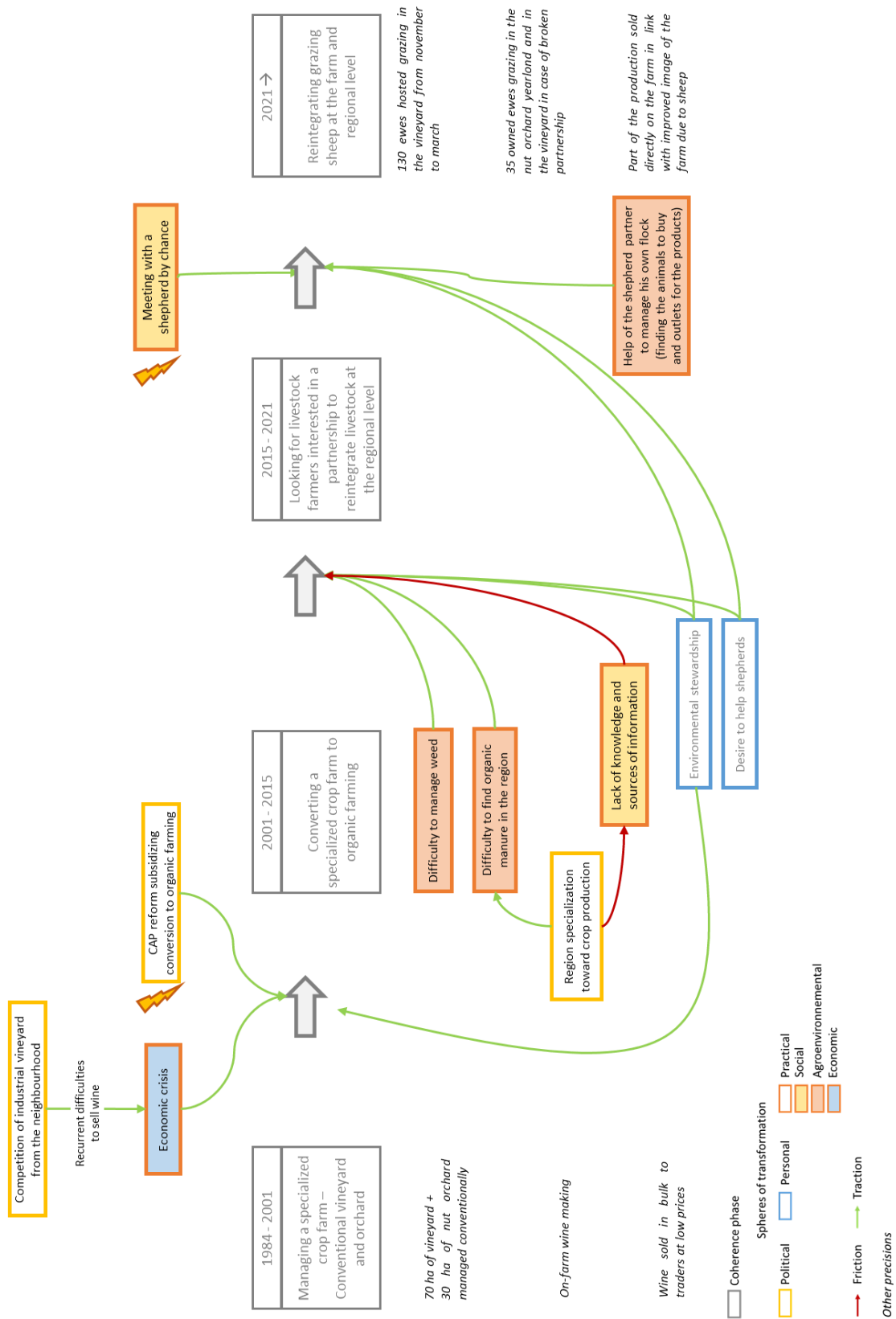


Figure 38 : Example of the trajectory followed by the farmer F2 when reintegrating livestock

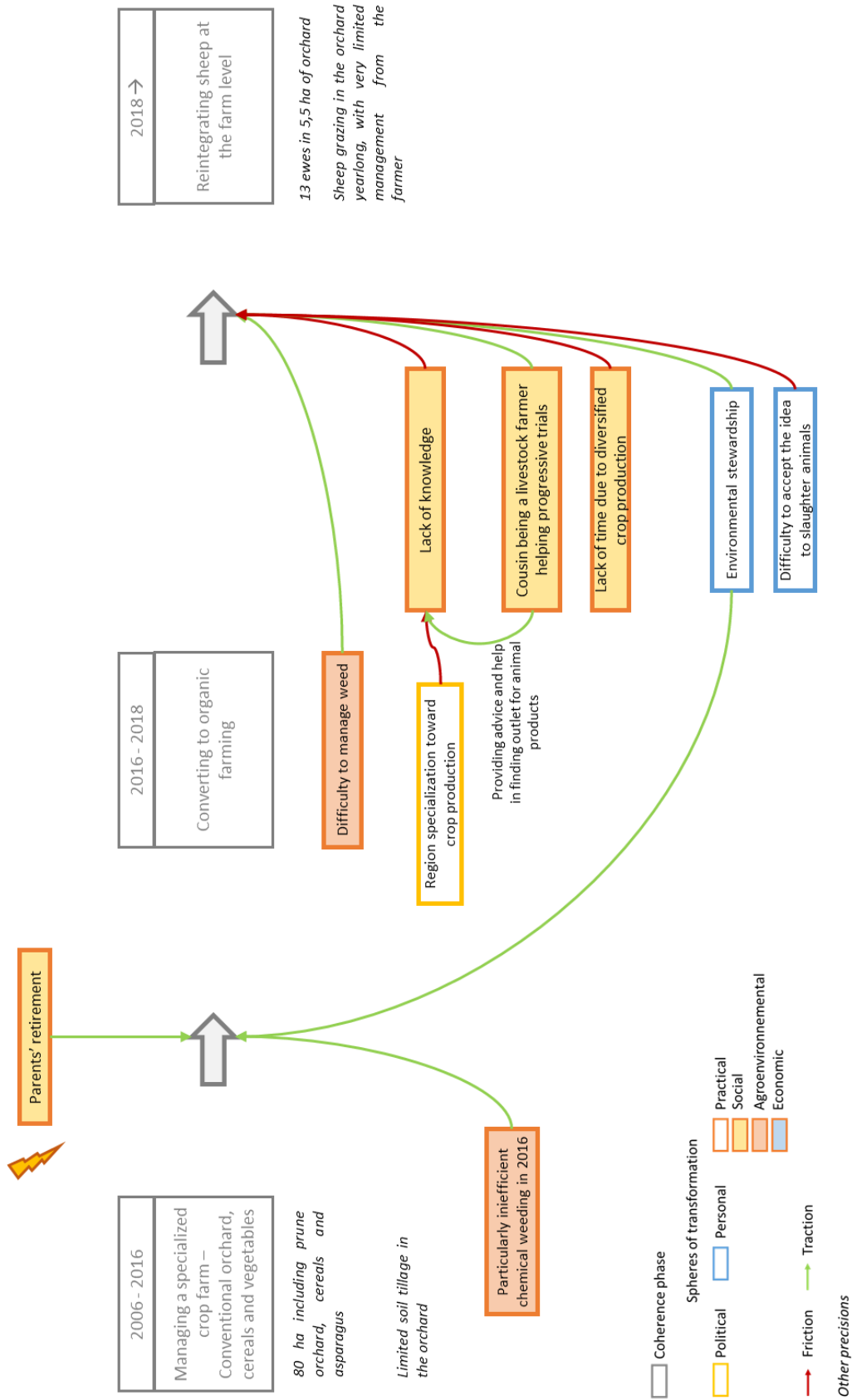


Figure 39 : Example of the trajectory followed by the farmer F5 when reintegrating livestock

#### 0.4. From an initial failure, to the idea of something else

As illustrated through three focus points in the above section, **trajectories followed by farmers when reintegrating livestock were all singular**. Maybe a typology could have been derived from their study, with the appropriate simplifications. However, **forcing such diverse data into a typology would have needed overshadowing a significant part of the complexity of these trajectories**, to the point it made me wonder **how faithfully they would still have retraced farmers' stories**. Addressing this question requires defining the key elements to capture the essence of trajectories followed by farmers toward reintegrating livestock. And this definition, this delineation of what to include or not in the analysis (e.g. what place give to uncertainty and unexpected events?), results from **our choices as researchers**. Confronted to this acknowledgement, I decided to **convert my failure** in building a typology of trajectories followed by farmers to reintegrate livestock **into an opportunity to reflect on my stance and practices as a researcher**.

Thus, in chapter 4, I invite agricultural scientists to **reflect on the worldviews underlying our research stances and practices, and on their impacts on our research results** (Figure 40). I address the second (emerging) part of my fourth research question: **What changes in researchers' stances and practices are needed to analyse these trajectories?**

*This chapter takes the form of a researcher paper, for which revisions were requested by Agroecology and Sustainable Food Systems in September 2024.*

Meunier, C., Darnhofer, I., Martin, G. (n.d.). A call for change: Contributing to a transition to agroecology requires questioning our assumptions.

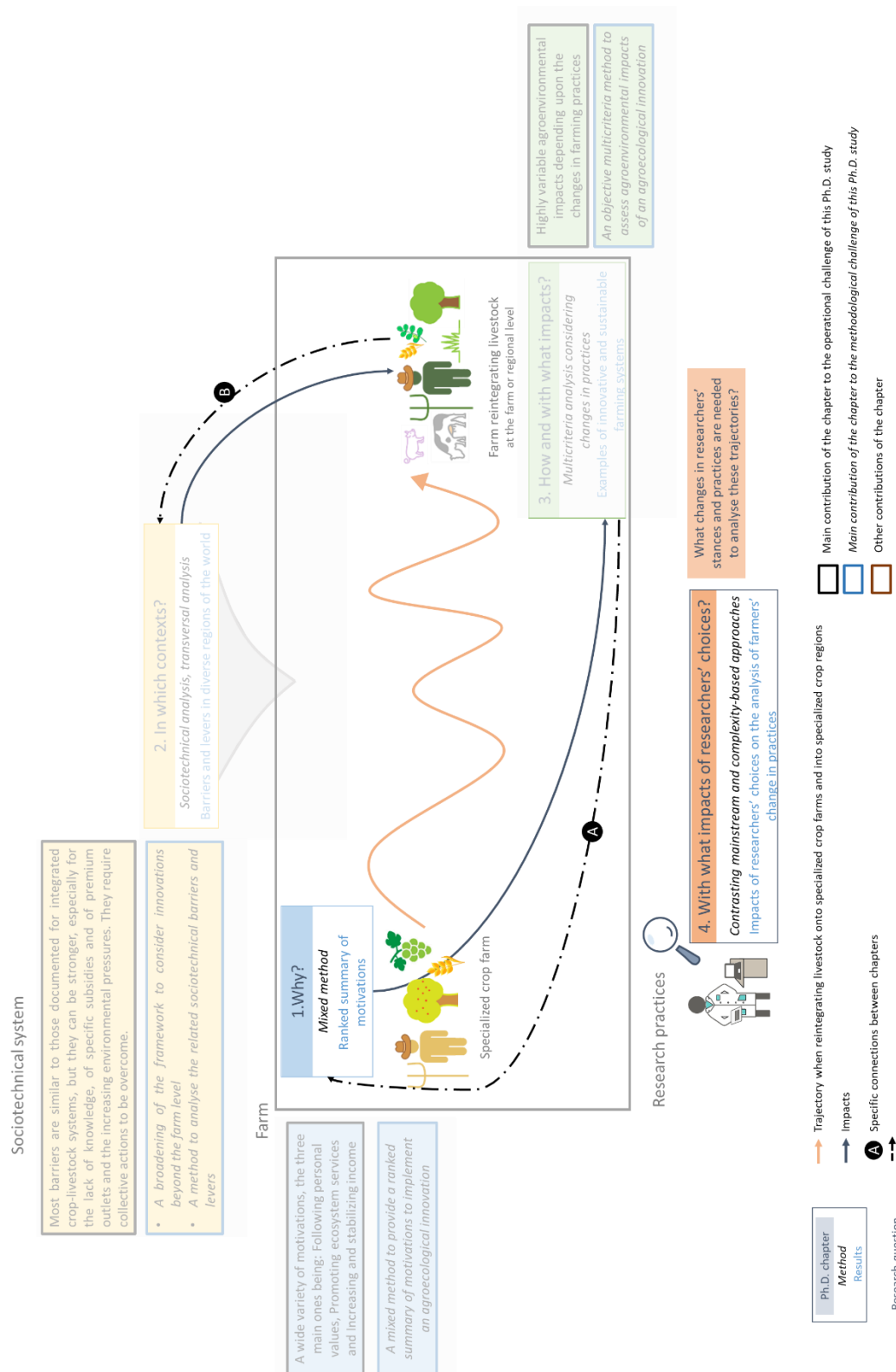


Figure 40 : Positioning Ph.D. work chapters along the journey followed by farmers toward reintegrating livestock onto specialized crop farms and into specialized crop regions: main actual focus of Chapter 4 on researchers' stances and practices. Operational challenge of this Ph.D. study: producing knowledge on why, in which contexts, how and with what impacts farmers reintegrate livestock into specialized crop farms and regions. Methodological challenge of this Ph.D. study: improving the innovation-tracking framework by studying at multiple levels the determinants that lead to agroecological innovations and assessing their performances objectively.

# A call for change: Contributing to a transition to agroecology requires questioning our assumptions

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## Abstract

We invite agricultural scientists aiming at contributing to a transition to agroecology to revisit their foundational assumptions and question norms guiding their stances and choices. We contrast two archetypal worldviews: a mainstream deterministic worldview emphasizing predictable stable states and planned adaptations carefully made by economically rational farmers to maximise income; and a complexity worldview embracing on-going changes and permanent adaptations made by farmers when creatively use emerging opportunities. To highlight the implications of implicit assumptions underlying agricultural scientists’ worldviews, we contrast two analyses of a farmer’s trajectory as he implemented agroecological production practices (Figure 41).

## Graphical abstract

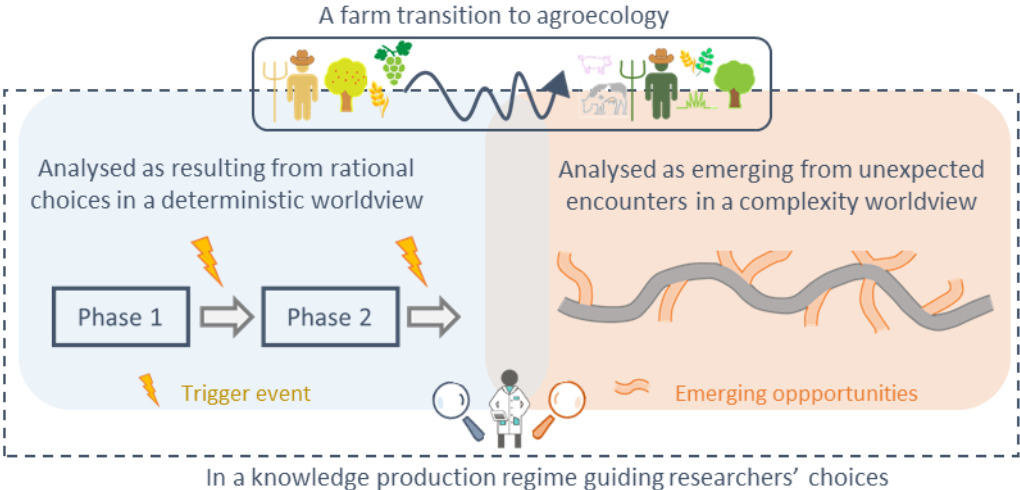


Figure 41 : Graphical abstract for Chapter 4 on the impact of researchers’ stances and practices on their research results

## Keywords

## 1. Introduction

**Things need to change!** This call is ubiquitous given the mounting scientific evidence that our western agrifood system **does not meet the responsible consumption and production development goal** (IAASTD, 2009; IPES-Food, 2016; McGreevy et al., 2022; Willett et al., 2019). Six out of the nine planetary boundaries have now been transgressed (Richardson et al., 2023; Steffen et al., 2015). Specialized input-intensive agricultural production systems are important drivers, contributing to biodiversity loss, the perturbation of biogeochemical flows (notably nitrogen and phosphorus), fresh water use, land system change and thereby climate change (Campbell et al., 2017). To mitigate these environmental impacts, a **transition to agroecology**– implying, according to the FAO, striving towards diversifying, reducing external inputs and closing nutrient cycles (FAO, 2018), e.g. by reintegrating livestock on crop farms – has been advocated by a number of researchers (Altieri, 1989; Gliessman, 2020; Levidow et al., 2014; Pimbert, 2015; Prost et al., 2023).

Numerous definitions have been proposed for the word ‘agroecology’, ranging from the implementation of ecological principles and sustainable practices at the farm level (Altieri, 1995) to including ‘all aspects and participants in the food system’ so as to build equitable, just and accessible market systems (Francis et al., 2003), as documented by Gliessman (2018). In most of them, **agricultural sciences** are understood as **playing a key role in identifying pathways to transition to agroecology** and **developing recommendations to guide farmers** in this process of change. Transitioning to agroecology implies going beyond improving practices efficiency or substitution, and requires redesigning the entire farming system (Hill and MacRae, 1996). It is then unclear if **mainstream research in agricultural sciences**, which has primarily developed to **propose standardized technical solutions**, often derived from **highly-controlled experiments** and **sophisticated mathematical models**, is **suited** to understanding and guiding farmers’ change of practices in the context of **transformative changes** called for by agroecology. Experiments and models often take a static-comparative approach, assessing the differences in various variables before and after a change has been introduced. This gives limited insights on the adaptation process itself, i.e. what **set of conditions or events lead farmers to introduce new practices** on their farm, which over time may redirect its **trajectory**. Yet, a better understanding of farm trajectories is crucial to understand how and why farmers transition towards agroecology (Chantre et al., 2015; Coquil et al., 2014; Revoyron et al., 2022), thus contributing to a more sustainable agrifood system.

The questions of ‘how’ and ‘why’ might seem straight forward, but we argue that the answers depend on the **assumptions and concepts that we, researchers, use** when designing our studies, when collecting and analysing data. Indeed: numerous choices need to be made, as researchers can never include ‘everything’ (Hazard et al., 2020). The crucial question then is: how do worldviews and concepts guide these choices?

In this article, we **invite agricultural scientists to revisit the foundational assumptions regarding how farmers make choices when transitioning to agroecology**, which are closely tied to how scientists conceptualize farmers and the world more broadly. To do so, we **contrast the assumptions** which tend to underlie most of **mainstream agricultural research** with assumptions that tend to be rooted in a **complexity worldview**. We illustrate the differences between these two worldviews and the insights they offer, by analysing the same empirical data from an interview with a farmer who retells the trajectory of his vineyard, as he steered it towards more agroecological practices, including the reintegration of livestock. We conclude by highlighting the implications for research, if it aims to effectively contribute to a transition to agroecology.

To make our point more clearly and support what might be the readers' first steps in reflecting on their research assumptions, in the next sections, we present these two worldviews in a somehow archetypal manner. We are well aware that it does not adequately represent the diversity of positions existing within each worldview, nor the overlap between them. Here, we do not aim at describing in details the diversity of assumptions underlying research in agricultural sciences, nor at claiming that some are to be favoured compared to others. Instead, we build on two extreme positions within this continuous range of assumptions to highlight through a clear contrast the extent to which diverse and often implicit assumptions lead to diverse analyses.

## 2. Assumptions underlying a deterministic worldview

### 2.1. Agricultural sciences: striving to control production conditions

In the early modern period, agricultural researchers focused on improving crop and animal productivity through the identification of locally-relevant practices suited to farmers' specific needs (Catalogna, 2018; Jouve, 2007; Salembier et al., 2018). From the 19<sup>th</sup> century onwards, thanks to a rapidly improving knowledge of biological and chemical processes, agricultural scientists aspired to **produce scientific explanations** of why and how phenomena occur. To comply with **norms of scientific rigour**, explanations had to **adhere to one of the two main models** (Woodward and Ross, 2021). The first is the **deductive-nomological model**, where a sound argument relates the outcome to a law of nature. For example, the outcome 'crop yield' is explained using Liebig's 'law of the minimum', which posits that if one of the essential plant nutrient is deficient, plant growth will be limited. The second is the **statistical relevance model**, which proposes that statistically relevant relationships among variables are explanatory (Woodward and Ross, 2021). For example, if crop yield increases significantly with nitrogen uptake, then the level of nitrogen supply explains crop yield. Beyond satisfying scientific curiosity, such **deterministic causal explanations** provide information that allow for **prediction** and thus **control** of crop and animal production.

To enable the identification of **causal connections**, the number of influencing variables in a trial has to be reduced, which led to the **reductionist deductive experimental paradigm**. Data collection shifted



**from farmers' fields to research stations and laboratories**, which allowed for **better-controlled environments** and experimental designs facilitating **statistical analysis**. This scientific rigour enabled the establishment of **cause-effect relationships** between input and output variables, from which standardized recommendations were derived (Jones et al., 2017; Keating and Thorburn, 2018). The aim of the recommendations was for **farmers to faithfully reproduce the environment of the research station on their farms**. This implied controlling the production conditions: higher yields were enabled by using genetically improved seeds, ensuring high-levels of nutrient supplies provided by synthetic fertilizers and using pesticides and herbicides (Cohen, 2017). This logic **underpinned the 'green revolution' in the late 1960s**, a period of strong crop productivity growth, allowing to feed a rapidly rising global population, with limited increase in cultivated land area (Pingali, 2012). This success of standardization and control, and of the underlying models, made it the mainstream in modern agricultural sciences. This logic also drives the on-going 'fourth agricultural revolution' (Javaid et al., 2022; Rose et al., 2023), characterized by digitalization, precision technology, robotics, and genomics, and relying heavily on the use of statistics to analyse large datasets.

Given its empirical success, little thought is given to the **limitations of the models** used to assert what constitutes a sound scientific explanation. The deductive-nomological model builds on laws of nature, which are seen as deterministic. However, in **the life sciences** – as opposed to the physical sciences – there **appears to be few such laws**: biology, psychology, and economics are full of generalizations that appear to play an explanatory role, yet fail to satisfy many of the standard criteria for 'laws' (Woodward and Ross, 2021). The statistical relevance model also has limitations, e.g. the focus on events of high probability **neglects low probability events** (see Taleb, 2007); the focus on statistically relevant relationships ignores that statistical relevance often greatly underdetermines the causal relationships among a set of variables; and that amongst the many variables present, there is **little to tell us which may be causally relevant to the outcome we want to explain** (Woodward and Ross, 2021).

These limitations, not least of which the question of choosing the variables to focus upon, opens **numerous questions regarding scientific objectivity**, i.e. that claims, methods, results, and scientists themselves are not – or should not be – influenced by particular perspectives, value judgements, community bias or personal interests. This has led the notion of scientific objectivity to be questioned, both regarding its desirability and its attainability (Latour and Woolgar, 1979; Reiss and Sprenger, 2020).

The limitations of both explanatory models are **particularly salient in the context of agroecology**. Indeed, agroecology fundamentally challenges uniform production methods as it questions the logic of applying on-farm the practices that were shown to work well under a standardized experimental setting. Rather, it aims to **identify locally-adapted practices** that are suited to make use of the specific environment of each farm (Altieri, 1989; Gliessman, 2020; Prost et al., 2023).

## 2.2. Farmers: conceptualized as economically rational decision makers

Just as researchers are considered as ‘objective’, farmers are conceptualized as complying with the **normative model of rational choice**. This model assumes that people maximise expected utility (Briggs, 2023). This model requires that all available options are known, and that the probability with which an option will lead to a specific outcome is also known. Agricultural scientists, in particular agricultural economists, usually operationalize utility in monetary terms, and assume that farmers aim to maximise their income by following the rational choice model to select appropriate activities and production practices, given their constraints (e.g. limited resources such as land, machines, labour, money or laws protecting the environment). This model allows to build decision-support tools predicting the performances of a farming system for a wide range of ‘what if’ scenarios such as the benefits of a new technology, the likely uptake of a new agricultural policy scheme, or the impact of climate change (Jones et al., 2017; Keating and Thorburn, 2018; van Ittersum and Sterk, 2015). In these tools, farmers’ choices are modelled as rational choices, formalized as equations and coefficients linking inputs, outputs and prices (Martin et al., 2011; Robert et al., 2016). The solution space to be explored to search for the combination of activities and practices maximising production or income is predefined by scientists, often reduced to the variables and practices for which sufficient data is available, leading them to primarily consider incremental changes and neglecting explorative practices (Huet et al., 2018; Kipling et al., 2016; Martin et al., 2013).

This **economic rationality** underlying neoclassical economic models, has been **critiqued as unrealistic**. Indeed, it assumes that **decision makers have complete information about the available options, perfect foresight of the consequences** from choosing each option, and the **cognitive resources to compute** which option will maximise their utility (Gigerenzer, 2008; Smith, 2003; Wheeler, 2020). Moreover, it has been shown that expected utility theory makes **faulty predictions** about people’s decisions in many real-life choice situations (Kahneman and Tversky, 1979). Agricultural scientists also tend to focus on problem solving and overlook problem finding, i.e. the reasons why a farmer actually looks for an alternative (McCown et al., 2006; Robert et al., 2016; Snow et al., 2014).

Some authors have highlighted these limitations (e.g. Martin et al., 2013; McCown, 2002; Passioura, 1996), indicating that the fact that farmers tend not to take up the recommendations to the expected extent may be linked to the unrealistic assumptions underlying the models. Nevertheless, the norm of rational choice prevails and it is still widely perceived that this is how farmers ‘should’ make decisions. Indeed, given that scientific results are assumed to be objective and generalizable, and that farmers are assumed to be rational, farmers are expected to follow the recommendations developed by researchers.

Next to agricultural economists who model farmer’s choices, why farmers do or do not adopt certain recommended practices is also studied by sociologists. However, as rural sociology is often institutionalized in agricultural universities, it has led to strong formative relationships with agricultural economics and natural sciences (Lowe, 2010). Moreover, given the applied orientation of studies that focus on farmer’s decision-making, they are often part of larger research projects designed to derive

recommendations for agricultural policies. As a result, some studies in effect take a **behaviourist approach**, where adoption is understood as primarily shaped by interaction with the environment, with a key role attributed to market opportunities, financial incentives and social norms (Lowe, 2010). Whether in the models of agricultural economists or adoption-based studies by rural sociologists, the **trajectory of a farm over time is understood as the result of a succession of rational choices** that allow maximising income in each period. Given that farmers are assumed to focus on income maximisation, they are expected to follow the same general trajectory that can be analysed as a predictable sequence of stable states. While it is acknowledged that not all farmers' trajectory comply with these expectations, these farmers are often perceived as either laggards or irrational. Indeed, farmers are primarily seen as 'appliers', 'technicians' or 'business people', rather than 'craftspeople' (see McCown et al., 2006; Salembier et al., 2018).

### 3. Assumptions underlying a complexity worldview

#### 3.1. Farming is complex: change is on-going and unpredictable

This **worldview** (as noted, this worldview is understood as an archetype, i.e. recurring patterns) does not deny that **regularities exist** and that these allow predictability and controllability. However, it emphasises that the domains where these foundational assumptions hold – or where they capture what is most essential about what we observe – are not as broad as assumed in mainstream agricultural sciences. Especially **in the context of agroecology** where diversity, synergies, recycling, resilience, and co-creation play a key role (FAO, 2018), and which is characterized by **calls for transformative changes that are locally-adapted**, it is important to understand the **dynamics** of the entire farming system (Darnhofer et al., 2012; Prost et al., 2023). Given the **multiple processes** unfolding on a farm, its **complexity**, its **context-dependency**, the **psychology** of those involved (interests, beliefs, etc.), and more generally the ability to thrive despite **surprise and unexpected developments** are foregrounded.

It is then helpful to conceptualize the world in line with the theory of **complex adaptive systems**, which recognizes that a particular outcome is the effect of a **network of interactions**, whose **dynamic processes are ever evolving and often unpredictable** (Morin, 2007; Urry, 2005). In a complex adaptive system, there is **no determinism**, as cause-effect relations depend on various ecological, social, and political processes. As these processes interact, they change, often in unpredictable ways (Chia, 1999; Tsoukas and Chia, 2002), not least under the influence of many unforeseen developments and unexpected events (e.g. climate crisis, new regulations, shift in market requirement, price volatility).

The dynamics unfolding on a farm are thus marked by **contingency**, and by considerable **instability** and **unpredictability**. As such, striving to optimize production conditions or maximize income through ensuring the most efficient use of available resources is unlikely to be effective, as this can only be modelled if conditions are known or change in a predictable way. This has led to the emergence of concepts such as robustness and resilience (Darnhofer, 2021; Urruty et al., 2016), which explicitly

address the **need to navigate unexpected change**. They build on the understanding that if change is ubiquitous and often unpredictable, **sufficient resources need to be dedicated to cope with surprises**, to buffer shocks, and to adapt to changing conditions. In other words, it becomes key to be able to engage in **open-ended processes**, i.e. a continuous redefining and reassembling of resources, to strengthen a farm's capacity to evolve, to experiment with new activities and recognize opportunities as they arise.

Transitioning to agroecology is an **on-going process of reconnection to the local context**, a process where adaptations can be both **intentional and emergent**. It implies a departure from recipe-like recommendations that might work in standardized and specialized input-intensive systems, in favour of **creatively adapting the general principles of agroecology to the specificity of a farm and its context**. The aim of agricultural sciences is then no longer to identify equations and to control variables to optimize productivity or maximize income, but to understand processes and what they enable. These processes are understood as **contingent and ephemeral**, always **reassembling in different ways** (Anderson and MacFarlane, 2011; Baker and McGuirk, 2017). This does not mean that there are no durable orders, but that these orders are **open, provisional achievements**, composed of complex and shifting relations (Anderson and Harrison, 2010). The attention is on the various processes at play, on the interactions, on the unpredictable ways in which assemblages of relations develop around actions and events (Deleuze and Guattari, 1987)

### 3.2. Farmers: conceptualized as engaged in on-going processes of (re)assembling

If the world is understood as turbulent and unpredictable, and given that time and information is limited, the choices farmers make may be more adequately captured by concepts such as 'bounded rationality' by Simon (1979), 'ecological rationality' by Smith (2003), or as reached by using rules of thumb and heuristics as proposed by Gigerenzer (2008). Sociologically-influenced approaches have highlighted that following a 'peasant rationality', **farmers do not ignore profit, but they do not all and always prioritize it**, as the aim is not short-term profit maximization, but the long-term prosperity of the farm enabling it to be handed-over to the next generation (Niska et al., 2012; van der Ploeg, 2018, 2013, 2008). The focus on the long-term implies **juggling competing demands** (e.g. economic constraints, environmental ambitions, wellbeing of all family members) as well as adapting and fine-tuning activities in response to changes off-farm (in the social, political, economic, and technological environments) and on-farm (e.g. shifts in preferences or available labour) (Darnhofer, 2022). Clearly much of this is idiosyncratic, ambivalent and **ever-changing**, and thus hardly amenable to prediction, standardization and modelling.

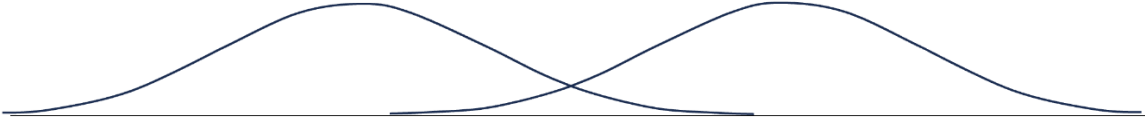
As such, **farmers navigate change** rather than trying to control it: they permanently adapt, keep options open to make different futures possible, and creatively use the unexpected openings emerging from uncertainty as opportunities for change. Individual choices are understood as **part of an unfolding, open-ended process**, where the aim is to take 'appropriate' rather than 'optimal' action (Jullien, 2004). Since one cannot know in advance what is appropriate, what will 'work', it seems

judicious to follow a **trial-and-error process**, a stepwise 'tinkering' (Jacob, 1977). These strategies enable farmers to work with the unforeseen by relying on simple heuristics (Gigerenzer, 2008), an intuitive grasp of the unfolding situation (Burke and Miller, 1999), allowing a mix of routine and novelty.

In this approach, **the trajectory of a farm is not given a priori**, not predictable based on a state at a time, nor is it predictable how a specific shock or incentive will shape the further trajectory. While there is an overall goal, e.g. quality of life and work satisfaction, the specific expression of that goal might well change over time. As such, managing a farm is more akin to a **captain navigating shifting currents**, turning winds and unexpected breakdowns, than a car on auto-pilot driving smoothly along a straight path, to a predetermined target.

Before we illustrate the implications of the differences between these two worldviews, we summarize the key assumptions of a deterministic worldview, which implicitly underlie many mainstream approaches, and contrast them with corresponding assumptions aligned with a complexity worldview, which might shed another light on the understanding of the trajectory of a farm transitioning to agroecology (see Table 11). Clearly, the statements in the table and the apparent dichotomy are a simplification that does not adequately represent the diversity of scientists' positions and how they may be combined. The aim is not to distort or misrepresent positions, but to build a contrast, so as to clarify differences and highlight the range of assumptions that may be used.

Table 11: Contrasting assumptions which tend to underlie worldviews that strive to standardize, control, and optimize agricultural production processes (e.g. a deterministic worldview), with the assumptions that tend to underlie worldviews that aim to navigate on-going change, emphasizing flexibility, adaptiveness and context-specificity (e.g. a complexity worldview). The two overlapping curves indicate that each worldview has a range of expression.

Key assumptions underlying farm management building on a deterministic worldview	Key assumptions underlying farm management building on a complexity worldview
	
The world is fundamentally <b>knowable</b> : once we know the most important causal relations, it is possible to predict future behaviour and outcomes ( <b>determinism</b> )	The world is a <b>complex adaptive system</b> : as such, its future behaviour is fundamentally <b>unknowable</b>
The world is <b>static</b> , in equilibrium: the mechanisms underlying the behaviour of systems are fixed and unchanging	The world is <b>dynamic</b> , i.e. change is on-going, resulting from both emergent and intentional adaptations
<b>Reductionist</b> , analytical worldview: divides systems into smaller elements, studied in isolation by specialist disciplines	<b>Systemic</b> worldview: elements of a system can only be understood in context of and through their interaction with other elements
Search is for <b>certainty</b> through clear causality (A leads to B) often established through statistical analyses that identify which relations are 'significant'. The aim is to maximize income through designing optimal production conditions	Given complexity and dynamics, <b>uncertainty</b> is pervasive. The aim is to creatively use the openings created by uncertainty
Since most causal relations between relevant variables are known, change processes can be controlled	<b>Control</b> will always be <b>incomplete, elusive</b> , not least because change processes are context dependent
<b>Change</b> needs to be carefully <b>planned</b> and tightly managed to ensure that the desired, pre-defined, goal is reached	<b>Change</b> is an <b>open-ended process</b> , where surprise and serendipity play a key role. The goal may well change in the process
<b>Decision-making</b> is driven by the rational model: farmers choose among available options by <b>maximizing</b> expected utility	Given limited information and time, decision-making is not about maximisation but about <b>sufficiency</b> ('good enough'). Moreover, new options emerge over time, leading to adaptation in decision-making
Focus on <b>risk</b> : decision-options are assessed using the tools of probability theory (risk: the range of possible outcomes is known, and the probability for the occurrence of each state is known)	Emphasis on <b>uncertainty</b> (range of possible outcomes is known, but probabilities are not) and the <b>ignorance</b> (neither the range of possible outcomes nor probabilities are known)

Source: own compilation, with elements from Allen and Boulton (2011), Bossaerts et al. (2019), Funtowicz and Ravetz (1993), Scoones and Stirling (2020) and Simon (1979).

## 4. Illustrating the two approaches to a farmer's journey towards agroecology

### 4.1. A farmer's trajectory

To illustrate the implications of our foundational assumptions, i.e. how they shape our analysis of empirical data and understanding of the drivers of a farm trajectory, we **contrast the analysis of one interview based on two archetypal worldviews**, one that foregrounds **determinism** and one that foregrounds **complexity**. The aim is not so much to identify the strengths and weaknesses of each approach, but rather to **illustrate the extent to which theories and the underlying worldview shape how we analyse empirical data**, and thus the **recommendations we might derive** from this analysis.

We thus apply each archetypal approach in turn to the analysis of the trajectory of Sebastien and his farm. The data stems from a semi-structured interview, which lasted two hours and was conducted in January 2022 by C. Meunier. The interview is part of a wider study aiming at identifying the motivations, barriers and levers, as well as overall trajectories of 18 crop farms which have intentionally reintegrated livestock, an innovative practice which counters the dominant trend towards specialisation (Meunier et al., 2024). Of the 18 interviews, **we chose** Sebastien's as he offered a **particularly detailed and nuanced narrative of the changes on his farm**, mentioning changes that were **intentionally introduced** as part of his deliberate choices, as well as changes that **resulted from surprises** and unplanned encounters.

As many farms in the South-West of France, while it used to be a diversified mixed crop-livestock farm, Sebastien's grand-father decided to specialize in the second half of the 20<sup>th</sup> century, to focus on vines (30 ha) and arable crops (30 ha). The vineyard was managed in accordance with the dominant conventional system: maximize grape production, on-farm wine-making and wine sold in bulk to traders at low prices. In 2012, Sebastien who had gotten diplomas in viticulture and oenology, returned to the farm, starting the process of generational succession.

### 4.2. The farm's trajectory as resulting from rational choices

In 2012, Sebastien took over the vineyard while his father continued managing the crop fields. Since he aimed to **implement environmentally friendly production practices**, Sebastien carefully planned how to reduce the use of chemical inputs. He knew that reducing herbicide use would increase weed pressure, which he aimed to manage using mechanical equipment; and that reducing fertilizers would decrease soil fertility, which he aimed to counter by sowing grass-legume cover crops, also contributing to control weeds. These changes required investments to purchase equipment, which he could partly cover using funds provided by the government as part of a start-up aid.

*"I began a transition on input reduction and changing my practices in the vineyard. And I bought equipment as well. I settled as 'young farmer' to have some financial aids and zero-*

*interest loans, so as to have what I needed for this transition, equipment to stop chemical weeding, to sow cover crops.”*

Next to implementing more environmentally friendly production practices, Sebastien aimed to **increase his income**. He thus decided to start direct marketing, while still selling some of his wine in bulk to secure a steady income stream. He developed the image of his bottled wine by communicating its high-quality given that it is locally-produced using agroecological practices. This allowed him to differentiate his wine from wine produced at neighbouring large industrial vineyards.

In 2019, **as a result of a very bad year** for wine production and considering the availability of subsidies, Sebastien decided to convert his vineyard to organic farming. This was in line with his environmental values, and allowed him to secure his income through both subsidies for organic farming and higher prices for organic wine sold in bulk to traders.

In 2020, the **full retirement of his father triggered the need to reorganize the farm**. On the one hand, he wanted to avoid too-high labour requirements. Indeed, he was already busy with managing the vineyard, wine-making and direct marketing, and now had to take over the arable fields. On the other hand, he wanted to maintain social connections on the farm and therefore looked for a partnership. In line with his environmental goals, since mechanical weeding consumes time and fuel, he considered sheep as an alternative way to manage his cover crops. Since he lived close to the Pyrenees where livestock farming is still widespread, Sebastien entered in a partnership with a shepherd and hosted 30 ewes to graze the cover crops in part of his vineyards from November 2020 to March 2021. The sheep also allowed Sebastien to increase his income by improving the image of the bottled wine marketed directly to consumers.

*“It was really ... There was not necessarily any precise objective it was more, dealing with the grass, having a first cut on the cover crop...”*

This first year of partnership having been successful, they decided to graze a larger area the following year with 120 ewes in the vineyard.

*“Everything went fine on the first year, so the aim was to do it again, trying to have some more ewes, and improve the way we were dealing with them.”*

As for the 30 hectares of arable fields that had still been managed conventionally by his father, Sebastien acknowledged that while conventional cereal production was profitable, it was not in line with his environmental objectives. He decided to convert them to organic farming and sow alfalfa. This allowed him to receive direct payments while avoiding the technical challenges of organic cereal production, since he did not have the necessary equipment and knew that organic contractors were hard to get at the optimal time.

*“It was either going on [growing cereals] with contractors, but my goal was to go for organic, and for cereals, regarding the seasons, it is hard to delegate. And I did not have the necessary*



*equipment for that. So I decided that CAP subsidies would pay for the land, without aiming to generate additional income.”*

As to the future, Sebastien planned to further reintegrate livestock on his farm. He aimed to settle a livestock farmer year-round on the farm, while still maintaining his seasonal partnership with the shepherd. This would allow him to ensure that the whole vineyard as well as the alfalfa fields are grazed, a rational choice allowing him to comply with both his objectives: implement environmentally friendly practices and increase income.

In this first analysis of the interview, Sebastien is conceptualized as a **rational decision-maker**, pursuing two main objectives: income increase and implementing environmentally friendly production practices. Through **careful planning**, he keeps the farm practices stable over extended time periods, **controlling** the implementation of **well-planned measures** leading to **predictable outcomes**. Changes are **triggered** by specific events which are not necessarily predictable for Sebastien (Figure 42). He responds to these events through **rationally analysing** his options.

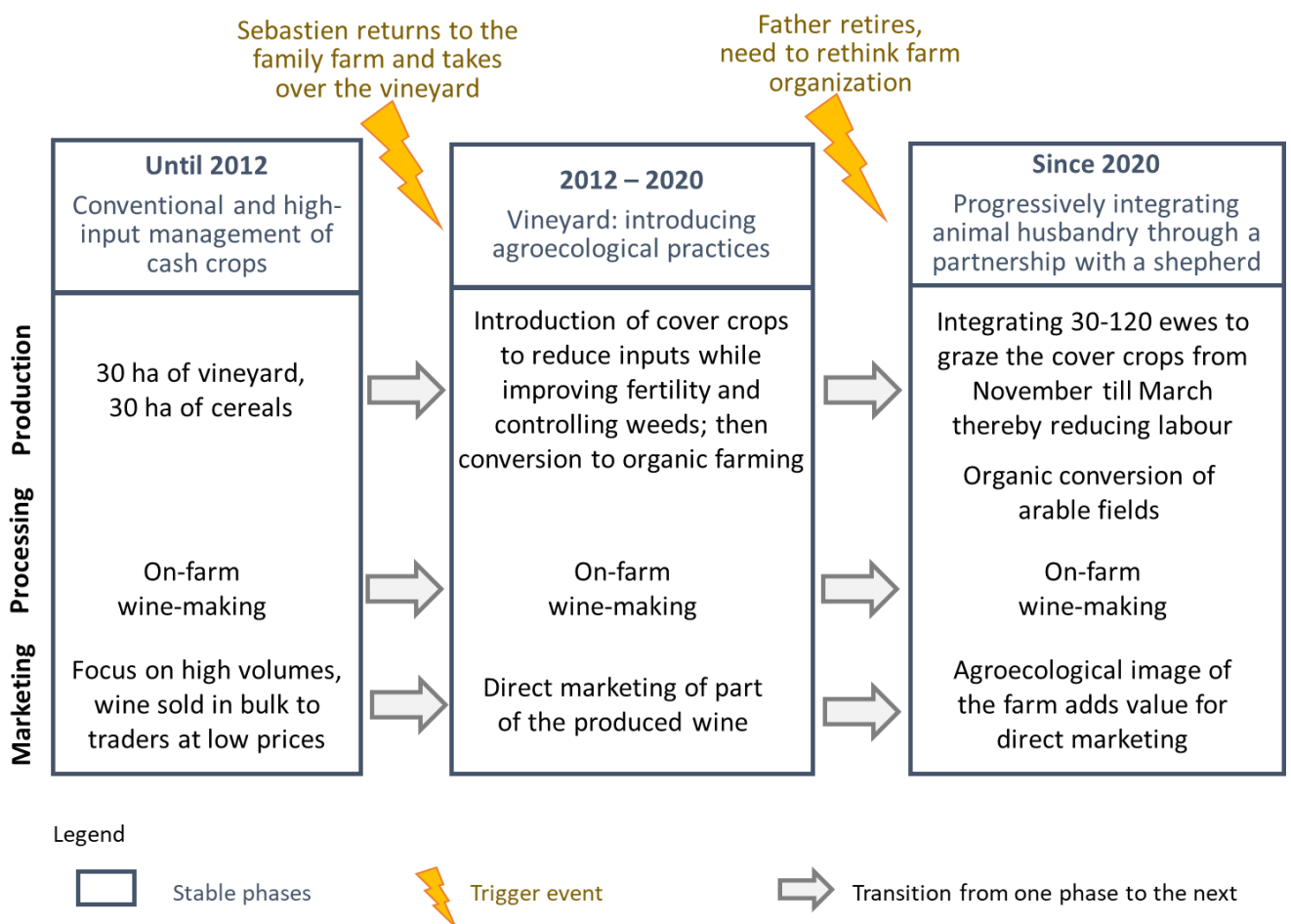


Figure 42: Trajectory of Sebastien’s farm, analysed based on the assumptions underlying most mainstream approaches to farm management. The farm trajectory is divided into coherent phases, during which the carefully-planned implementation of practices that aim to control production processes remain unchanged. A trigger event leads to the switch from one phase to the next, which Sebastien plans in a rational manner, in alignment with his two stable goals, i.e. income increase and compliance with his environmental values.

### 4.3. The farm's trajectory as emerging from unexpected encounters

This second analysis is in line with a **complexity worldview** which conceptualizes change as on-going and open-ended. Thus, while taking over his father's farm has always been a possibility, the **timing had never been openly discussed**, and came rather **surprisingly**. Sebastien had not really anticipated, nor carefully planned this change in his life.

*"In 2012, he wanted to retire. I got diplomas in viticulture and oenology, then I worked in France and travelled. So, I never really considered returning on the farm, while knowing that, one day, it would happen [...]. So, I did not anticipate things! But, yeah, I came back, and my father was in conventional farming."*

While Sebastien's choices are guided by an overall desire to use environmentally friendly production practices while securing his income, the 'how' is **emerging in the doing**, rather than the result of a careful weighing of options. His choice to sow cereal-legume cover crops in his vineyard is an intentional choice to realize his objective of securing fertility in his low-input system, but how he implemented the broad goal resulted from **unexpected encounters**. Indeed, Sebastien chose to use seeds he could find locally rather than optimizing the composition of the cover crop mixture to maximize nitrogen fixation, as would be expected, would he have followed an economically rational approach.

*"I have a friend [nearby], I began buying a mixture of faba bean, vetch, pea, triticale, oat, rye from him. I add phacelia, rapeseed, seeds I find nearby. I wanted to stay local, even if it was not exactly the species I was looking for."*

Similarly, converting the vineyard to organic was guided by Sebastien's objectives, but it was not a straightforward path, **nor a carefully planned decision**. It resulted from a **long struggle on whether to convert**. Indeed, he resented having to pay the fees for the certification, which he perceived as an unjustified penalty since his practices were more environmentally-friendly and thus provided a public good. Yet, in 2018, he suffered a particularly poor harvest. This unexpected event led him to question his crop protection practices and the advice he received from an external expert. He thus searched for a different way to manage his vineyard. **Per chance**, this poor harvest occurred at a time when direct payments for conversion to organic farming were offered, and a new marketing opportunity for organic wine presented itself. Yet, his decision to convert to organic farming was mainly influenced by an **emotional reaction** to the poor harvest, rather than being the result of a rational planning process, and led to unexpectedly positive experiences.

*"I did not want to convert to organic farming, I did not want to be part of the "marketing" system of organic products, which is nonsense for me. At the same time, I thought, maybe it is better than nothing, so I was a little struggling to make my mind on that. [...] In 2018, I totally failed with the vines, with such a high disease pressure [...] I wondered why my vines had that much disease, what I had missed. Now, I think this misfortune was an opportunity! It made me*

*go further, change my practices. And since then, I am 1000 times more passionate and involved!”*

Similarly, the reintegration of animals on his farm was the outcome of a process full of **unexpected developments**. While Sebastien’s initial objective to identify an environmentally-friendly and cheap way to manage the cover crops in his vineyard was clear, how to achieve it was an **open-ended process** driven by **casual observations and chance encounters**:

*“How did I end up thinking about reintegrating ewes? I think I read something about that... Well, wait, no, I know how! I heard [another farmer], he has many hectares of alfalfa, and I saw ewes in his fields, then I found the road to go and talk to the shepherd, but they were not his ewes [...] then I knew that it went through a [neighbouring] butcher. So I went to the butcher’s and [...] explained him my project, and he put me in touch with [the shepherd he’s partnering with].”*

The process was an **unpredictable sequence of events**, from meeting the shepherd, to having him committing to the partnership as, by chance, the cover crops had grown unexpectedly well that year, thereby raising the shepherd’s interest in bringing his ewes to graze them. Had they grown less abundantly, e.g. due to a year with poor rainfall, the shepherd might not have been interested, and Sebastien might have dropped the idea of integrating livestock in the vineyard.

*“The autumn weather was wonderful in 2020 [...] the harvest was incredible, the weather was sunny, warm, and the cover crops had grown really well. So [the shepherd] came, and they were already [really high], so he was interested!”*

The success of the initial experiment with 30 ewes encouraged the next step of hosting 120 ewes the following year. But again, this was the **outcome of a coincidence**, as the shepherd had lost another field and needed feed for his animals, which led him to bring even more ewes than initially planned, and raised questions on how to manage grazing to ensure sufficient feed for 50 additional ewes that unexpectedly ended up on his farm.

*“Well, there are two flocks, he brought another one no so long ago. Because he lost [some neighbouring] plots of alfalfa due to another shepherd, so he did not have enough to feed his ewes. So he brought them here. We were supposed to have 70 ewes with their lambs. He brought 50 more.”*

While Sebastien felt lucky to find a shepherd with whom to form a partnership, he had little knowledge about how sheep grazing would affect the vineyard. He **did not anticipate some of the benefits** it brought for biodiversity, nor the **pleasure** he would derive from them.

*“What I found amazing, I had begun settling nests for [birds] and bats [...] and I found sheep wool inside [...] so it’s useful for biodiversity, birds can use it!”*

*“I think you really need to be there, surrounded by [the sheep], to feel how nice it is.”*

Neither did he anticipate the **complications** that would arise from hosting animals, since they were not always well-behaved.

*“The other day, they escaped on the neighbour’s field over there. It was a bit of a nightmare! I was driving over there, and I saw them, it was almost dark, they seemed to enjoy being in this field, they did not want to come back! It was really a hassle!”*

As for the future, Sebastien was not quite sure what he would do next. While intensifying his partnerships with shepherds and further integrating livestock by settling a shepherd on the farm year-round was one option, he also acknowledged that there were constantly new opportunities emerging:

*“There are always novelties, things you did not know, things you learn. There is no recipe [...] I can’t [manage the sheep] on top of what I’m already doing. Those are still just ideas, but it could be, finding something, someone who would like to [set a livestock production on the farm], or maybe just making land available for market gardeners, there are so many possibilities! [...] It would not prevent going on working with [the shepherd], maybe with a smaller herd, but he could go on coming, and they could share feed.”*

In this second analysis of the interview, the farm’s trajectory is the result of **emerging opportunities** (Figure 43). At various points, Sebastien creatively uses unexpected events and chance encounters, while making choices with incomplete knowledge and limited control of outcomes.

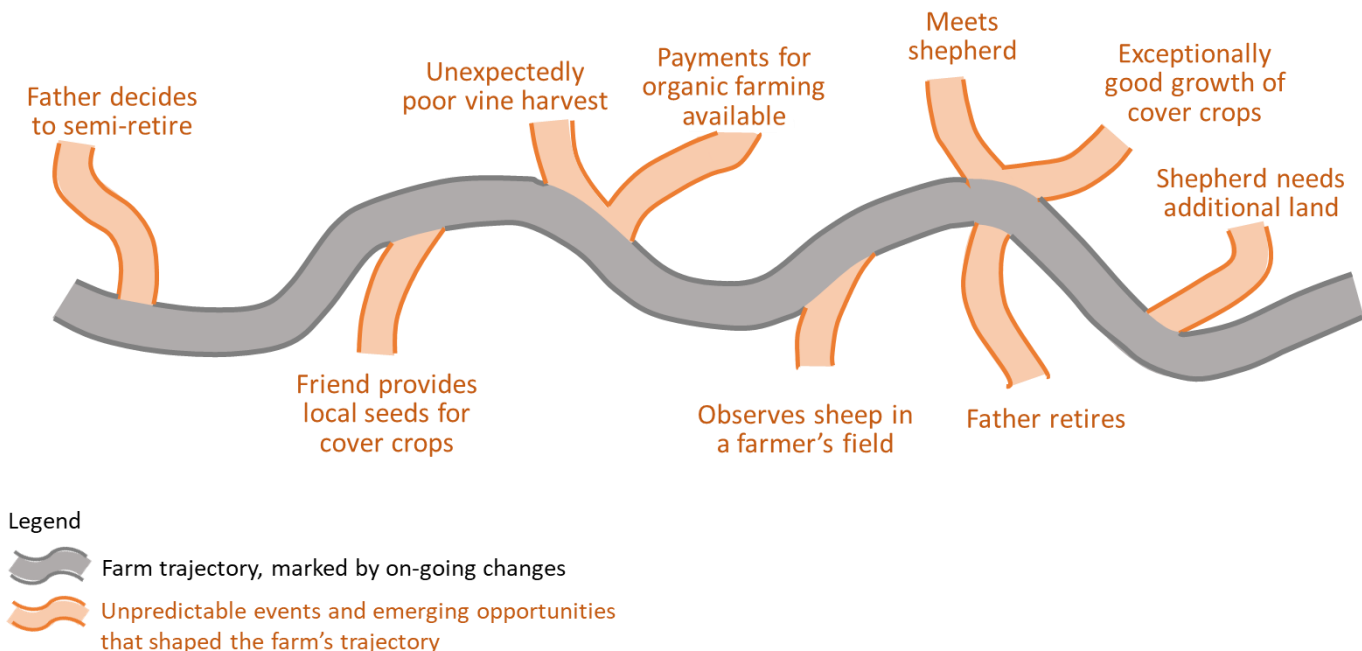


Figure 43: Trajectory of Sebastien’s farm, analysed based on the assumptions underlying a complexity perspective of farm management. The farm is seen as engaged in an on-going process of adaptation, including the introduction cover crops in the vineyards, the conversion to organic farming and the reintegration of livestock. Unexpected events and chance encounters lead to the emergence of diverse opportunities at various points along the trajectory. Sebastien navigates these changes by keeping his options open and engaging in stepwise tinkering.

## 5. Some implications for research for a transition towards agroecology

Through contrasting the insights that can be derived from two different archetypal approaches when analysing how and why farmers make important decisions shaping the trajectory of their farm, our aim was to **illustrate the role of the foundational assumptions underlying the choices made by agricultural scientists throughout the research process**. Clearly, both approaches are legitimate, as would have been other approaches resulting from diverse combinations of the assumptions underlying the two archetypal approaches we contrast here. They propose **two different abstractions from reality**, focusing on the aspects they conceptualise as capturing the essence of the farm's trajectory.

It points towards the insight that **there is no such thing as objective knowledge**. Indeed, 'objective' knowledge is often understood as singular, unsituated 'truth', which implies that researchers are able to perform the 'god trick' (i.e. the ability to see everything from nowhere) (Haraway, 1988, p.582). Yet, **our choices are necessarily socially situated**, linked to power constellations, tacit institutional influences, various political and academic interests, disciplinary boxes that systematically shape theoretical analyses of empirical phenomena and shape the stories researchers tell (Thompson, 2002). **We researchers choose to foreground and emphasize certain aspects over others**, we choose which variables we include in our models and which to 'neglect', not least to reduce complexity and to make quantitative models tractable. These choices are not innocent, as different methods, concepts and assumptions lead to different conclusions regarding effective ways to promote agroecological practices. Our choices are thus political, and research is directly implicated in the construction of social worlds (Law and Urry, 2004). We do not merely 'report' on something that is already there thanks to methods that capture the world 'as it is' as purely technical devices (Law et al., 2011; Law and Urry, 2004) and concepts that are "abstract ideations of inherent attributes of independently existing objects" (Baker and McGuirk, 2017, p. 432). Rather, through our choices and our deployment of particular methods, **we help produce social realities** by producing specific arrangements of presences and absences (Law, 2004, p.143). In other words: we intervene in the world, bringing one of its versions into being (Mol and Law, 2002, p.19). It points towards the performativity of research, e.g. that agricultural economics "*does things, rather than simply describing (with greater or lesser degrees of accuracy) an external reality that is not affected by economics*" (MacKenzie, 2006:29, italics in original ; see also Callon, 2007; Daniel, 2011; Røpke, 2020)

The questions we need to ask ourselves are: What worlds do we contribute in making? What do we strengthen? What fixities do we produce? What stabilities do we reinforce? What do we keep invisible and unsaid? What (im)possibilities do we highlight? **If we want to contribute to a transition towards agroecology, we might need to reintegrate these questions in our considerations, making our commitments transparent**. Research may then be less guided by an illusory search for 'truth', but by an ethics of engaging with the world.

At the same time, our choices, which are guided by **norms and expectations**, also need to be understood as **entangled in a wider knowledge production regime**, that has been enforcing compliance with the ideals of modern science, and that does not necessarily leave much place for

different ways of doing (Vanloqueren and Baret, 2009). Similar to the quantitative models that are understood as capturing the salient features of farmer's choices, **researchers are themselves trapped in research metrics** and the 'publish or perish' mentality (Becker and Lukka, 2022; Elbanna and Child, 2023). As institutions focus on assessing the quality of our research based on such performance metrics, we may not have the leeway to reflect on how our models are used or what impact our recommendations have on the real world (Keating and Thorburn, 2018; Martin et al., 2013; van Ittersum and Sterk, 2015). When we hardly ever do it, we realize they are often diverted and used for unintended purposes (Ravier et al., 2016).

Thus, what was once the main objective of agricultural scientists – producing locally-adapted knowledge for action (Salembier et al., 2018) – has too often become **a welcome side-effect**. Yet, especially in the context of agroecology, researchers have begun advocating this as a priority, calling for interdisciplinary and transdisciplinary research involving stakeholders at each step of the research project to ensure it stays grounded in their reality (Berthet et al., 2016; Gliessman, 2018; Meynard et al., 2023; Prost et al., 2012).

Contributing to farmers' transition toward agroecology may then very well require a **similarly transformative process in the way we do research**, what we value, and which norms guide us. The call with which we started our paper, that "Things need to change" if we are to contribute to the transition towards agroecology, then seems to apply to the farmers and their farms, but also to us and the worldview which guides our research, and to values and metrics prevalent in the knowledge production regime more broadly.

## 6. Acknowledgements

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## Conclusion of Chapter 4

In chapter 4, I did not produce knowledge on livestock reintegration as initially planned (Figure 44). Due to too high diversity in my farm sample, I failed at providing a typology of trajectories followed by farmers when reintegrating livestock. Instead, I contributed to the field of research on agroecology through **providing an invitation to agricultural scientists to reflect on our stances and practices, and on the way they impact our research results.**

I still partly contributed to enrich the innovation-tracking framework through providing an **initial idea of framework to analyse trajectories followed by farmers when implementing an agroecological innovation**, considering trigger events and factors that can facilitate or hinder the passage to the next step. The epistemological reflection I provided regarding researchers' stances and practices may as well be **particularly insightful for study leaders of innovation-tracking initiatives**, who need to reconstruct farmers' stories to capitalize on them.



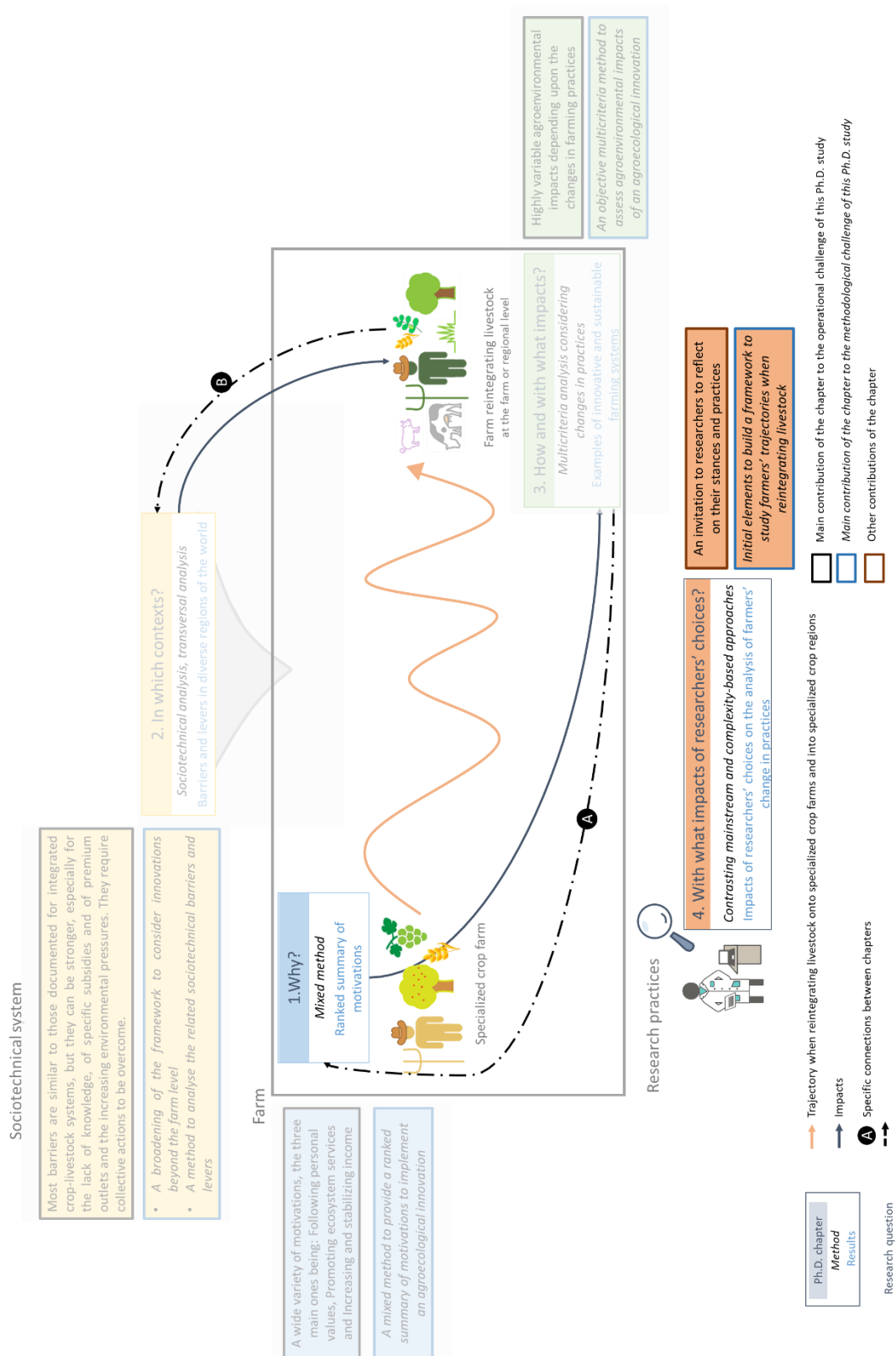


Figure 44 : Positioning Ph.D. work chapters along the journey followed by farmers toward reintegrating livestock onto specialized crop farms and into specialized crop regions: main results of Chapter 4 on researchers' stances and practices. Operational challenge of this Ph.D. study: producing knowledge on why, in which contexts, how and with what impacts farmers reintegrate livestock into specialized crop farms and regions. Methodological challenge of this Ph.D. study: improving the innovation-tracking framework by studying at multiple levels the determinants that lead to agroecological innovations and assessing their performances objectively.



## Episode 4: Staying open to emerging opportunities regarding the future of the farm

I do not know what my farm will be like in a few years. To be honest, I am not sure I would ever have imagined it would be like that some day. I like it the way it is. But it will keep evolving, it has to ! It's life, you know. Things happen. You have opportunities. Sometimes you use them, and it does great things. Sometimes you miss them, and then you regret. Sometimes you try, and you fail, and you also regret, but at least, you tried. This is what I always tell to my son. He wants to take over the farm, and I'm very happy of that, but he sometimes has a twisted vision of the reality. He says "Dad, I will do this, and this, and when this is done, I can do that...". And I tell him "my son, go slowly. It is nice to have projects, but if you have a project that is too predefined, you will always be disappointed, because it will never happen exactly as you predicted. Instead, if you have an overall idea of where you want to go, but you stay open regarding the path to go there, then you can have beautiful surprises". I feel old when I say that. I feel like Master Yoda in Star Wars...

Yesterday, a young woman phoned me. She said she worked at INRAE, as a Ph.D. student, something like that. She wanted to come on the farm to talk about my farming practices, to interview me and "know my story", she said ! Ah, I am not a star, I am not much sure what I am going to tell her, I just do simple things here. But, she seemed to really want to come, and I like helping when I can, so I told her to come tomorrow. I think her name was Clementine.







## Discussion

### Part I: Main results and insights

My Ph.D. study continues the efforts of many studies that emphasize the need to depart from the dominant regime of high-input specialized farming to **transition to agroecological systems** (Darnhofer et al., 2012; Prost et al., 2023). To contribute to this research field, I focused on **one example of agroecological innovation: livestock reintegration** onto specialized crop farms and into specialized crop regions. Farms that reintegrate livestock were **an enigma** when I started my study. **Pioneer farmers who reintegrated livestock opposed the trend of farm and regional specialization in crop production in France.** They **intentionally organized the return of animals** onto specialized crop farms and into specialized crop regions, while i) the number of **mixed crop-livestock farms continues to decrease**, while the number of specialized crop farms increases, and the former are **marginalized** into regions where specialized crop or livestock production cannot reach high yields (Chatellier and Gaigné, 2012; Roguet et al., 2015) and ii) the number of **livestock farms continues to decrease**, and livestock production continues to **concentrate** in specialized livestock regions (e.g. Brittany, Figure 3b) (Bonaudo et al., 2014; Domingues et al., 2018; Garnier et al., 2016).

These pioneer farmers faced an overall **lack of knowledge on how to reintegrate livestock sustainably at the farm or regional level.** In particular, they lacked examples of **technical or organizational solutions** for reintegrating livestock and were uncertain about the (positive or negative) **impacts** of reintegrating livestock on the **sustainability of their farms.** To my knowledge, livestock reintegration onto specialized crop farms and into specialized crop regions had **rarely been studied.** Consequently, my first objective in this Ph.D. study was to **produce knowledge on this reintegration.** To do so, I focused in particular on **why, in which contexts, how and with what impacts farmers are reintegrating livestock, which served as initial insights into determining whether scaling up of livestock reintegration should be supported, and if so, how.**

#### I.1. Summary of the main thematic results and insights of the Ph.D. study

*As mentioned in the Introduction (Part IV), I present my results following the same trajectory that farmers would use when considering reintegrating livestock onto specialized crop farms and into specialized crop regions (Figure 45). I include reminders of specific elements of Eric's story to illustrate the results.*

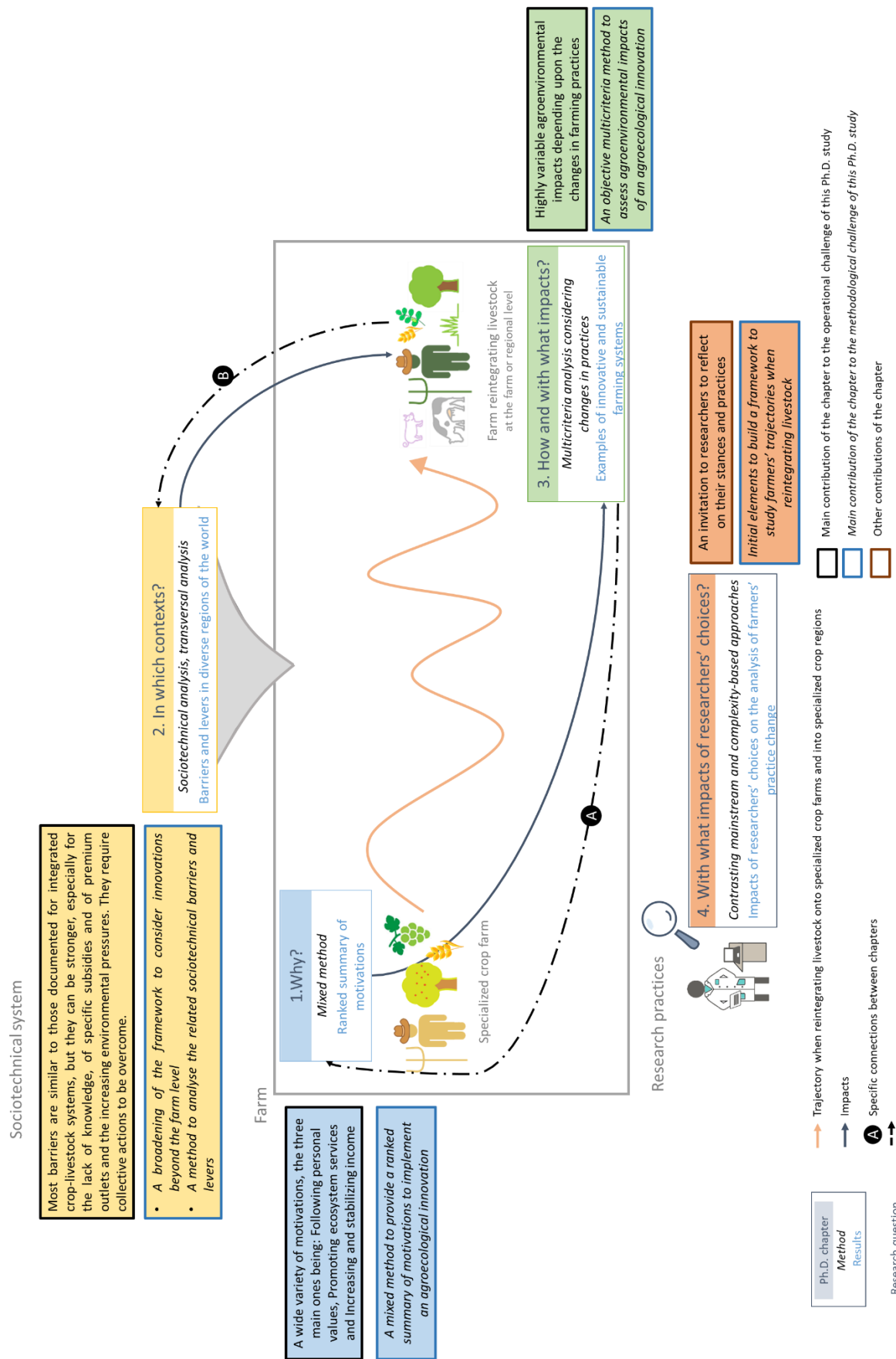


Figure 45. Positions of Ph.D. results along the trajectory that farmers follow to reintegrate livestock onto specialized crop farms and into specialized crop regions



*For a farmer, the first step on the trajectory of reintegrating livestock into specialized crop farms and regions is to consider why to do so. This was also the first focus of my Ph.D. study.*

### 1.1.1. A diversity of farmers' motivations for reintegrating livestock

In chapter 1, I provided a **ranked summary of farmers' motivations** for reintegrating livestock. I performed semi-structured interviews with 18 French farmers who had reintegrated livestock in a wide diversity of farming systems (annual or perennial crops, reintegration of monogastrics or ruminants, at the farm or regional level).

I built on an **original mixed method** (DeCuir-Gunby, 2008; Greene et al., 2005) that combined qualitative inductive discourse analysis (Elo and Kyngäs, 2008) with quantitative analysis of farmers' rankings of motivations. I found that **farmers had multiple motivations for reintegrating livestock**, the three main ones being **aligning with personal values, promoting ecosystem services and increasing income**.

I provided initial insights into **differences in farmers' motivations for reintegrating livestock depending on their farming system** (e.g. poultry highly integrated into the value chain vs. sheep grazing outdoors full-time (Figure 46, Figure 47)).

I found that most of the farmers' motivations for reintegrating livestock **aligned with the main advantages of ICLS documented in the literature** in the agroenvironmental and economic dimensions (Figure 10) (Bell and Moore, 2012; Gil et al., 2016; Peterson et al., 2020; Ryschawy et al., 2012). However, although farmers often mentioned **social motivations**, such as aligning with personal values, for reintegrating livestock, **few studies have emphasized the social benefits of ICLS** (Garrett et al., 2020).

I also found that most of the farmers' motivations for reintegrating livestock were **similar to those for implementing other agroecological practices**, such as decreasing pesticide use (Pergner and Lippert, 2023), converting to organic farming (Bouttes et al., 2019), adopting conservation practices in organic farming (Casagrande et al., 2016), developing circular agriculture (de Lauwere et al., 2022) or implementing agroforestry (Banyal et al., 2015; Schaffer et al., 2024). In particular, promoting **ecosystem services provision** (Casagrande et al., 2016; Pergner and Lippert, 2023; Schaffer et al., 2024), **securing income and increasing farm self-sufficiency** (Banyal et al., 2015; Bouttes et al., 2019; de Lauwere et al., 2022), **increasing work satisfaction** (Bouttes et al., 2019; Duval et al., 2021) and **aligning with values of environmental stewardship** (de Lauwere et al., 2022; Prokopy et al., 2008; Sutherland et al., 2016) were cited often.

The high diversity of farming systems in the sample allowed me to identify a **wide range of motivations**, although **this range is not exhaustive**. **These results need to be taken with caution** given the few farmers I interviewed, in total and for each system. Interviewing more farmers in each type of system and mapping the relations among their motivations (Lalani et al., 2021; Tessier et al., 2021) could identify profiles of farmers who share similar combinations of motivations that lead to

reintegrating livestock, as done for other agroecological innovations (de Lauwere et al., 2022; Greiner and Gregg, 2011).

In Eric's story, the main motivations that led him to reintegrate sheep on his farm were promoting ecosystem services, especially regarding soil quality, as he saw sheep as a way to limit mechanical interventions on the cover crop while providing manure. He also wanted to undertake a new technical challenge, after several previous tests on his cropping system. Another motivation was to align with values of environmental stewardship, as he liked the idea of having both crops and animals interacting on the farm. He also liked the idea to use livestock as a way to derive human food from cover crops and land that were difficult to crop.

*However, beyond these psycho-cognitive determinants, other determinants at the farm and sociotechnical system levels also facilitated and hindered this reintegration, and were key to explaining his changes in farming practices. I thus broadened my analysis to consider these other determinants.*

#### 1.1.2. A diversity of sociotechnical barriers to reintegrating livestock and some promising levers to remove them

In chapter 2, I performed **transversal analysis of sociotechnical barriers** to reintegrating livestock in three regions of the world (eastern Scotland, south-western France and northern California (USA)) where this farmer-led agroecological innovation had been observed.

I built on **inductive analysis** of 32 semi-structured interviews with **key actors of the sociotechnical system** surrounding livestock reintegration (i.e. farmers, advisors, researchers, teachers, public-policy specialists) in each of the three regions. I used the **multi-level perspective** (Geels, 2011, 2004) to ensure that barriers and levers were targeted at all levels of the sociotechnical system (Figure 13, Box 4).

I found that there were **many barriers** to scaling up livestock reintegration (Figure 46, Figure 47). Most of them were **found in each of the three regions, even though their sociotechnical contexts differed greatly**. The main barrier to scaling up livestock reintegration was a **lack of knowledge** by **all actors** of the sociotechnical system, especially on **how to** reintegrate livestock and what **benefits** to expect. While a lack of knowledge was also identified as a barrier that hindered other agroecological innovations (Boulestreau et al., 2021; Mamine and Farès, 2020; Meynard et al., 2018; Schaffer et al., 2024), it was **even greater** for livestock reintegration on specialized crop farms and into specialized crop regions, from where **the entire sociotechnical system surrounding livestock production had disappeared** (Garrett et al., 2020; Schut et al., 2021) and would need to be re-created. The **lack of specific subsidies** and **premium outlets** for the products also hindered scaling up of livestock reintegration, like for many agroecological innovations (Magrini et al., 2016; Meynard et al., 2018), although public policies may begin to support some of them (e.g. crop diversification, legume cropping

(Bourget, 2021; MASA, 2023). **Increasing societal pressures on livestock production regarding its environmental impacts** (Garnett et al., 2017; Torpman and Rööös, 2024; Van Zanten et al., 2019) was another barrier to scaling up livestock reintegration, whereas other agroecological innovations associated more directly with environmental benefits, such as agroecological vegetable protection (Boulestreau et al., 2021), may instead be supported by positive societal opinions.

I identified the **main factors that favour livestock reintegration**: positive memories of the cultural heritage of mixed crop-livestock farming, the global context of increased fertiliser prices and new incentives for agroecological practices that indirectly favour livestock reintegration. I provided **inspiring examples of innovation-oriented initiatives** that connect researchers, farmers and policy-makers and can facilitate livestock reintegration.

**Such collective actions** are required to overcome sociotechnical barriers that hinder reintegrating livestock into specialized crop farms and regions (Meynard et al., 2017; Pigford et al., 2018). **Researchers need to produce and disseminate knowledge** on sustainable forms of livestock reintegration (i.e. in farming systems in which reintegrating livestock increased farm sustainability). Building on such knowledge, **policy-makers** could favour **scaling up the sustainable forms of livestock reintegration** identified. To do so, they could offer **payments for ecosystem services** (Alderkamp et al., 2024; Dennis et al., 2011; Garrett et al., 2017; Grima et al., 2016) or **collective bonus payments** (i.e. additional monetary bonus paid “if a given threshold is reached in terms of aggregate farmer participation” (Kuhfuss et al., 2016)), especially for livestock reintegration at the regional level. **Consumers** should consider the **true costs of agroecological products** (i.e. including their societal and environmental costs), which are lower than those of their conventional counterparts (Michalke et al., 2023; Rockefeller Foundation, 2021).

This analysis of barriers to and levers for reintegrating livestock was performed regardless of the type of farming system or livestock reintegration observed. To favour scaling up of **sustainable forms of livestock reintegration**, it needs to be supplemented with **in-depth study of specific barriers** to each sustainable form of livestock reintegration identified (i.e. per type of sustainable livestock system reintegrated, type of crop farm and level of livestock reintegration (farm or regional)). To prioritize actions, the relative weight of each barrier to each sustainable form of livestock reintegration should also be assessed.

In Eric’s story, livestock reintegration was hindered by his lack of knowledge on how to reintegrate livestock onto a specialized grain crop farm, and by the lack of services in the specialized crop region. It was facilitated by his meeting with Marie, a shepherdess, with who he collaborated to benefit from the ecosystem services provided by the sheep with minimal investment and additional skills.

*Once farmers have the motivation for reintegrating livestock and have managed to overcome the sociotechnical barriers to it, they can begin to reintegrate livestock onto specialized crop farms and into specialized crop regions. To do so, they still need to determine how to make the changes in farming practices needed to reintegrate livestock. These practices need to align with their initial farming systems, their motivations and sociotechnical contexts, and allow them to obtain the expected benefits. I thus focused on characterizing the diversity of these farming practices and their agroenvironmental impacts on farms' sustainability.*

### 1.1.3. Variable agroenvironmental impacts of reintegrating livestock depending on changes in farming practices

To address the knowledge gap identified as the main barrier to reintegrating livestock, in chapter 3, I documented a **wide range of farming-practice changes beyond livestock reintegration** and performed **multi-criteria assessment of their impacts on the agroenvironmental dimension of farm sustainability**.

To do so, I interviewed 15 French farmers who had reintegrated livestock in diverse farming systems. I assessed **three indicators** calculated at the farm gate: **nitrogen surplus, direct and indirect energy consumption, and greenhouse gas emissions** (including their compensation through carbon storage). I selected these three indicators because they aligned with **the main advantages documented for ICLS** (Figure 10) (Bretagnolle et al., 2011; Brewer and Gaudin, 2020; Franzluebbers et al., 2014; Martin et al., 2016; Ryschawy et al., 2012) and with the **farmers' motivations** for reintegrating livestock identified in chapter 1. I used equations and coefficients from IDEA4 (Frédéric Zahm et al., 2019), a well-known method for assessing farm sustainability, and used a diachronic approach to **focus on changes related to reintegrating livestock** (Nandillon et al., 2024).

I found that **agroenvironmental impacts of reintegrating livestock can vary greatly depending on the main characteristics of livestock reintegration**, in particular **the extent to which farmers adapt their cropping system** to develop interactions with the reintegrated livestock. For example, reintegrating **high-input poultry production** can **greatly increase the farm nitrogen surplus, direct and indirect energy consumption and greenhouse gas emissions**. However, reintegrating **grazing sheep** can result in a **similar farm nitrogen surplus, lower direct and indirect energy consumption and similar greenhouse gas emissions**. Other studies have highlighted that farming systems often need to be transformed beyond implementing an agroecological innovation in order to increase their sustainability (Craheix et al., 2016; Hill and MacRae, 1996; Rosset and Altieri, 1997). Differences in farming-practice changes are also caused by those in **farmers' motivations** and **sociotechnical contexts** (de Lauwere et al., 2022) (Figure 46, Figure 47).

In this analysis, I provided initial insights to determine **whether scaling up of livestock reintegration should be supported**, and if so, **in which form**. I also provided a **range of possible benefits to expect**. Again, my assessment was based on a **small and highly diverse sample** and thus needs to be taken with caution. More in-depth study and quantification of the agroenvironmental impacts of **specific forms of livestock reintegration** on farm sustainability are needed to provide more robust knowledge on which forms of livestock reintegration should be supported. Socio-economic dimensions of farm sustainability should also be assessed.

In Eric's story, livestock reintegration consisted in hosting Marie's sheep to graze his cover crops during the winter. This allowed to decrease the number of cuts of his cover crop, hence saving time, money and fuel. He also benefitted from sheep manure, even though it did not lead him to decrease his organic fertilizer input. The lasting partnership led him to make more subsequent adaptations of his farming system, by adjusting the composition of this cover crop to make it more nutritional for the sheep, and by stopping cropping hilly areas with low productivity to convert them into pasture for sheep.

*Once farmers have reintegrated livestock, reflexive analysis of the trajectory that led them to this current state of the system may help them envision its evolution. While the first three chapters of the Ph.D. study provide a static understanding of determinants that led to reintegrating livestock, and a snapshot comparison of the farming practices implemented and their impacts, I did not consider the dynamic dimension of reintegrating livestock. Supporting the scaling up of sustainable forms of livestock reintegration requires supplementing these results by identifying the resources and strategies that farmers use during the process of change (i.e. analysing reintegrating livestock in action).*

#### 1.1.4. From initial failure to create a typology of trajectories that farmers followed to reintegrate livestock to epistemological reflection on researchers' stances and practices

In chapter 4, I aimed at developing a **typology of trajectories that farmers followed when reintegrating livestock**, depending on their initial motivations, farming systems and sociotechnical contexts. Similar studies have been performed for several agroecological innovations (Chantre et al., 2015; Moojen et al., 2024; Revoyron et al., 2022). They identified **common steps and trigger events** in trajectories that led to implementing the agroecological innovation considered, to support farmers' reflexive analysis and help them envision the evolution of their farming system. They highlighted **key strategies** (e.g. stimulating learning, increasing farm resilience) **to promote farmers' adaptive capacity** in an ever-evolving context, thereby helping support scaling up of the agroecological innovation considered (Bouttes et al., 2019; Chantre and Cardona, 2014).

The **small size and high diversity of my sample** did not provide sufficient **redundancy** among farm trajectories to build a robust typology. Each farmer followed a **unique** trajectory. Although there were some similarities, **forcing** this diverse data to fit into a typology would have required **ignoring much of the complexity of these trajectories**, which might have discarded some essential elements of farmers' stories. Addressing this issue requires defining the essential elements that shape farmers' trajectories toward reintegrating livestock, which depends strongly on **what we, researchers, choose to emphasize or deemphasize in analyses** (Thompson, 2002). Faced with this recognition, I decided to **convert my failure** with the typology project into an **opportunity to reflect on my stances and practices as a researcher** (Hazard et al., 2021).

In chapter 4, I thus called on agricultural scientists to reflect on the need to **acknowledge our underlying worldview** and its **impact on our research stances and results**. By providing **two contrasting analyses of one trajectory** that a farmer followed when reintegrating livestock, I highlighted how differences in **two researchers' worldviews could lead them to tell two different stories**, from which diverse analyses could be derived. Indeed, farmers' trajectories when reintegrating livestock are **partly planned** and result from **rational decisions** (Briggs, 2023; Gigerenzer, 2008). However, these trajectories are also **influenced greatly by unexpected events** and farmers' **adaptive capacity** to reorient their trajectories by using these **emerging opportunities** creatively (Darnhofer, 2021; Tsoukas and Chia, 2002; Urruty et al., 2016). Such opportunities are often **deemphasized in traditional research** in agricultural sciences (Scoones and Stirling, 2020; Woodward and Ross, 2021). I argued that studying agroecological systems requires that we, agricultural broaden our mainstream worldview to capture this complexity and uncertainty.

In Eric's story, livestock reintegration was shaped by his decisions (e.g. converting to organic farming, reintegrating sheep on the farm), that were driven by his motivations to promote ecosystem services while undertaking technical challenges and aligning with his environmental stewardship values. Reintegrating livestock was thus, in part, the planned continuation of the farm trajectory toward matching these motivations. However, if he had not met with Marie, he may never have reintegrated sheep, as he was confronted with strong barriers. As he explains to his son, farmers have to stay open to emerging opportunities, as their farm are ever-evolving, and surprises and uncertainty are everywhere.

### I.1.5. Impacts of this unplanned epistemological reflection: what would I have done differently?

This step to the side made me wonder **what I would have done differently** in my Ph.D. study to follow the **insights of my epistemological reflection**. I see two main avenues. First, I still think that the **trajectories** that farmers follow to sustainable forms of livestock reintegration need to be **documented** to support scaling them up, in agreement with other studies (Coquil et al., 2014; Moojen et al., 2024). I would divide this analysis into two steps. First, I would use the first interview with farmers to **trace the trajectory that each had followed**, focusing on how determinants, such as their motivations and sociotechnical contexts, shaped it (Chantre et al., 2015; Gosnell et al., 2019). This approach is similar to my initial attempts. However, I would focus on **a specific and sustainable form of livestock reintegration** rather than seeking a diversity of farming systems. Doing so would **increase the chances of redundancy** and of identifying **common phases** and **trigger events** (Chantre et al., 2015), and could allow a typology of trajectories to be developed. Then, I would interview the farmers again to discuss the trajectories that I had reconstructed and supplement them with **unexpected events** that had strongly influenced how the farmers had reintegrated livestock that I might have overlooked in the first interview. In addition, I would focus on **documenting farmers' adaptive capacity** by identifying the **material** (e.g. financial, infrastructure) and **psycho-cognitive** (e.g. knowledge, risk preference, feelings) **resources and strategies that enabled them to take advantage of these unexpected events and transform them into emerging opportunities** (Bouttes et al., 2019; Coquil et al., 2014; Darnhofer, 2021; de Boon et al., 2024). This latter analysis could be performed for a specific form of livestock reintegration and/or with a diverse sample to provide a panorama of **key resources and strategies that increase farmers' adaptive capacity** when reintegrating livestock. Comparing the resources and strategies identified to those in other studies of farmers' adaptive capacity (Bouttes et al., 2019; Coquil et al., 2014) when implementing agroecological innovations could help produce more generic knowledge on common resources, thus easing implementation of agroecological innovations.

Second, I would supplement **objective assessment of impacts of reintegrating livestock** on farm sustainability (chapter 3) with **subjective self-assessments by farmers**, using their own indicators. The latter was often the only way that innovation-tracking initiatives assessed innovations (Salembier et al., 2021; Verret et al., 2020b). It would supplement objective multi-criteria assessment in three main ways. First, although I attempted to assess impacts of reintegrating livestock on farm sustainability using indicators that matched farmers' motivations, I could not assess all of the motivations that I inventoried in chapter 1. Thus, farmers' self-assessments would **address this diversity of motivations more fully**. Second, acknowledging the impacts of my research choices on my results made me question the objectivity of my research (Haraway, 1988; Law and Urry, 2004). The results of my "objective" assessment actually depended on assumptions that I made throughout the study, from defining system boundaries to simplifying the calculations. I attempted to remain as transparent as possible when reporting these choices. Adding farmers' self-assessments to the "objective" assessment, made by one single researcher (me) at a given time and under specific conditions, would **highlight the importance of considering farmers' knowledge, expertise and**

**perceptions** (Darnhofer et al., 2012; Lacombe et al., 2018; Toffolini et al., 2023). Third, self-assessments could provide insights into analysing farmers' trajectories, as it would help understand **how farmers adjusted their system over time** depending on their perception of the indicators that mattered to them (Chantre and Cardona, 2014; Toffolini et al., 2019).

## 1.2. An initial panorama of the diversity of farming systems in which livestock can be reintegrated

### 1.2.1. An exploratory approach that uses a diverse sample to build a panorama of options

#### 1.2.1.1. *An exploratory approach to the diversity of farming systems that reintegrate livestock...*

To date, livestock reintegration had been **understudied**. As my study was among the first on this topic (to my knowledge), I emphasized **diversity over representativeness** to provide a **comprehensive understanding** of livestock reintegration (Salembier et al., 2021). I **explored a wide range of farming systems** in which livestock had been reintegrated. I inventoried the **diversity of motivations, sociotechnical barriers and levers** that lead to these diverse forms of livestock reintegration. I developed **panorama of options for how livestock could be reintegrated** onto specialized crop farms and into specialized crop regions and then assessed **their impacts**. To do so, I studied a **diverse sample** that included the following:

- a **diversity of crop** (annuals: grain crops, market gardens; perennials: vineyards, orchards) and **livestock** (ruminants: cattle, sheep; monogastrics: pigs, poultry) **production**
- **livestock reintegration at the farm and/or regional level**
- **conventional and organic** farming systems
- farms with **utilized agricultural area** of 5-500 ha and that had reintegrated from 20 owned meat sheep to 15 000 owned fattening lambs each year, or from 200-10 000 laying hens

The panorama I developed is based on a **small and diverse sample**, which is not sufficient to derive **robust and actionable knowledge** for farmers or recommendations for technical advisors and policy-makers. **My results must thus be considered as initial stepping stones that provide overall trends and ranges of possibilities for motivations, barriers, changes in practices and impacts of reintegrating livestock**. They should be supplemented with further in-depth studies of sustainable forms of livestock reintegration.

#### 1.2.1.2. *...To be supplemented with future studies of the most promising initiatives*

This exploratory approach allowed me to identify **forms of livestock reintegration that can be particularly sustainable** (e.g. grazing sheep, chapter 3) and that should be **targeted first in future studies**. Other examples of livestock-reintegration initiatives have been studied recently, such as grazing poultry in orchards (Bosshardt et al., 2022; Paut et al., 2021). Although French farmers rarely graze poultry, doing so could provide environmental benefits and should be further studied as well.



For each of these two forms of livestock reintegration (i.e. sheep and poultry grazing), **in-depth study of the same research questions** addressed in this Ph.D. study would help produce **actionable knowledge** by documenting: i) specific farmers' motivations and their relative importance; ii) specific sociotechnical barriers, their relative weights and examples of levers to overcome them; iii) specific changes in farming practices and their agroenvironmental impacts, based on both an objective assessment and farmer self-assessments and iv) the trajectory that farmers followed to reintegrate livestock, from which a specific typology could be derived, along with particular emphasis on farmers' adaptive capacity.

Supporting the scaling up of sustainable forms of livestock reintegration would also require **addressing the technical knowledge gaps** that farmers mentioned, such as how much pasture should be reintegrated to feed livestock and store enough carbon to compensate for livestock emissions, and which plant species to include in the pasture to increase both carbon and nitrogen storage while providing nutritious feed to livestock. This could be done by combining **factorial and system experiments on commercial farms and at research stations** (Brewer and Gaudin, 2020; McKenzie et al., 2016; Puech and Stark, 2023; Simon et al., 2017).

#### 1.2.2. A core sample of farmers followed during the Ph.D. study to highlight inter-relations among determinants, practice changes and their impacts

Throughout the Ph.D. study, I studied a **core sample** of farmers who had reintegrated livestock. I analysed their farming systems under the **diverse lenses** of my chapters, through two successive interviews (one for chapters 1, 2 and 4, and one to collect additional data for chapter 3), supplemented by informal intermediate discussions with certain farmers (Figure 17, Table 12). This core sample **changed slightly** during the Ph.D. study depending on **farmers' availability and willingness** to be further involved in the study and on the specific objectives and **needs of the chapters**. Thus, to develop a **panorama** of the diversity of farmers' motivations for reintegrating livestock in France (chapter 1), I interviewed **as many French farmers who had reintegrated livestock as I could find** in two regions (i.e. 18 farmers). To perform transversal analysis of sociotechnical barriers to and levers for livestock reintegration (chapter 2), I selected a **sub-sample** of 7 farmers from the Occitanie region. Doing so allowed me to **represent the diversity of French farming systems** by interviewing a **similar number** of farmers **as I had in eastern Scotland and northern California**. To estimate agroenvironmental impacts of reintegrating livestock on farm sustainability (chapter 3), I **interviewed** 15 French farmers, 13 of whom I had already interviewed for chapter 1. For chapter 4, I selected **one farmer** involved in the previous chapters **whose story served as a particularly appropriate example** for emphasizing the importance of considering both rational decisions and unexpected events when studying the trajectory that leads to reintegrating livestock. Six farms were included in chapters 1, 2 and 3 (Table 12).

Table 12. Contingency table of farmers involved in the chapters of the Ph.D. study

Number of farms involved	Chapter 1	Chapter 2	Chapter 3	Chapter 4	Chapters 2 and 3	Chapters 1, 2 and 3
Chapter 1 (n=18)		7	13	1	6	
Chapter 2 (n=7)			6	1		
Chapter 3 (n=15)				1		
Chapter 4 (n=1)					1	1

**Repeatedly exchanging with farmers over three years** (e.g. organizing the second interview, asking follow-up questions, updating them with feedback on the analysis, keeping them involved in the study) helped me **contextualize the information** that they provided and **supplement my understanding of how their farming systems functioned**. It allowed me to **monitor their rapid evolution**, as **many farming systems that reintegrate livestock are still “in-the-making”** (Toffolini et al., 2019).

This **follow-up analysis of the same farms under diverse lenses** allowed me to emphasize the **complex inter-relations** among i) the **determinants** that led to reintegrating livestock (i.e. farmers’ **motivations, sociotechnical contexts and emerging opportunities** that they use creatively) and ii) **changes in practices** besides livestock reintegration and their **related impacts**. To my knowledge, these relations have rarely been studied in depth for other agroecological innovations (de Lauwere et al., 2022; Salembier et al., 2016). To **illustrate** how diverse combinations of motivations, sociotechnical contexts and emerging opportunities can lead to diverse forms of livestock reintegration and drive diverse agroenvironmental impacts, I provide **two contrasting archetypal examples** (Figure 46 and Figure 47, described in Box 8 and Box 9, respectively). I constructed them based on the diverse farmers’ stories that I heard throughout my Ph.D. study. They aim at emphasizing two “extremes” that can be reached when reintegrating livestock.

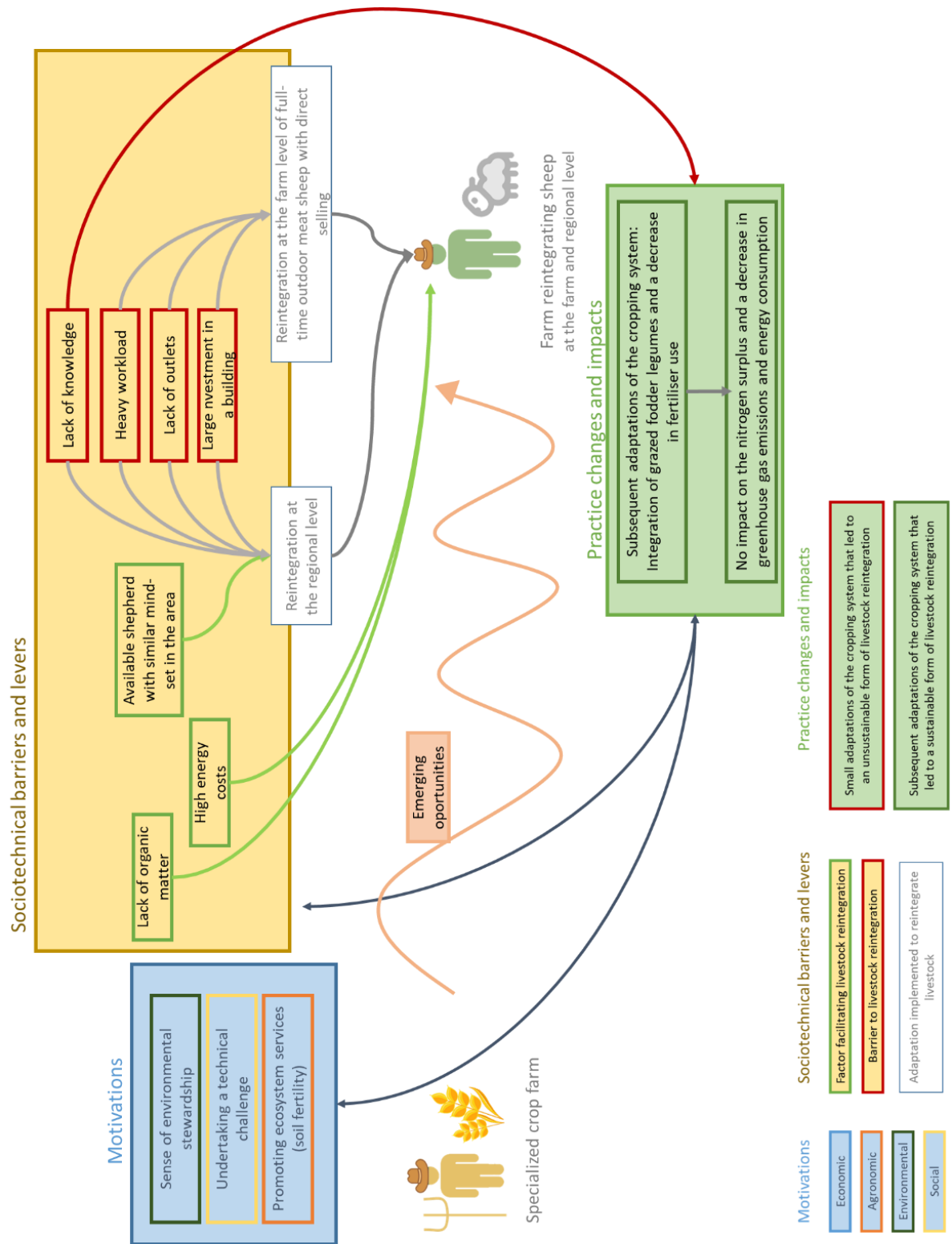


Figure 46. Example of inter-relationships among motivations, the sociotechnical context, farming-practice changes and agroenvironmental impacts: an archetypal case of sheep reintegration

I illustrate **two archetypal examples** (Figure 46 and Figure 47) that explain how **diverse motivations and sociotechnical contexts can lead to diverse forms of livestock reintegration that have contrasting environmental impacts**.

*In the latter (Figure 47), a specialized grain-crop farmer, Catherine, wants to reintegrate livestock on her farm to **fulfil her sense of environmental stewardship, undertake a technical challenge and promote ecosystem services**, especially soil fertility.*

*In her area, Catherine **lacks organic matter and faces high energy costs**. As she has always specialized in crop production, and her farm is located in a specialized crop region, she **lacks the knowledge and skills needed to manage livestock**. She believes that reintegrating livestock on her farm would **increase her workload greatly** and require **large investments in a building**. In addition, she has no idea for potential **outlets for livestock products**. She considers **partnering with a shepherd to benefit from the advantages** that she expects from livestock reintegration while **decreasing the need to learn additional skills, increase her workload, make investments and find outlets**. She does not imagine hosting cows on her farms, as she is afraid that they may trample her soils. However, meeting a livestock farmer in a specialized crop region is not easy.*

*One day, at the restaurant in her village, while she is complimenting the chef on the lamb dish, he tells her that the sheep farmer also happens to be there. She thus meets Nicolas **by chance**. As their conversation goes well, Catherine suggests that he graze his sheep on her cover crops. Despite the distance (ca. 50 km), Nicolas agrees to visit her farm the next day. As he finds her 100 ha of cover crops to be widely sufficiently large to feed some of his flock, when he finishes grazing his own farm's pasture three weeks later, he brings 50 sheep over as **an initial trial**. Things go well during the first year, as Nicolas' sheep can graze Catherine's farm from November-March. Nicolas is happy about the growth of his ewes and lambs, and Catherine is happy that she did not need to terminate her cover crops mechanically.*

*Over the years, Nicolas and Catherine continue their partnership. Nicolas **gradually** brings more sheep, but they still stay on the farm only during winter. As Catherine would like to **benefit from the advantages of sheep throughout the year and gradually learned how to manage sheep** due to her shared experience with Nicolas, she decides to **buy a small flock of meat sheep**. She raises them in a **full-time outdoor system to have less need for additional investments, skills and workload** than those required by indoor dairy sheep, for instance. She decides to **sell some of her products directly to consumers** on her farm to ensure **higher prices**.*

*Catherine's **deep environmental values and desire to undertake a technical challenge** lead her to make **subsequent adaptations to her cropping system to maximize interactions with sheep** (both Nicolas' and hers). She **introduces pasture** into her crop rotation and **adds more legumes to her cover crops** to make them more nutritious for livestock. She also **decreases inputs of organic fertilisers** to consider deposition of sheep manure, which decreases her need for organic matter. These adaptations lead her to **reintegrate livestock with beneficial agroenvironmental impacts** consistent with **her initial motivations**. She does not increase her farm nitrogen surplus, compensates for the sheep's greenhouse gas emissions through the additional carbon stored by the pasture and decreases energy consumption because the sheep now terminate her cover crops by grazing them.*

Box 8. Example of inter-relations among motivations, the sociotechnical context, farming-practice changes and agroenvironmental impacts: an archetypal case of sheep reintegration

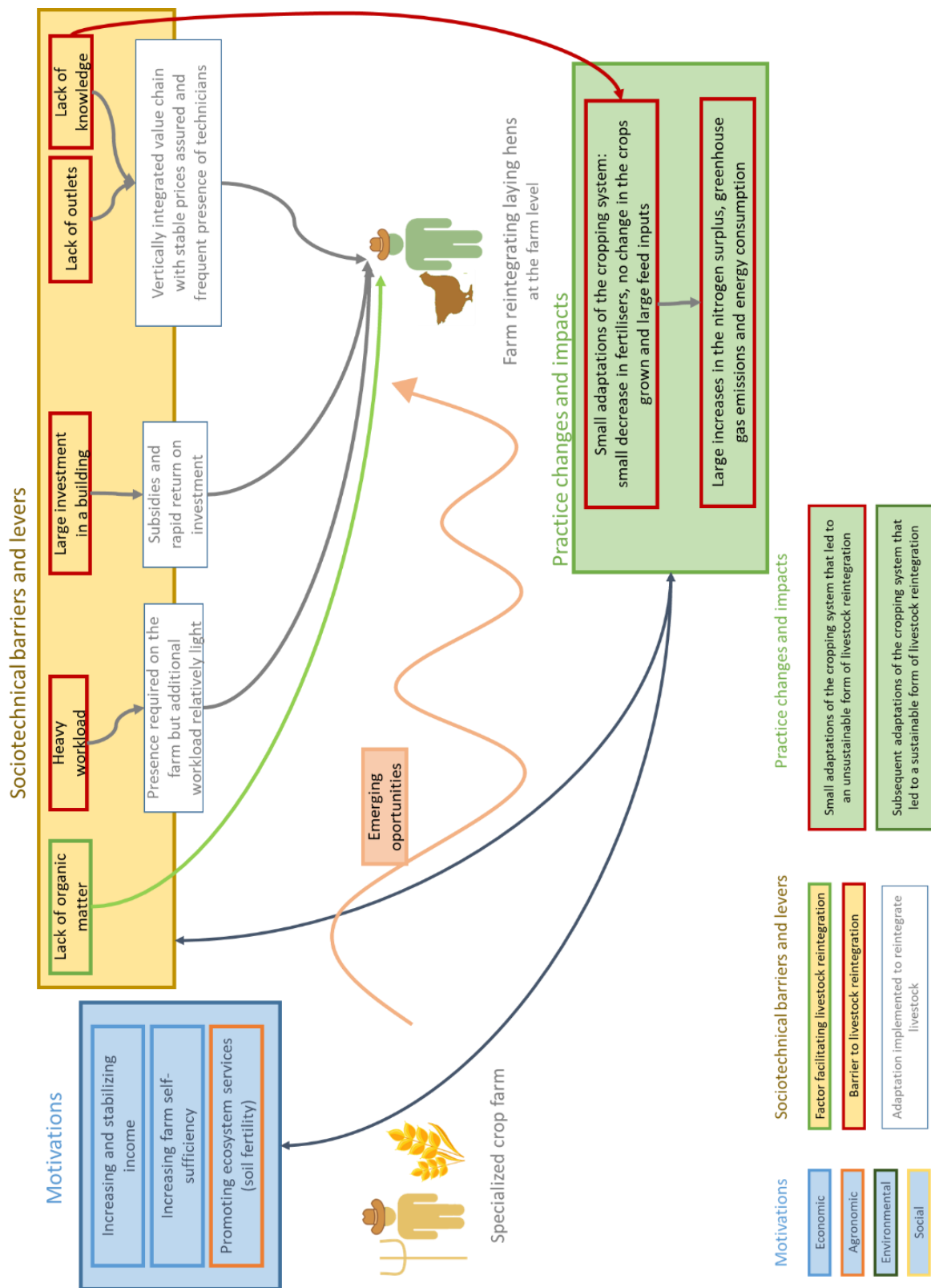


Figure 47. Example of inter-relationships among motivations, the sociotechnical context, farming-practice changes and agroenvironmental impacts: an archetypal case of poultry reintegration

I illustrate through **two archetypal examples** (Figure 46 and Figure 47) that explain how **diverse motivations and sociotechnical contexts** can lead to **diverse forms of livestock reintegration** that have **contrasting environmental impacts**.

*In the former (Figure 47), a specialized grain-crop farmer, Jean, wants to reintegrate livestock to **increase and stabilize income, increase farm self-sufficiency and promote ecosystem services**, especially soil fertility. Located in the same region as Catherine (Figure 46), he also **lacks organic matter** for his fields and faces a **lack of knowledge and skills** to reintegrate livestock. He does not know to **whom he could sell livestock products, has no buildings** that could be used for livestock production, **does not want to make large investments for them** and cannot increase his workload.*

*One day **at the village fair**, he meets a **technician from a laying-hen cooperative** who promotes egg production. The technician's rapid estimate of the **profit** that Jean could earn if he reintegrated poultry according to his recommendations convinces Jean to take the plunge, as he sees it as the opportunity to **increase and stabilize income** that he was looking for. Jean thus reintegrates 10 000 laying hens on his farm. His **investment** for the building is **secured by the technician's estimated return on investment**. Jean even manages to have construction of the building **subsidized** by the region. As egg production in a cooperative is **heavily integrated vertically**, Jean **does not have to manage any outlets** for livestock products **or have much additional knowledge**, given that the technician can support him.*

*After a few years, Jean believes that the **additional workload** caused by reintegrating poultry (2 hours of work on the farm each day) is **small**, as he feels that **the economic benefits that it provides are worth it**. He also feels that interacting with the animals increases his overall work satisfaction. As his poultry reintegration aimed mainly at **ensuring economic sustainability**, Jean **did not adapt his cropping system beyond what was necessary**: converting one crop field into an outdoor area for laying hens. He **buys ready-made concentrate feed from the cooperative**, as he does not have the equipment (e.g. on-farm mill, storage silo) or knowledge to produce it from his own grain, and he is afraid that its variable protein content would decrease egg production. He would have liked to decrease the amount of organic matter that he buys to increase farm self-sufficiency, as he has difficulty finding it, but **he does not know how to quantify the input of poultry manure and is afraid that decreasing the input of other organic matter would decrease his cereal yields**. He still thinks that spreading chicken manure promotes soil fertility, consistent with his initial motivations. The **lack of adaptations** made to his cropping system, along with the lack of knowledge, fear of decreased production and **strong reliance on feed input** leads to **high agroenvironmental impacts** of poultry reintegration, with large increases in the farm nitrogen surplus, greenhouse gas emissions and indirect energy consumption.*

*Box 9. Example of inter-relations among motivations, the sociotechnical context, farming-practice changes and agroenvironmental impacts: an archetypal case of poultry reintegration*

### I.2.3. An exploratory approach: needed to document pioneer farmer-led initiatives

My **choice** to study a **core sample** of farmers who had reintegrated livestock and to include a **wide diversity** of farming systems was **intentional**, as it **aligned with my research objectives** to provide initial insights into an understudied research topic and highlight relations among determinants, changes in practices and their impacts. However, it was also **influenced greatly by the “reality” of studying such pioneer farming systems**. Indeed, as several other studies of agroecological innovations reported, **identifying farmers** who implement these innovations **is difficult** and relies mainly on advisor networks and word of mouth, as there is no database that lists these farming systems (see the concept of "silent agroecology" of Lucas (2021) and the few ways to identify innovations described by Salembier et al. (2021)). This is even truer for the **pioneer farming systems** that reintegrate livestock. In particular, at the beginning of my Ph.D. study (2021), livestock reintegration was not known at all, as only a few farmers had done it. All of the advisors I contacted to identify farmers who had reintegrated livestock said that they had not paid attention to such initiatives and were often surprised by my interest (Box 10). Consequently, including the widest possible diversity of farming systems in the sample and relying on the same farmers throughout the Ph.D. study was **the only possible strategy to study** the determinants that led farmers to reintegrate livestock, their changes in practices and related impacts. Such **exploratory approaches raise methodological challenges and have limits** (see the Introduction, Part II, section 2 and Discussion, Part II, section 2). However, they are **necessary to document breakthrough farmer-led agroecological innovations** such as livestock reintegration (Salembier et al., 2021).

Although **livestock reintegration remains a niche practice**, its situation has **evolved** somewhat since the beginning of my Ph.D. study. Mostly independent of this study, **livestock reintegration has gained interest**. **More farmers have decided** to reintegrate livestock onto specialized crop farms and into specialized crop regions, as shown by the many testimonials in the specialised agricultural press (L'Humanité, 2022; La France Agricole, 2023; Pleinchamp, 2022; Reussir Patre, 2024). **More technical days** on the topic have been organized (GABB32, 2022; La Dépêche, 2024) or are planned later this year. **More research projects** that include initiatives of livestock reintegration are being performed (e.g. SagiTerres, on collective strategies for facilitating exchanges between crop farmers and shepherds in a territory (INRAE, 2022-2024); Interagit+, on cover-crop grazing by sheep and cattle (IDELE, 2022-2025); LAPOESIE, on orchard grazing by rabbits (INRAE, 2020-2022)).

*Box 10. Changes in research and development efforts on livestock reintegration since the beginning of the Ph.D. study*

### I.3. A return to initial concepts and hypotheses

#### I.3.1. Reintegrating livestock and integrated crop-livestock systems ICLS: common points but diverse research objects

##### *I.3.1.1. The need to study livestock reintegration itself*

In the Introduction, I stated that **farming systems that reintegrated livestock were similar to ICLS**, but I hypothesized that **their differences justified studying livestock reintegration itself** (Part I, Section 3). My results confirmed this hypothesis. ICLS and livestock reintegration **are two different research objects**. They differ mainly in that **ICLS connect or reconnect elements that are already present** (i.e. crop and livestock enterprises at the farm or regional level), while **reintegrating livestock introduces a new element** (i.e. livestock) that had completely disappeared from the farm and the region. This difference has two main consequences for the study and development of these systems.

#### *Stronger sociotechnical barriers to reintegrating livestock*

First, **the same sociotechnical barriers hinder both ICLS and livestock reintegration** onto specialized crop farms and into specialized crop regions: a lack of knowledge, of skilled versatile workforce and of equipment for ICLS and livestock reintegration at the farm level (Garrett et al., 2020; Ryschawy et al., 2013) and difficulty identifying a suitable partner and maintaining the partnership over the long term for ICLS and livestock reintegration at the regional level (Asai et al., 2018; Martin et al., 2016; Schut et al., 2021).

Although similar, **these barriers were much stronger and more difficult to overcome for reintegrating livestock**, which involves re-creating an entire sociotechnical system that had disappeared (Cortner et al., 2019). For instance, farmers were faced with a **lack of knowledge on technical aspects** (e.g. how many sheep to graze a cover crop, and when), but also on the **potential services** that livestock once provided in the region, and could not rely on a neighbouring livestock farmer or technical advisor to provide this knowledge (Dumont et al., 2019; Moojen et al., 2024). Similarly, the **lack of processing facilities** (e.g. slaughterhouses) and **services** (e.g. veterinarians) was much more common for livestock reintegration, which occurred in specialized crop regions where all livestock-related facilities and services had been decreasing for decades (Chatellier and Gagné, 2012; Cortner et al., 2019; Roguet et al., 2015). For livestock reintegration at the regional level, overcoming the **difference in mind-set** between crop and livestock farmers and **making trade-offs between individual and collective objectives** was even more difficult than doing so for ICLS (Asai et al., 2018; Martin et al., 2016; Ryschawy et al., 2019), as the disconnect between crop and livestock farmers was even greater.

Besides the disappearance of the sociotechnical system, the fact that livestock reintegration is still in a **pre-niche phase\*** (i.e. implemented by **pioneer farmers** and not yet “anchored” (Elzen et al., 2012) in a protected market, network or ecosystem of innovation) (Pigford et al., 2018; Weituschat et al., 2023) could be dissuasive (Lähdesmäki et al., 2019; Sutherland, 2013). Indeed, farmers who reintegrated livestock were **isolated**, as they lacked examples of similar initiatives. They also often faced **criticism** from their specialized crop-farmer neighbours, but it may have had little impact, as farmers who reintegrated livestock usually already had an innovative farming system (Lähdesmäki et



al., 2019; Moojen et al., 2024; Sutherland et al., 2016). However, if farmers felt fear and uncertainty in the face of the many barriers they had to overcome, they could rely only on their **individual motivations and personal conviction** that “this was the right thing to do”. ICLS are more common than farms that reintegrate livestock. For ICLS, farmers’ motivations and profiles described in the literature were often similar to those identified for livestock reintegration (Cortner et al., 2019; Ryschawy et al., 2021), but seeing similar initiatives on their neighbours’ farms often strengthened farmers’ individual motivations for implementing such farming systems (Lucas, 2021; Moojen et al., 2024).

**These stronger barriers retrospectively justify studying livestock reintegration itself to document promising farming systems in which farmers managed to find levers to reintegrate livestock sustainably.**

#### Deeper transformative changes in farming systems that are still “in-the-making” for livestock reintegration

Second, **reintegrating livestock is by nature a process of change**. Reintegrating livestock either at the farm or regional level, implies **making transformative changes of the farming system to render its agroenvironmental impacts sustainable**. For instance, it could require redesigning the crop rotation to include pasture for livestock grazing or developing on-farm direct selling to ensure outlets for livestock products (Figure 46, Box 8). For livestock reintegration at the regional level, it could also imply switching from making all decisions about a farming system individually to making compromises with a livestock farmer to maintain a partnership in the long term (Asai et al., 2018; Martin et al., 2016). Reintegrating livestock could even **cause farmers to question their identity** (Bruno et al., 2022; Cullen et al., 2020), changing from a “crop farmer” to a “mixed crop-livestock farmer”. This was true for sustainable forms of livestock reintegration at the farm and regional levels, as both involved technical and organizational adaptations to maximize synergistic interactions with the animals, which became an integral part of the farming system regardless of who owned them or how long they stayed on the farm.

**Making such deep changes was not straightforward**, especially given the many complex sociotechnical barriers mentioned. They often required that farmers’ motivations went beyond economics included provision of ecosystem services and the desire to undertake a technical challenge. These transformative changes were also made in part due to unexpected events that farmers used creatively (Darnhofer et al., 2010). Farmers used **trial and error** and progressed **step-by-step based on their observations** (Coquil et al., 2014; Darnhofer et al., 2012; Meynard et al., 2023; Toffolini et al., 2019). For instance, they could begin by reintegrating a few sheep for a few weeks, initially in partnership with a shepherd, then host more sheep for a longer duration if everything went well during the first year, and finally buy their own sheep and graze them on the farm throughout the year if they were completely satisfied (Figure 46, Box 8). Making such changes thus required **time and adaptations**. It also required **substantial learning** by farmers, such as “how to manage livestock when you have always only grown crops” (Chantre and Cardona, 2014; Coquil et al., 2014). As livestock reintegration

was still **recent** (the mean time since reintegration was ca. 6 years in my sample), most of these farming systems were still **“in-the-making”** and had not yet reached a dynamic steady state (assuming that they would someday reach one) (Toffolini et al., 2019).

However, ICLS studied in the literature were usually **already in a steady state**. They **did not involve transformative changes to the same extent as reintegrating livestock did** (Garrett et al., 2020; Ryschawy et al., 2013). For ICLS at the farm level, **integration between crop and livestock enterprises had always existed**, with various degrees of spatial, temporal and organizational integration (see the Introduction, Part I, section 3.2) (Bell and Moore, 2012; Moraine et al., 2014). It may have changed over time (e.g. from indoor animals fed harvested fodder to outdoor animals grazing), and these changes did influence the farming system, but they **rarely involved transformative changes as deep as those of reintegrating livestock** (e.g. when changing from indoor animals fed harvested fodder to outdoor animals grazing, pasture was already present). Similarly, these changes did not require **as much learning as livestock reintegration did** (e.g. mixed crop-livestock farmers had always managed both crops and animals, and had always known where to buy and sell livestock-related inputs and products). For ICLS at the regional level, crop farmers often considered hosting animals (usually sheep) as a simple alternative to chemical or mechanical termination when managing grass in vineyards or orchards, or cover crops on grain-crop farms. Reintegrating livestock decreased their herbicide or fuel consumption and working time (Niles et al., 2018; Ryschawy et al., 2012) while supporting a shepherd from the region. These partnerships were often **occasional and opportunistic** (Asai et al., 2018; Martin et al., 2016) and thus **rarely generated transformative changes of the cropping system**. Consequently, **ICLS at the farm and regional levels were in more “stable” states than farms that reintegrated livestock sustainably**.

**These differences justify documenting livestock reintegration itself** for two reasons. First, doing so implies **characterizing the specific transformative changes required to reintegrate livestock sustainably**. It implies investigating the farming system that resulted from the change process, but also farmers’ motivations and sociotechnical contexts that led them to make the changes, and the many adaptations they made over time. Second, **studying farming systems “in-the-making” raises specific methodological challenges** (see the Introduction, Part II, section 2.2 and Discussion, part II, section 2.2). It calls in particular for long-term follow-up approaches to monitor changes in farmers’ practices and their impacts.

#### *1.3.1.2. Results on livestock reintegration that can inform research on ICLS*

Although livestock reintegration is a different research object than ICLS, **the results I produced may help inform research on ICLS**. First, **most of the motivations** for reintegrating livestock that I identified were **similar** to those documented for adopting ICLS (Cortner et al., 2019; Garrett et al., 2020; Moojen et al., 2024; Niles et al., 2018; Paut et al., 2021). However, to my knowledge, **no study has examined in depth farmers’ motivations for implementing ICLS**. I thus improved this field of research by providing a ranked summary of motivations for reintegrating livestock, along with initial insights into how these motivations differ depending on the livestock system reintegrated. Second, as the barriers

to reintegrating livestock were similar to those of ICLS (Asai et al., 2018; Garrett et al., 2020; Martin et al., 2016), **the examples of levers that farmers implemented to overcome barriers to reintegrate livestock** identified in this Ph.D. study **may be inspiring to support the scaling up of ICLS** as well. Third, to my knowledge, **agroenvironmental impacts of ICLS have rarely been assessed using data collected on commercial farms** or from **such a diversity of farming systems** (Ryschawy et al., 2012). My assessment of agroenvironmental impacts of farming-practice changes thus provided initial insights into the sustainability of farms that integrate crops and livestock compared to that of specialized crop farms, for a variety of farming systems.

### 1.3.2. Reintegrating livestock: agroecological and sustainable?

In the Introduction, I argued that livestock reintegration is **aligned with the principles of agroecology** as it increases **farm diversity** (Figure 7), which allows for **synergistic interactions** between crop and livestock enterprises that can increase farm **self-sufficiency** in biomass, nutrients and energy (see the Introduction, Part I, Section 1.3) (Altieri, 1995; FAO, 2018; Wezel et al., 2009). However, saying that reintegrating livestock is agroecological in principle does not provide insights into its **actual sustainability**. This issue is not trivial. Several **studies have highlighted environmental benefits of systems that integrate crop and livestock enterprises at the farm or regional level** (Baker et al., 2023; Martin et al., 2016; Ryschawy et al., 2012), but these studies were rarely based on commercial farm data. However, **societal pressures on livestock production continue to increase due to livestock-related environmental impacts** (FAO, 2023; Franzluebbers, 2005; Lassaletta et al., 2009). Many studies call for **changing the current regime of specialized and input-intensive livestock farming** and even **question whether livestock are necessary in future food systems** (Garnett et al., 2017; Torpman and Röö, 2024; Van Zanten et al., 2019). In my Ph.D. study, **I informed this debate** by providing **initial insights into the sustainability of reintegrating livestock** by assessing impacts of farming-practice changes beyond reintegrating livestock in diverse farming systems. I found that **addressing this issue is not straightforward** and that **reintegrating livestock is not a panacea**.

Reintegrating livestock onto specialized crop farms **can provide environmental benefits** (i.e. decreasing energy consumption without increasing the nitrogen surplus or greenhouse gas emissions), **but only when it is accompanied by transformative changes of the farming system to maximize synergistic interactions between crop and livestock enterprises** (Figure 46, Figure 47, Box 8, Box 9). For instance, reintegrating sheep in a full-time outdoor system, along with converting cropland into pasture, decreased mechanization (partly replaced by grazing) and the amount of fertilisers used (partly replaced by sheep manure). **Informing the debate on the role of livestock in future farming and food systems, reintegrating livestock onto specialized crop farms along with systemic adaptations could thus be a sustainable option**. It could help decrease consumption of fossil fuels while improving crop performances and producing human-edible protein with little feed-food competition (Hennessy, 2021; Thornton, 2010). **Scaling up such sustainable forms of livestock reintegration should be supported**.

However, as mentioned, **making such transformative change is complex and requires time**. A lack of systemic adaptations early on may lead to the conclusion that such systems are not sustainable, but **this conclusion might change later when subsequent adaptations are made or when the farming system reaches a dynamic steady state** (Magne et al., 2024). Similarly, reintegrating livestock required making **trade-offs between individual and collective objectives** in the **short term** (e.g. annual profitability) and **long term** (e.g. improving soil quality to maintain yields over years), and in **multiple dimensions** (e.g. socio-economic, agroenvironmental) (Klapwijk et al., 2014; Kopainsky et al., 2019; Ryschawy et al., 2019). The answer to the question “Is reintegrating livestock sustainable?” thus **depends on the definition of sustainability used** and may also **change over time** and.

### 1.3.3. Reintegrating livestock as a retro-innovation

#### *1.3.3.1. Arguments for considering livestock reintegration as a retro-innovation*

In the Introduction (part II, section 1), I also presented livestock reintegration as generally consistent with the definition of a **retro-innovation** (Figure 48) (Stuiver, 2006; Zagata et al., 2020). My results allowed me to elaborate on this initial statement.

Retro-innovations consist of taking **inspiration from farming practices that have been abandoned and forgotten** and **adapting them to meet objectives and match constraints in the modern world** (León-Bravo et al., 2019; Stuiver, 2006; Zagata et al., 2020). They differ from modernization in that they imply a breakthrough and a **departure from traditional practices that need to be remembered** (Zagata et al., 2020). **This was true for farms that reintegrated livestock**, which were originally mixed crop-livestock farms that specialized in crop production before intentionally organizing the return of animals (see the Introduction, Part 1.3) (Garrett et al., 2020; Schut et al., 2021). Conversely, farms that had always been mixed crop-livestock farms modernized.

According to Zagata et al. (2020), **retro-innovations emerge** due to **“reflexivity”** (i.e. **criticism of modern agriculture**) and/or **“nostalgia” for traditional farming systems** (Kilis et al., 2022; Zagata et al., 2020). Although farmers did not specifically mention their opposition to the dominant regime, their **motivations for reintegrating livestock were based on questioning the high-input specialized regime of crop production**. Farmers often emphasized promoting ecosystem services and increasing farm self-sufficiency in reaction to volatile input prices and to align with personal values of environmental stewardship. Even farmers who prioritized economic motivations to increase and stabilize their income were motivated by criticism of the dominant regime, in which they could not earn a viable income. Moreover, **most farmers in the sample already had an innovative system** before they reintegrated livestock. Most of their farms were **certified organic**, which Zagata et al. (2020) identified as an example of retro-innovation. Although I did not specifically investigate why they converted to organic farming, as it lays beyond the scope of the study, this reinforced the idea that these farmers were already **“opposed” to the dominant regime** and that reintegrating livestock continued this history of opposition. Reintegrating livestock also led them to implement other practices identified as examples of retro-innovation, such as on-farm direct selling (Kilis et al., 2022).

In retro-innovations, the “reflexivity” about the current system combines with **“reminiscence” of long-forgotten farming practices that are considered desirable** (Zagata et al., 2020). This was true for livestock reintegration, which was deeply **inspired by farmers’ positive memories of traditional mixed crop-livestock farms**. Most actors of the sociotechnical systems surrounding livestock reintegration who I interviewed identified this cultural heritage as a key element that facilitated reintegrating livestock. Beyond “reminiscence” of these farming practices, retro-innovation implies their **“revival” to align with the current context into which they will be integrated** (Zagata et al., 2020). This was true for livestock reintegration, which **hybridized the traditional model of mixed crop-livestock farms with modern needs, constraints and expectations**. When reintegrating livestock, farmers **did not copy or apply the traditional model of mixed crop-livestock farms of the preindustrial era** (Schiere and Kater, 2001). First, as part of the “revival” process, they **selected the practices** that interested them given their objectives and contexts. For instance, they rarely used animal traction, and when they did, it only supplemented mechanization on areas that could not be tilled otherwise (Cerutti et al., 2014; Spugnoli and Dainelli, 2013). Although they often attempted to maximize farm self-sufficiency, they could use inputs if necessary. Their products were sold on local or global markets, in much larger quantities than those of mixed crop-livestock farms of the preindustrial era to ensure farm economic sustainability. The use of new technologies, such as WhatsApp groups, could ease long-distance management of livestock and facilitate communication between crop and livestock farmers in a partnership (Prost et al., 2024). Besides selecting certain practices from traditional mixed crop-livestock systems, farmers who reintegrated livestock also **adapted them in response to constraints and opportunities of the current regime**, as part of the “revival” and “integration” processes described by Zagata et al. (2020). These adaptations required **learning**.

I identified **two main strategies that farmers followed to adapt the traditional mixed crop-livestock farming system to their sociotechnical context and motivations**: reintegrating sheep in a full-time outdoor system or poultry in highly-integrated value chains (Figure 46, Figure 47, Box 8, Box 9). These two strategies **allowed farmers to overcome the sociotechnical barriers of the regime of specialized crop farming**, such as the need for additional knowledge, the difficulty in finding inputs and outlets, and the lack of infrastructure, which could require large investments. They also allowed farmers to minimize the additional workload. They gave farmers the opportunity to reintegrate livestock in an initial form and **learn progressively through trial and error**, which led them to adapt of their farming systems step-by-step (Chantre and Cardona, 2014; Coquil et al., 2014).

The first strategy was to reintegrate **sheep in a full-time outdoor system** at either the farm or regional level. In these systems, farmers **benefited from the ecosystem services** that the pasture and sheep provided (Bretagnolle et al., 2011; Brewer and Gaudin, 2020; Franzluebbbers et al., 2014), while investments were small. For sheep reintegration at the regional level, the lever found to overcome sociotechnical barriers was to **rely on the livestock farmer to address all animal-related issues** (Asai et al., 2018; Martin et al., 2016; Moraine et al., 2014). This freed farmers **from issues related to inputs and outlets** for livestock production. It also **limited the initial need for additional skills and knowledge**, and gave farmers the opportunity and time to **learn** from the livestock farmers’

experience. In addition, it helped them **decrease their workload**, such as not needing to terminate cover crops mechanically because the sheep had grazed them (Niles et al., 2018). For sheep reintegration **at the farm level**, farmers limited the **supplementary workload and initial need for additional skills and knowledge** by designing livestock systems that **limited sheep management and mitigated risks** (i.e. full-time outdoor grazing to produce meat). They usually began with **small flocks** whose size progressively increased as farmers became more familiar with livestock production. They often used **rustic breeds** that were best suited for outdoor conditions and less sensitive to any mistakes they made in managing them. These rustic breeds were often difficult to find and less productive than the high-yielding breeds of specialized high-input systems. Farmers thus needed to **make trade-offs** (Garbach et al., 2017; Garrett et al., 2017; Ryschawy et al., 2019) and use **trial and error** to simultaneously adjust their management strategies and livestock breeds (e.g. through cross-breeding) (Quéron et al., 2023). In such systems, farmers often **did not use any livestock feed** besides grazing, which **decreased their need to find input suppliers**. Due to their small flocks and rustic breeds, however, farmers often had difficulty finding outlets for their products, which sometimes drove them to begin **on-farm direct selling** and required acquiring new skills (Mcelwee and Bosworth, 2010).

The other strategy was to reintegrate **poultry in highly-integrated value chains**. In these systems, farmers benefited from the **economic advantages of diversifying farm production**. They limited the need for additional skills and knowledge by relying on **technicians from the cooperative**, who **strongly supported the poultry management. The cooperative managed all inputs and outputs**, which freed farmers from having to find new suppliers and outlets. Farmers minimized the financial risks of large investments by relying on technician's **estimations of expected returns on investments and signing production contracts**. This approach allowed farmers to **progressively familiarize themselves with poultry production and learn step-by-step**. Additional labour and its difficulty could be limited by using **new technologies**, such as robotic egg collection and packaging. In this farming system, **farmers took advantage of the modern organization of the value chain to benefit from the advantages of mixed crop-livestock farms while minimizing the constraints**. Although this form of livestock reintegration has negative environmental impacts (chapter 4), it **may serve as an initial step toward a return of livestock farming** (Sutherland et al., 2016) and may lead farmers to reintegrate other types of livestock.

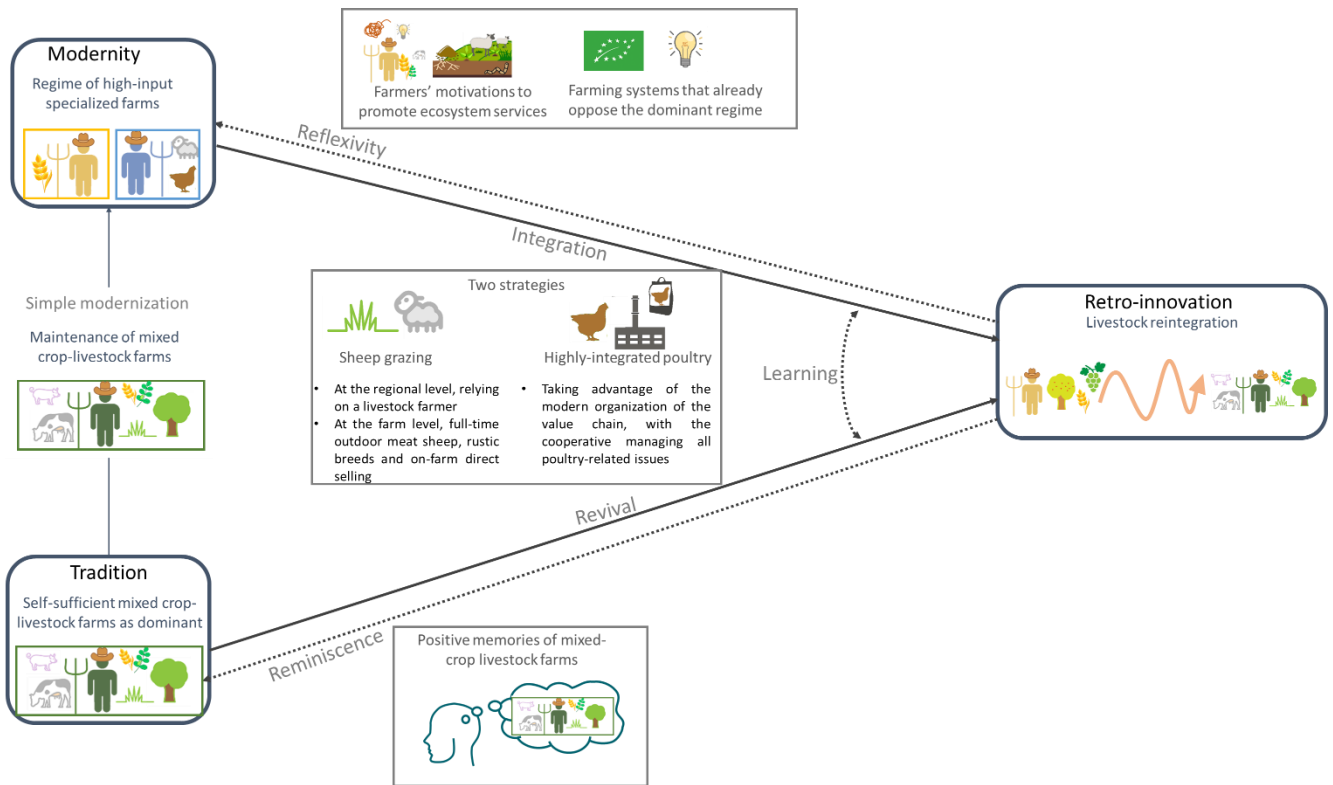


Figure 48. Conceptualization of retro-innovations applied to livestock reintegration (adapted from Zagata et al. (2020))

### 1.3.3.2. Utility of basing livestock reintegration in the retro-innovation framework

Labelling livestock reintegration as a retro-innovation may **improve the opinion that actors of the sociotechnical system have of it**, by **making it seem more similar to their sociotechnical imaginary of progress in farming**, and thus supporting scaling it up (Polzin, 2024; Rudek, 2022; Shortall, 2019). For the actors I interviewed, livestock reintegration was associated with **positive memories** of traditional mixed crop-livestock systems, which the actors considered to be **desirable farming systems** that could **inspire** them. However, I interviewed only **actors of the sociotechnical system surrounding livestock reintegration**. It is likely that some **actors from the regime** of high-input specialized farming may share a different imaginary of progress in farming, one that is more similar to the **most common sociotechnical imaginary of industrial agriculture and the techno-centric vision of progress**. Like many farming systems or practices inherited from or inspired by traditional ways of farming (e.g. organic farming, grazing cows), livestock reintegration **may not fit with this sociotechnical imaginary** (Polzin, 2024; Shortall, 2019).

**Innovation is associated mainly with societal benefits in most sociotechnical imaginaries** (Strand et al., 2018). It is seen as the way to address the “grand challenges” of the 21<sup>st</sup> century. It is being **promoted by many governments** (Alderkamp et al., 2024), which are funding ever more research projects on the subject (European Commission, 2021). In the techno-centric vision of progress, innovation in farming is often associated with technology, such as sensors that can make huge

numbers of measurements and generation of big data to increase precision and efficiency (Felt, 2015). However, the theorization of concepts such as retro-innovation emphasizes the diversity of forms that innovations can take. **Highlighting the innovative component of reintegrating livestock** (i.e. the “revival”, “integration” and “learning” processes that go beyond applying an old recipe or simply modernizing it (Zagata et al., 2020)) **could help benefit from the innovation-friendly context to improve imaginaries of the actors of the sociotechnical system around livestock reintegration.** It would favour scaling up of sustainable forms of livestock reintegration.



## Part II. Methodological contributions

In my Ph.D. study, I aimed at helping to **improve the innovation-tracking framework** (Salembier et al., 2021) to increase the understanding that it provided of agroecological innovations and broaden its ability to address the methodological challenges raised when studying them. In this section, I discuss **how my results can help improve this framework** (Table 13, Box 11) **and how I addressed the methodological challenges raised by studying agroecological innovations.**

Table 13. Main contributions of the Ph.D. study to improve the innovation-tracking framework (by stage, defined by Salembier et al. (2021)) and further improvements needed

Stage of innovation tracking	Main focus of most published innovation-tracking initiatives	Suggested improvements	Application of the innovation-tracking framework to livestock reintegration	Additions made for livestock reintegration	Further improvements to consider
<b>1. Defining a tracking project</b>  <b>2. Revealing innovations</b>  <b>3. Learning about innovations</b>	Tracking that focuses on farmers	Target diverse actors to increase understanding of the sociotechnical contexts surrounding farmers' innovations	<p>Targeted innovation tracking of livestock reintegration "in-the-making" with farmers</p> <p>Farmers identified using an advisor network and snowball sampling</p> <p>Individual interviews with farmers supplemented with farm visits</p>	<p>Involvement of other key actors of the sociotechnical system surrounding livestock reintegration</p> <p>Other actors identified through purposive sampling (Campbell et al., 2020; Tongco, 2007) using a researcher network</p> <p>Individual interviews with other key actors of the sociotechnical system surrounding livestock reintegration</p>	-
	<b>4. Analysing learning from the innovations</b>  Farmers' motivations ignored or reduced to their objectives	Deepen the study of farmers' motivations for implementing this innovation	-	Mixed method to provide a ranked summary of motivations for reintegrating livestock	Mapping motivations  Strengthening relations with social science researchers to deepen the analysis
	Focus on the cropping-system or farm level	Include initiatives beyond the farm level, such as cooperation among farms	Analyse livestock reintegration at the farm level	Analyse livestock reintegration beyond the farm level (i.e. at the regional level)	-

		Analyse the farm's sociotechnical context to increase understanding of the context that led to the innovation	Farm-level analysis of changes in farming practices caused by reintegrating livestock	Analyse sociotechnical barriers to and levers for reintegrating livestock involving actors besides farmers	Combining analysis of the sociotechnical context, on-farm innovation tracking and coupled-innovation tracking at the agri-food system level
	Relying only on farmers' self-assessment of performances of the innovation	Supplement farmers' self-assessments with objective assessment of the performances of the cropping system to support scaling it up	-	Objective multi-criteria assessment of agroenvironmental impacts of livestock reintegration	Comparing farmers' self-assessments and objective assessment and discussing the results with farmers
	Static approach	Combine static and dynamic approaches to highlight the evolution of relations among determinants that lead to the innovation, changes in practices and their impacts	-	(Initial elements to build a framework to study farmers' trajectories when reintegrating livestock)	Designing a framework to study the trajectories followed toward agroecological innovations and successfully applying it to case studies
	-	-	-	Reflection on researchers' stances and practices when tracking agroecological innovations such as reintegrating livestock	Further emphasizing the role of uncertainty and emerging opportunities when studying an agroecological innovation (e.g. the trajectories followed to implement it)
<b>5. Generating agronomic content</b>	Not described in published studies and not considered in this Ph.D. study.	-	-	-	-

## II.1. Improvements in the innovation-tracking framework

### II.1.1. A mixed method to inventory and rank farmers' motivations for implementing an agroecological innovation

As mentioned in the Introduction (Part II, section 3), to my knowledge, **published studies of innovation tracking rarely studied farmers' motivations in depth** (Barzman et al., 1996; Blanchard et al., 2018; Jagoret et al., 2012; Perinelle, 2021). Information about farmers' motivations was collected during interviews, but not capitalized on, while motivations were identified as a **key determinant of change** (Casagrande et al., 2016; de Boon et al., 2024; Greiner and Gregg, 2011).

In chapter 1, I developed an **original mixed method to inventory and rank farmers' motivations** for reintegrating livestock. This method **helped improve the framework of innovation tracking**. To develop the method, I built on a conceptual framework that I borrowed from **social psychology** (

Figure 16) – the Theory of Planned Behaviour (Ajzen, 1991) – to ensure that all components of motivations were targeted during the interview. The mixed method that I developed combined i) **inductive analysis of semi-structured interviews with farmers** to inventory their motivations for reintegrating livestock, ii) **analysis of farmers' selection and ranking of motivation cards** that summarized the main advantages of ICLS found in the literature and iii) **comparison** of these two analyses to increase the completeness and robustness of the results (Hussein, 2009).

This mixed method could **be applied easily to study other agroecological innovations** during interviews with farmers in the framework of innovation-tracking initiatives. It would likely require spending more time than that in most interviews on questions that target farmers' motivations for innovating. With minor adjustments, it could also **be applied to other actors**. It could benefit from collaboration with social science researchers to refine the questions and the analysis of farmers' motivations.

### II.1.2. A multi-level approach to consider sociotechnical barriers to and levers for implementing an agroecological innovation

As mentioned in the Introduction (Part II, section 3), to my knowledge, most innovation-tracking initiatives focused on **the cropping-system and farm levels** (Salembier et al., 2016; Verret et al., 2020b). Few published studies on innovation tracking **considered innovations beyond the farm level** or studied in depth the **sociotechnical context in which innovations emerged**. While Salembier et al. (2021) highlighted that most studies asked farmers about the sociotechnical barriers they faced and the levers they found to overcome them, this **information did not seem to be capitalized on beyond individual testimonials**. Moreover, few studies interviewed **actors besides farmers** to increase understanding of the sociotechnical context, as recommended by other studies (Boulestreau et al., 2021; Salembier et al., 2021). Studying in depth the specific sociotechnical context that enabled the emergence of an innovation is **key to support scaling it up** (Geels, 2010; Weituschat et al., 2023).

In chapter 2, I developed **an original approach to broaden the scope of innovation tracking beyond the farm level**. First, I applied the innovation-tracking framework to livestock reintegration that involved either one single farm (livestock reintegration at the farm level) or cooperation between

several farms (reintegration at the regional level). **I thus improved the innovation-tracking framework by adapting it to study innovations beyond the farm level.**

I then studied in depth **sociotechnical barriers to and levers** for livestock reintegration. I borrowed a framework from **Sustainability and Transition Studies** (

Figure 16) – the multi-level perspective (Gaitán-Cremaschi et al., 2019; Geels, 2011, 2004) – to ensure that I targeted barriers and levers at the niche, regime and landscape levels (Figure 13, Box 4). I applied it to an innovation that was **still in a pre-niche phase** (Elzen et al., 2012; Weituschat et al., 2023). I performed inductive analysis of interviews with **purposively sampled key actors of the sociotechnical system** surrounding livestock reintegration to inventory barriers to and levers for scaling it up in sustainable forms. I thus **improved the innovation-tracking framework by developing a method to combine it with in depth analysis of the sociotechnical context that led to the emergence of an innovation**, by interviewing actors besides farmers.

This method **could be applied to study other agroecological innovations on farms or beyond the farm level**. It has already been used in several studies of agrifood systems, even though it has not been included in the framework of any innovation-tracking initiative (Angeon et al., 2024; Meynard et al., 2018; Ryschawy et al., 2021). Including it in an innovation-tracking initiative would require **interviewing actors of the sociotechnical system besides farmers** (Casagrande et al., 2024; Pigford et al., 2018). Moreover, identifying actors of the sociotechnical system surrounding such niche innovations is not always easy, as they often believe that they do not know enough to be the right person to ask (Lucas, 2021).

**Supplementing on-farm innovation tracking more frequently with sociotechnical analysis** of the barriers to and levers for an innovation would help support scaling it up. Combining such analysis with **coupled-innovation tracking** (Boulestreau et al., 2022) would further document examples of joint innovations from the farm to agrifood-system level that are necessary to scale up farmers' agroecological innovations (Meynard et al., 2017). Such coupled-innovation tracking should be performed for niche innovations that are more "anchored" (Elzen et al., 2012) than livestock reintegration, for which few coupled innovations have been developed.

### II.1.3. A method to study farmers' practice changes when reintegrating livestock and objectively assess its impacts on farm sustainability using multi-criteria assessment

As mentioned in the Introduction (Part II, section 3), **nearly all published innovation-tracking initiatives assessed innovation performances**, often using **farmers' self-assessments** (Barzman et al., 1996; Périnelle et al., 2021; Verret et al., 2020b). Supplementing self-assessments with an **objective assessment** could improve the **robustness and scope** of the knowledge on such innovations and help determine whether they could actually be sustainable and whether their scaling up should be supported.

In chapter 3, I improved the innovation-tracking framework by developing a **method to study changes in farming practices caused** by reintegrating livestock and **to objectively assess their impacts** in the agroenvironmental dimension of farm sustainability using **multi-criteria assessment**. The method I developed used i) **data that can be collected easily** by interviewing farmers; ii) **indicators aligned with farmers' motivations** and **the main advantages of ICLS** found in the literature, and that could be communicated easily to farmers and iii) **equations and coefficients from IDEA4** (Frédéric Zahm et al., 2019), which I adapted to focus on agroenvironmental impacts of reintegrating livestock in a **diachronic approach** (Nandillon et al., 2024).

The method I developed **could be used easily to assess performances of other agroecological innovations objectively** in the framework of innovation-tracking initiatives at **low cost**, as it uses only information provided by farmers. The questions asked to farmers should be adapted slightly to focus on the changes in practices related to the innovation under study. Although the indicators that I selected are commonly used to assess farm sustainability, using them for another innovation should be determined by how closely they **align with farmers' motivations** for implementing the innovation and by the **main impacts** this innovation could have. These indicators could be supplemented with others, for instance to include more summary assessment of overall farm crop and livestock diversity (Keichinger et al., 2021), socio-economic assessments (Brennan et al., 2023; Roesch et al., 2017; Schanz et al., 2023) or indicators chosen by farmers when self-assessing the innovation. The ranking of indicators should be discussed with farmers (Lamarque et al., 2011). Multi-annual assessments of farmers' innovations would be needed to monitor impacts of adaptations of the farming system (Magne et al., 2024). These kinds of assessments have rarely been performed.

Objective assessments should **supplement the farmers' self-assessments** often obtained in innovation-tracking initiatives. **Comparing the results** of these two types of assessments and **discussing them with farmers** could help refine calculation assumptions. It could also increase farmers' knowledge on agronomic processes beyond reintegrating livestock or provide them with technical information (e.g. fertilizing value of chicken manure). How the results of such an assessment may influence future changes in practices is rarely studied, but would be insightful.

#### II.1.4. From a framework to analyse trajectories to an epistemological reflection on researchers' stances and practices when studying agroecological innovations

##### *II.1.4.1. Further work needed to improve the innovation-tracking framework by studying farmers' trajectories*

Like motivations and barriers, Salembier et al. (2021) identified the **trajectories that farmers followed** when implementing an agroecological innovation as one of the key questions asked farmers in most innovation-tracking initiatives. However, to my knowledge, **few published studies capitalized on this information** (Blanchard et al., 2018; Verret et al., 2020b). Understanding the trajectories that farmers followed when implementing an agroecological innovation (i.e. the succession of intermediate states

of the system, their disturbance by events, adaptations in response to these events and as a function of their initial motivations, sociotechnical contexts and adaptive capacity) is **key to support the scaling up of agroecological innovations** (Chantre and Cardona, 2014; Coquil et al., 2014; Darnhofer et al., 2010; Revoyron et al., 2022).

In chapter 4, I initially aimed at developing an **original framework to design a typology of trajectories** that farmers followed when reintegrating livestock. This framework would have helped improve the innovation-tracking framework by **providing a tool to capture the dynamic component of the changes that lead to agroecological innovations**. It would have helped analyse how the diverse determinants I identified (i.e. farmers' motivations and elements of the sociotechnical context, including farm characteristics), interacted over time, led to changes in farmers' practices and had diverse agroenvironmental impacts (Alderkamp et al., 2024; de Lauwere et al., 2022; Gosnell et al., 2019).

As mentioned, I did not manage to create a typology of trajectories that farmers followed when reintegrating livestock. Nevertheless, I do believe that **improving innovation-tracking initiatives by studying farmers' trajectories would be insightful**. Although I could not finish it, performing this analysis helped me better understand interactions among the diverse determinants of practice changes, actual practice changes and their impacts. These insights shed additional light on my other results.

**I developed an initial framework to study farmers' trajectories** when implementing an agroecological innovation. Although this framework was not applied successfully to real data, it aimed at broadening the framework of Chantre et al. (2015) and Chantre and Cardona (2014), which considered a succession of coherence phases of the system, disturbed by trigger events, usually at the farm level. The framework I developed combined **coherence phases and trigger events**, but also considered **factors that facilitated or hindered transition to the next stage**, as Gosnell et al. (2019) did. These factors covered **multiple levels**, from the farmer to the farm and sociotechnical system, and **multiple dimensions** (e.g. psycho-cognitive, socio-economic, agroenvironmental). This framework still needs work before it can be applied, but it may provide **an idea that informs future studies of trajectories toward agroecological innovations that consider a multi-level approach**.

#### *II.1.4.2. An epistemological contribution to reflect on researchers' stances when tracking innovations*

Despite my initial failure to improve the innovation-tracking framework with a method to create typologies of farm trajectories, I still think that the epistemological reflection I describe in chapter 4 can provide **insights for future study leaders of innovation-tracking initiatives**.

Indeed, in addition to the methods used and analyses performed, **the stances of the study leader when tracking innovations is important to consider**. In chapter 4, I built on the **complexity perspective** from the Sociology of Change (Bossaerts et al., 2019; Scoones and Stirling, 2020) (

Figure 16) to emphasize **how our individual researchers' worldviews can impact the results of our research**. This can be **particularly stressing in innovation-tracking initiatives**, as researchers aim at

reconstructing and capitalizing on farmers' stories by reconstructing them (Cialdella et al., 2009; Isern and Nissen, 2012). However, **differing worldviews can lead them to study particular topics in more depth during the interview, deemphasize diverse elements during inductive analysis of interviews and ultimately disseminate different stories that are simultaneously true but incomplete** (Haraway, 1988; Scoones and Stirling, 2020). Acknowledging our underlying worldviews and the often-unconscious bias that may come from them would help **broaden our understanding of farmers' stories**. In particular, doing so would emphasize the **unpredictability and uncertainty** in documenting the specific context that led to innovation. It also highlights the importance of farmers' **adaptive capacity** in transforming these events into emerging opportunities that shape the future trajectory of their farms (Bouttes et al., 2019; Darnhofer et al., 2010).

These initial insights into a reflection on the stances and practices that researchers should have when tracking innovations **can be broadened easily to other methods, as it raises questions about researchers' worldviews more than it does about specific tools**.

Most of the knowledge collected during innovation-tracking initiatives seemed to be capitalized on in individual testimonials intended to inform design processes (Périnelle et al., 2021; Salembier et al., 2021; Verret et al., 2020b). However, to my knowledge, no study has assessed their actual use for and contribution to practice changes (Salembier, 2019). Most published innovation-tracking initiatives focused on innovations at **the cropping-system or farm levels**, involved **only farmers** and considered mainly **agroenvironmental determinants** of practice change. They often used only **farmers' self-assessments** to assess performances of the agroecological innovation studied. They adopted a **static approach** that described the current state of the innovation.

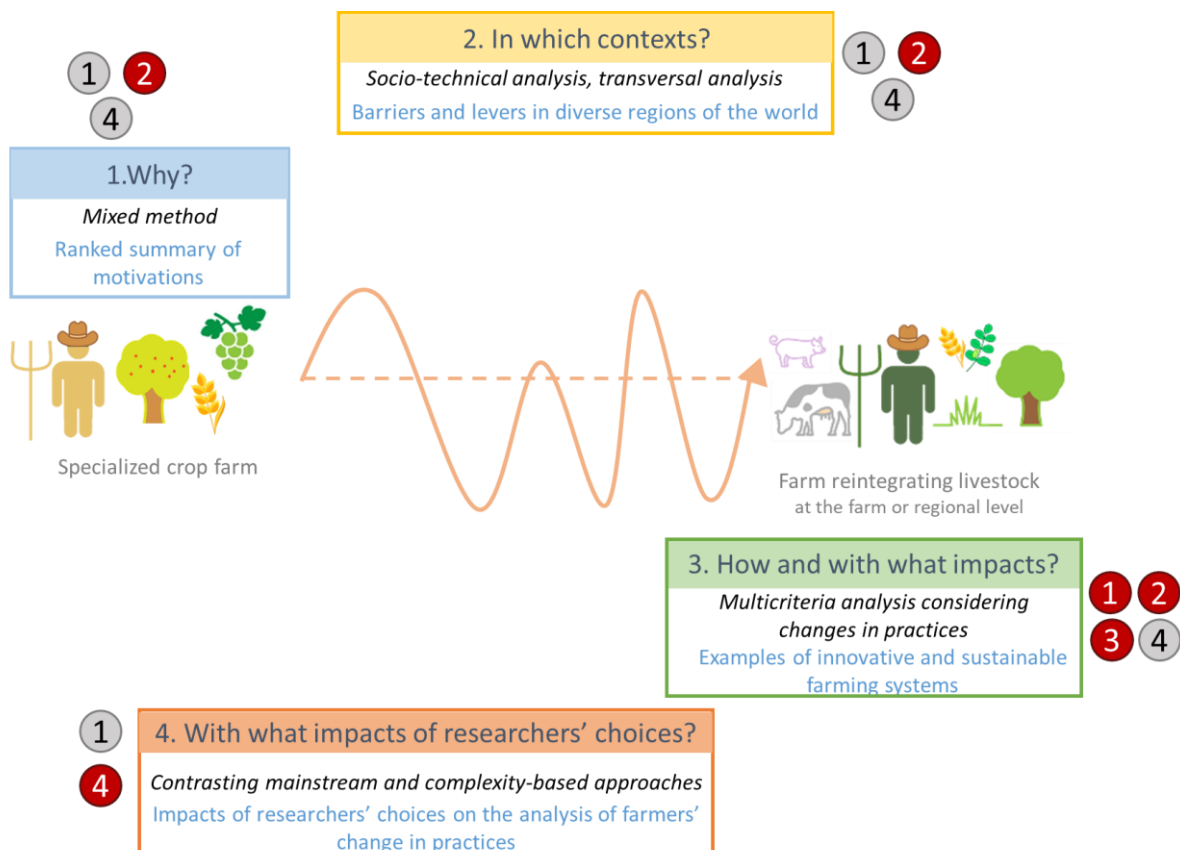
I improved the innovation-tracking framework (Table 13) by developing a **multi-level approach**, from the individual farmer to the farm and sociotechnical system, to consider **innovations that occur on one farm or involve cooperation between several farms**. I also combined analyses that included determinants in **several dimensions** (i.e. agroenvironmental, sociotechnical and socio-economic). I developed a multi-criteria assessment method to **assess** livestock reintegration **objectively** as an example of agroecological innovation. I developed an initial **framework to highlight the dynamics of change** toward agroecological innovations. I provided an **epistemological reflection on impacts of researchers' stances and practices** on the results of innovation tracking to invite researchers to acknowledge their underlying worldviews and their impacts, and then broaden them.

*Box 11. Summary of contributions to improve the innovation-tracking framework*



## II.2. Contribution to embracing methodological challenges when studying agroecological innovations

When studying livestock reintegration, like most researchers who study agroecological innovations, **I was faced with methodological challenges** (see the Introduction, Part II, section 2). These challenges were even greater given the wide diversity of farming systems included in my sample. Below, **I discuss how I attempted to address them in my study**, in the hope that it may inspire future studies (Figure 49).



Methodological challenges to studying livestock reintegration as an example of agroecological innovation faced in each Ph.D. chapter

- |   |   |
|---|---|
| <ul style="list-style-type: none"> <li>1 Defining system boundaries</li> <li>2 Deriving generic knowledge from studying pioneer and ever-evolving farming systems</li> <li>3 Assessing the multi-performance of the agroecological innovation</li> <li>4 Revisiting researchers' stances and practices</li> </ul> | <ul style="list-style-type: none"> <li>n Lower impact of the challenge n in this chapter</li> <li>n Higher impact of the challenge n in this chapter</li> </ul> |
|---|---|

Figure 49. The main methodological challenges to studying livestock reintegration as an example of agroecological innovation faced in the chapters of the Ph.D. study

### II.2.1. Challenge 1: Defining system boundaries appropriate to the agroecological innovation under study

I was faced with this challenge throughout the Ph.D. study, especially for chapter 3, when studying changes in farming practices beyond reintegrating livestock and their agroenvironmental impacts, as I needed to determine exactly what to include in my calculations (Figure 49).

#### *Spatial boundaries*

For **spatial boundaries for livestock reintegration at the farm level**, it was obvious to use the **farm boundaries** as system boundaries (Le Gal et al., 2022; Puech and Stark, 2023; Ryschawy et al., 2012). For **partnerships** between crop and livestock farmers, **defining the system boundaries was more difficult** (Magne et al., 2024) due to the **temporary presence of the livestock farmer's animals on the crop farm**. I decided to consider only agroenvironmental impacts caused by changes in cropping practices (e.g. decrease in mechanization or fertiliser input). I excluded livestock-related greenhouse gas emissions and animal products, as they were related to the livestock farm and not specifically caused by the animals on the crop farm. This decision was also supported by the **difficulty that some farmers** who reintegrated livestock in a partnership had **providing the information on livestock needed** to make calculations (e.g. number and duration of presence of lambs), as they exclusively relied on the livestock farmer to manage the animals and did not monitor them.

This study should be supplemented by **assessing impacts of partnerships** between crop and livestock farmers on the **sustainability of livestock farms**. Similar to my approach, emphasis should also be placed on the **determinants that led livestock farmers to engage in partnerships**, the **actual practice changes** they implemented and the **trajectory** they followed, to **contextualize** the impact assessment (Asai et al., 2014; Moojen et al., 2024; Ryschawy et al., 2021). **Broadening spatial boundaries of the system studied** to assess impacts of partnerships on both crop and livestock farm sustainability would **increase understanding of the overall sustainability of livestock reintegration**, thus further addressing the question of whether scaling it up should be supported and, if so, in which forms.

More broadly, **assessing in depth the sustainability of agroecological innovations**, such as livestock reintegration, **also requires combining and comparing their impacts at multiple spatial scales** to consider trade-offs between field, farm and upper levels.

#### *Temporal boundaries*

For **temporal boundaries**, I used an **annual approach**. I assessed agroenvironmental impacts of livestock reintegration based on the **state** of the farming system at the time of the interview (i.e. 2023-2024). Nevertheless, as mentioned, farming systems in which livestock have been reintegrated are **recent** and **far from having reached a dynamic steady state** (Magne et al., 2024; Toffolini et al., 2019). Farmers mentioned **many projects** that they wanted to start in the future (e.g. increasing flock size, grazing cereals at early stages on top of cover crops, buying their own animals). This **snapshot assessment** of agroenvironmental impacts of **ever-evolving farming systems** requires **supplementing them with follow-up assessments that consider such future adaptations** (Magne et al., 2024).

More broadly, **assessing the sustainability of agroecological innovations that require transformative changes**, such as livestock reintegration, calls for performing **multi-annual assessments** to capture how **their sustainability evolves during the change process** (Magne et al., 2024). Such **long-term monitoring is currently hindered by the short duration of research projects** and the need to create brand new ideas in every new project (Becker and Lukka, 2022; DeLonge et al., 2016; Elbanna and Child, 2023).

### II.2.2. Challenge 2: Deriving generic knowledge on agroecological innovations by studying a wide diversity of locally-adapted and ever-evolving farming systems

I was faced with this challenge throughout my Ph.D. study (Figure 49). To **derive generic knowledge** on livestock reintegration by studying **locally-embedded pioneer farming systems “in-the-making”** (Toffolini et al., 2019), I used an **exploratory approach** that examined the **highest possible diversity of farming systems** (Salembier et al., 2021), but it raised **challenges**. Producing contextualized knowledge on such a diversity of farming systems required developing **an original approach beyond the statistical analyses usually used**, designing **new tools and methods**, developing a **multi-level approach**, combining several frameworks from **diverse disciplines** to study determinants in **multiple dimensions** and involving **diverse actors** (Darnhofer et al., 2012; de Boon et al., 2024; Geels, 2011).

This exploratory approach had three main **strengths**. First, it was particularly useful for **documenting the diversity** beyond livestock reintegration (i.e. **providing a panorama** of the diversity of motivations, sociotechnical contexts, farming-practice changes and range of impacts beyond the reintegration). Second, it **provided generic knowledge on issues that were relatively independent of the form of livestock reintegration**, such as motivations and sociotechnical barriers. Indeed, although some motivations may have had greater importance, and some forms of livestock reintegration may have been hindered by additional barriers - both of which could have required further study - the overall trend was generally shared. For instance, sociotechnical barriers such as a lack of knowledge or outlets existed regardless the form of livestock reintegration. Third, it helped **identify and prioritize research avenues on sustainable forms of livestock reintegration to document in the future** (e.g. grazing sheep, see chapter 3).

However, this approach also had **limits**. In particular, it was not sufficient for **producing precise knowledge on issues that were influenced strongly by the form of livestock reintegration**, such as the trajectories that led to reintegrating livestock or the farming-practice changes needed to make livestock reintegration sustainable and their impacts. These limits could be addressed in two ways.

First, exploratory approaches **need to be supplemented with future studies** that focus specifically on the most sustainable forms of livestock reintegration identified **to generate actionable knowledge** (Geertsema et al., 2016) **and support scaling them up**. These approaches would need to be performed in a second step, as they would require i) interviewing farmers who have similar farming systems, which would imply waiting for the agroecological innovation to be implemented by enough farmers to

find such similarities and redundancies, and/or ii) producing knowledge on sustainable forms of livestock reintegration identified through experiments, which are time-consuming and thus need to focus on specific issues identified through exploratory approaches (Brewer and Gaudin, 2020).

Second, **researchers may need to reconsider what is most important to include in their studies** when they face such a diversity of ever-evolving farming systems “in-the-making” (Haraway, 1988; Thompson, 2002; Toffolini et al., 2019). For instance, to support the scaling up of an agroecological innovation, researchers can study the **trajectories** that farmers followed when implementing it. They thus look for **similarities in how stable phases succeeded one another over time** and were disturbed by events that triggered passage to the next step toward this agroecological innovation (Chantre and Cardona, 2014; Coquil et al., 2014; Revoyron et al., 2022). When studying a diversity of pioneer and ever-evolving farming systems, such similarities are difficult to find. However, some generic knowledge can be obtained by studying the trajectories that farmers followed to implement them. To do so, a study **could focus simply** on i) identifying **phases** that systems experienced **and/or events that contributed (with differing degrees of directness and differing time lags)** to implementation of the agroecological innovation and ii) characterizing the **resources and strategies** that allowed farmers to use these events creatively (Bouttes et al., 2019; Darnhofer, 2022; Darnhofer et al., 2010). Thus, **by freeing themselves from the order** in which events occurred, researchers may find similarities in farmers’ trajectories, even when using exploratory approaches to study a wide range of farming systems. For instance, almost all farmers I met who had reintegrated livestock had met someone who influenced them, sometimes years later, to reintegrate livestock. The knowledge derived from such a study could still help farmers expect what step to take next. Instead of providing them with a predetermined path, it would emphasize a panorama of what could occur on their farm due to the temporary assemblage of resources and emerging opportunities (chapter 4) (Allen and Boulton, 2011; Baker and McGuirk, 2017; Bossaerts et al., 2019; Scoones and Stirling, 2020).

Although challenging and insufficient, **exploratory approaches are necessary to produce generic knowledge on niche farmer-led agroecological innovations “in-the-making”**, such as livestock reintegration. **Researchers thus need to accept and embrace the difficulties, challenges and risks of failure that come with exploratory approaches** if they want to actively contribute to the agroecological transition.

### II.2.3. Challenge 3: Assessing the multi-performance of agroecological innovations

I was faced with this challenge in particular in chapter 3 (Figure 49).

#### *Choice of indicators*

Although I did not rely on farmers' self-assessments, as many innovation-tracking initiatives have done (Salembier et al., 2021), I initially aimed **to align the indicators I chose with the diversity of farmers' motivations** identified in chapter 1 in order to produce easily actionable knowledge. I managed to do this only partially, for two main reasons. First, some **agroenvironmental indicators** could not be calculated easily using **only data collected during interviews**. For instance, impacts of reintegrating livestock on soil organic matter can be assessed using either i) long-term monitoring and repeated measurements, which I could not perform in the framework of my Ph.D. study (Brewer et al., 2023a), or ii) modelling, which can require large amounts of data (Holzworth et al., 2014; Keating et al., 2003).

Second, **while I had initially included socio-economic indicators** to assess impacts of reintegrating livestock in all three dimensions of sustainability, most **farmers' were reluctant to provide economic data**, which led me to exclude the economic dimension from my analysis. I also realized through my interactions with farmers that **studying the issue of workload and work satisfaction in depth required designing an entire specific framework of analysis**. Indeed, farmers often reported that reintegrating livestock may have increased the amount of time that they spent on the farm, but that they did not necessarily consider it as additional workload, as the pleasure they derived from managing the animals made them question whether they were actually "working" (Schanz et al., 2023). Moreover, addressing the issue of farm work in depth can require spending time working on the farm with farmers, such as through participant observations (Perrin et al., 2024), which I did not have time to do during my Ph.D. study. I thus decided to focus my assessment only on the **agroenvironmental dimension**.

Future studies should **broaden the range of assessment** by using multi-annual assessments and other indicators, as mentioned previously. To decrease farmers' reluctance to provide data, **economic indicators** should be either **self-assessed** by farmers **or determined from a precise description of farmers' practices** (Verret et al., 2020a), which can require large amounts of time and data. Supplementing the assessment of agroenvironmental impacts of reintegrating livestock with a **socio-economic assessment** is indispensable to learn about the **trade-offs** needed to reintegrate livestock sustainably (Klapwijk et al., 2014; Ryschawy et al., 2019) and support the scaling up of such sustainable forms of livestock reintegration. This is **also true for other agroecological innovations**.

#### *Reference system*

As I aimed at **assessing impacts of reintegrating livestock** on the sustainability of crop farms, I used a **diachronic approach** (Nandillon et al., 2024) and **compared farm sustainability before and after reintegrating livestock** (Magne et al., 2024). To assess the **relative weight** of reintegrating livestock on **overall farm sustainability**, I compared changes in the values of indicators related to reintegrating livestock to those for **reference specialized crop farms** that had the same types of production as farms in my sample. For instance, after reintegrating poultry, energy consumption of a specialized crop farm

increased by 21 047 MJ/ha, which was much higher than the energy consumption of reference specialized grain-crop farms (13 425 MJ/ha) (INRAE, 2023; Zahm et al., 2019; 2023). I extracted values for reference specialized crop farms from Web Idea (INRAE, 2023; Zahm et al., 2019; 2023), a platform that compiles the sustainability of farms assessed using IDEA4 (i.e. the tool I used for my assessment). This approach ensured that the equations and calculation assumptions for the reference data were similar to those that I used in my assessment, and thus that the **data were comparable**.

#### II.2.4. Challenge 4: Revisiting researchers' stances and practices when producing knowledge on agroecological innovations

I had to **reflect on my stances and practices as a researcher** when studying agroecological innovations throughout my Ph.D. study, especially for chapter 4, in which I invited agricultural scientists to **reflect on their stances and practices** and the **impacts** they can have on their results (Figure 49). This kind of reflection may be challenging and uncomfortable, as it switches the focus of analysis from external elements (e.g. crops, farms, farmers) to internal elements (i.e. personal research practices and stances). It calls for departing from the vision of "objective researchers" to embrace our subjectivity and analyse ourselves as humans practicing research (Haraway, 1988; Law and Urry, 2004). Because I believe such reflection is **necessary to support the agroecological transition**, I relate my own personal reflection below, in the hope that it may reassure, support and perhaps inspire other researchers to open themselves to another worldview.

At the beginning of this Ph.D. study, I was convinced that I had an "open-minded" vision of research overall, which aligned with the requirements of researching agroecological innovations and supporting the agroecological transition. I had chosen to rely on innovation tracking, which is by nature deeply embedded in a bottom-up approach to research, as it aims at capitalizing on farmers' experiential knowledge (Darnhofer et al., 2012; Salembier et al., 2021). I had also decided to adopt an interdisciplinary approach in which I included social sciences (

Figure 16).

Nevertheless, failing to develop a typology of trajectories drove me to **reflect more deeply on my actual research stance and practices**. I realized that I was still influenced much more by the underlying worldview of mainstream research in agricultural sciences than I had expected. This was difficult to accept at first, as it made me feel like I had failed twice: once when analysing my data and once when analysing myself (i.e. my own stance and practices). Becoming open to another worldview was extremely **challenging** and required **resilience**. It still does, **as I consider that this process continues**. It involves **always paying attention** not to revert to my former habits, accepting that it sometimes occurs insidiously anyway, and starting again. Difficulty did not discourage me (well, maybe sometimes), as I felt that I had no other choice if I wanted to support the agroecological transition. Transitioning toward agroecology is not easy for farmers, and yet we, researchers, keep repeating "you need to do it !". How could I continue telling them that if I myself did not accept and embrace the necessary transformation of my own stance and practices when studying agroecological systems?

Despite the difficulty, opening to the complexity perspective made me feel that my research stance and practices were becoming **more aligned with farmers' realities**, which made me able to produce knowledge that could more easily have an actual impact. I hope that this personal reflection may inspire my researcher colleagues and strengthen my invitation that they reflect on their stances and practices in order to further support the agroecological transition.

### Part III. Propositions

In this last part of my Ph.D. manuscript, I make **propositions** mobilizing the results I produced in order to **derive actionable knowledge** and **support the scaling up of livestock reintegration** onto specialized crop farms and into specialized crop regions. Those **personal propositions** build on **my own perception of some of the changes** necessary across the entire sociotechnical system to support livestock reintegration. They do not come along with scientific results from this Ph.D. study or from the literature, and rather originate from **personal reflections** on the issue, after three years scrutinizing it. As such, they build on **my own opinion as an engaged researcher**. For each proposition, I briefly mention how I started contributing to it in my Ph.D. study. I hope I will have the chance to continue in this direction along my future journey into research.



### III.1. Researchers need to further engage into high-quality communication and dissemination of their findings beyond the scientific community.

*To me, the first step in supporting the scaling up of livestock reintegration is to disseminate research results beyond the scientific community, to all actors of the sociotechnical system.*

Researchers have to **engage in communicating and disseminating their findings beyond the scientific community** (Box 12, Figure 50). This is an **integral part of their missions**. Researchers have to reflect further on the **appropriate formats** to disseminate results to a diversity of actors (e.g. farmers, technical advisors, policy-makers, citizens) (Box 13, Figure 51). Monitoring and regular update of actors' expectations and preferences regarding the format to disseminate knowledge is needed. **Collaborations with ergonomists and specialists of communication** will help. To push researchers further communicating their results beyond the scientific community, **engagement in and quality of such communication has to be considered when assessing researchers' performance**.

Over my Ph.D. study, I shared my results with actors beyond the scientific community. This was notably the case by being involved in **two technical field days** organized by **farmer groups** dedicated to crop-livestock integration. I also contributed to facilitate knowledge exchange between farmers and researchers and between farmers over technical issues surrounding crop-livestock integration by being involved in the **organization of a field trip** during which farmers from the South of France visited their peers and a research group in Scotland.

Box 12 : *My contributions to communicate research findings beyond the scientific community during this Ph.D. study*



Figure 50 : *My contributions to communicate research findings beyond the scientific community during this Ph.D. study. On the left hand side, presentation of my Ph.D. study results during a technical day organized by an organic farmer group (Credits, A. Peter). On the right hand side, knowledge exchange between French and Scottish farmers, in Scotland, during the visit of a field grazed by sheep that I contributed to organize. (Credits, T. Elosegui).*

I followed a **sketchnoting training** to improve my skills in **producing relevant visuals for dissemination of scientific findings** and to **promote learnings of the recipients**. I **transmitted** some of the skills I developed during this training to **colleagues** of my lab. I am also **working with a professional drawer** to produce **animated movies** on the key results of my Ph.D. study.

Box 13 : My contributions to reflect on the appropriate format to disseminate research findings during this Ph.D. study.



Figure 51 : My contributions to reflect on the appropriate format to disseminate research findings during this Ph.D. study: example of two sketchnotes made during the conference on on-farm experiment (December 2023) as an alternative way to summarize oral presentations followed.

### III.2. Participatory workshops need to engage diverse actors of the sociotechnical system to co-design scenarios of livestock reintegration.

*Organizing participatory workshops is one way to disseminate research results and hybridize them with actors' experiential knowledge. It can be used to derive actionable knowledge under the form of sustainable scenarios of livestock reintegration.*

Such workshops have to **include a diversity of actors beyond farmers** in order for scenarios to have a chance being scaled up. **Ad hoc tools** are needed to facilitate projections into alternative ways of doing and organizing activities, to promote knowledge exchange among actors and to identify trade-offs between them, considering issues of power (Box 14, Figure 52).

Over my Ph.D. study, I **adapted the serious game** Dynamix (Ryschawy et al., 2022) to specifically **consider cases of livestock reintegration** and organized a **first co-design workshop to test it**. In its original version, Dynamix aims at facilitating the co-design of scenarios of crop-livestock integration at the regional level, mostly by easing annual exchanges of biomass between specialized grain crop and livestock farmers. I adapted it to the case of sheep grazing into cereals, orchard and vineyards in California, for each season of the year. I **tested** this adapted version during a co-design workshop with a **group of Californian farmers and advisors**. I also used it with **Master students** in Agroecology in France. With further development, this adapted version of Dynamix could be a step of a multi-level co-design process engaging the various actors of the sociotechnical system.

*Box 14 : My contributions to adapt and test appropriate tools to co-design scenarios of livestock reintegration in participatory workshops during this Ph.D. study*



*Figure 52 : My contributions to adapt and test appropriate tools to co-design scenarios of livestock reintegration in participatory workshops during this Ph.D. study. Pictures of the adapted version of Dynamix used in California, in August 2022 (Credits P. Binsfeld).*



### III.3. Agricultural education programs need to bridge the divide between crop and livestock.

*Beyond communicating with current actors of the sociotechnical system, disseminating research results on livestock reintegration to students from agricultural schools, i.e. future farmers, technical advisors, teachers and researchers, is essential to favour its scaling up in the long term.*

In France, most often, **students have to choose** whether they want to study **crop or livestock production**, even when universities emphasize integrating lessons on agroecology and sustainability. **They should not have to make such a meaningless choice. The divide has to be bridged between crop and livestock production in education** to contribute breaking the self-reinforcing mechanism of specialization and building more positive imaginaries on agroecological innovations such as livestock reintegration.

Revisiting the agricultural education system will necessarily be a **long process** that may partly require generational renewal of the teachers. In the meantime, **further lessons on integrated crop-livestock systems need to be included**, both in crop and livestock production education programs (Box 15, Figure 53). Such lessons have to **extend the formats used beyond PowerPoint presentations**, and include pedagogical tools such as serious games, as well as **meetings with farmers and other actors of the sociotechnical system**.

Over my Ph.D. study, I strongly committed in **transmitting my results to students**. I **taught** above 130 hours to master students, and **co-supervised a 3-month internship**. Among my teaching hours, I twice participated in a 3-day teaching unit in which I **directed groups of students in designing their own serious games** on integrating sheep into vineyards and grain crop farms. I also produced a **pedagogical tool** that can easily be used by teachers to disseminate knowledge on livestock reintegration to students. It presents the story of a farmer who reintegrated livestock, divided into several stages. At each stage, a perturbation happens on the farm, and students need to imagine and discuss in groups what they would have done if they had been the farmer. They then discover what the farmer has actually done. Then another perturbation that occurs and so on.

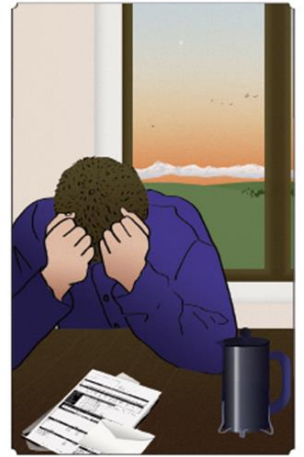
*Box 15 : My contributions to teaching on the topic of livestock reintegration through original formats during this Ph.D. study*



In addition to our farm, we're both workers on a large cash crop farm because we don't earn enough at home to repay all the loans for land and equipment.

We also just created an agricultural work company specialized in detasseling corn, but that's still not enough, and to make matters worse, we are now overwhelmed.

... having a hard time to earn a living



We received a phone call this morning. The owner of the cash crop farm on which my father and I have worked for almost 20 years is laying us off, all because of an argument last week.

We were starting to get our heads above water a little with the company, but now, I don't know what we're going to do.

Risk 1 / Jérôme's and his father's dismissal

Figure 53 : My contributions to teaching on the topic of livestock reintegration through original formats during this Ph.D. study. On the left hand side, pictures of serious games on sheep grazing into vineyards and orchards designed by students from an agricultural university during a 3-day teaching unit (Credits: C. Meunier, M. Grillot). On the right hand side, extract of the pedagogical tool reporting a farmer's story when reintegrating livestock.

### III.4. Livestock is a key component of future sustainable food systems, and needs to be portrayed as such in the media.

*Beyond current and future professionals of the agricultural sector, communication on the benefits of reintegrating livestock onto crop farms and into crop regions, and on the role of livestock production in tomorrow's food systems needs to target citizens.*

Mass media currently portray livestock production as mainly disastrous for the environment and regarding animal welfare. Most of those accusations actually relate to the high-input specialized livestock production regime rather than to livestock production in general. However, no such nuance is shared to citizens. **The media need to stop transmitting this Manichean vision that livestock production is necessarily negative and has to be banned.** Instead, **they have to clearly highlight what kind of livestock production needs to be supported** to benefit from the numerous services livestock can provide to the environment and to the society (Box 16, Figure 54). They need to emphasize that when farming systems are designed to increase interactions between crop and livestock enterprises while paying attention on limiting direct and indirect feed/food competition, livestock can actually improve the sustainability of agricultural production. This way, the media will contribute to **make citizens aware they have the power to support the development of sustainable farming systems** involving livestock **through their consumption choices.**

With my Ph.D. study, I contributed to **advocate for the maintenance and development of specific forms of sustainable livestock farming systems** in future food system by providing inspiring examples of how reintegrating livestock can actually improve farm sustainability.

Beyond the **animated movies** mentioned above, I am also planning to further disseminate those results through creating **technical data sheets**, including farmers' testimonials. Such communication supports may as well be used to convince the media that livestock reintegration can be sustainable.

*Box 16 : My contributions to advocate for the key role of livestock in future sustainable food systems in this Ph.D. study*

## When sheep come back in the plain

### Winter cover crop grazing: a winning situation

As an alternative to cover crop shredding, cover-crop grazing by sheep helps saving working hours and fuel. On the short term, the effects on the soil fertility and organic matter content seem limited. This sheet resumes the main results of a recent study alongside with crop and livestock farmers' testimonies.

#### No effect on crop yield

Even if the most part of the fifteen plots studied until harvest in the framework of this project show an increased yield for the crop following the cover crop when they were grazed (see table below), the variability of the results does not allow to conclude to a positive effect compared to cover crop shredding. The only certitude so far is that cover crop grazing by sheep does not decrease the yield of the following crop.

#### Different impacts on the yield of the following crop

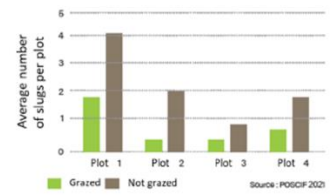


#### What a researcher says



« Slugs have been counted thanks to small amount of wheat put in the plots grazed or not grazed in the morning. At the end of the day, slugs meet there to eat wheat bran they like a lot. Our counts show a decrease by 60% of the number of slugs after grazing. Ewes may eat them at the same time as they eat the leaves, destroy them and their eggs by trampling ».

#### Vacuating slug



#### Without compacting the soils

Ewes trampling has only a minimal impact on soil compaction. It has no consequence on the following crop. Spade tests show a very slight degradation after grazing, especially in low carrying capacity of the soils. Visual evaluation of the soil structure remains below the 'compacted' level. Penetrometry measures show that the additional compaction on the first soil layer is around 50 kPa, which is low (see figure below).

#### What a farmer says



« Before seeing the ewes in my plots, trampling was a real fear. It is not a problem in the end ».  
Julien Manière,  
Farmer in an area close to Paris

Figure 54 : Example of a technical datasheet that could be used to contribute advocating for the role of livestock in future sustainable food systems. This technical datasheet was produced in the framework of the POSCIF project on sheep grazing on grain crop farms in the Parisian Basin (POSCIF, 2022). I translated this datasheet in English to share it with Scottish farmers and researchers during the field trip to Scotland I was involved into.



### III.5. Reterritorialization of food systems is a necessary condition to the scaling up of sustainable crop and livestock production.

**Communication to consumers needs to be made on the actual costs and benefits of food produced in sustainable farming systems**, that are not higher than that of food produced in high-input specialized farming systems when including indirect health and environmental costs. **Levers to include such products in citizens' diets with marginal additional costs also have to be communicated on.** In particular, when limiting food waste all along the value chain and reducing the share of more expensive animal proteins at the benefit of plant proteins in the diet, higher-priced products of sustainable farming systems become more easily accessible. **Such communication needs to come from researchers as well as from governments, through the media and at school.**

**Territorialized food systems** (i.e. inter-related actors who are located in the same geographical area and who produce, process, sell, circulate, buy and consume local food) are key to **enhance connections between actors and facilitate such communication.** More participatory and interdisciplinary research projects involving actors from production to consumption need to be led to identify promising initiatives to scale sustainable farming systems up, by supporting modifications of dietary habits (Box 17). In particular, institutional catering is a key place to sensitize consumers to such dietary changes. Children have to be particularly targeted, as diet preferences strongly build over childhood.

I did not address such broader questions at the food system level in my Ph.D. study. Though, I will further include it in **future research projects** I will be involved into. In particular, I contributed to **elaborate the proposal** for a 3-years European research project, which aims at **upscaling minor crops with institutional catering**, through considering **all stages of the value-chain** (from crop cultivation to cooking and serving of meals). If this project is funded, I will **co-coordinate** it.

*Box 17 : My contributions to contributions to address issues at the food system level during this Ph.D. study, and further contributions to come*



### III.6. Pushing researchers to reflect on their stances and practices, and on their impacts on results, is essential, both at school and in research laboratories.

*Beyond communicating on existing results, researchers need to produce further knowledge on agroecological innovations. Doing so requires departing from the mainstream approach of research that relies on a vision of the researcher as perfectly objective, and invites researchers to reflect on their stances and practices.*

**Researchers and future researchers need to be trained to the impacts of their choices on their research results** (Box 18, Figure 55). This will push them to be **transparent on their hypotheses** and how they shape their conclusions, and lead them to **include previously overshadowed elements in their analyses** that will contribute to **understand more in-depth the complex reality** of farmers' practice changes.

To trigger reflection, **training on researchers' stances and practices cannot only rely on conceptual thinking**. They need to be **grounded in data from the real world** to allow researchers **experiencing** the extent to which their stances and practices lead to an incomplete vision of reality. Such training can include:

- i) Interviewing a farmer as a first step, as many researchers have actually not been to a farm and talked to a farmer for years.
- ii) Asking researchers to analyse and relate the farmer's story.
- iii) Highlighting what they overshadowed, and asking them to reflect on the reasons underlying their choices and on how including such elements could actually enrich their analysis.

Over my Ph.D. study, I gave **lectures to students** from agricultural schools and **presented my results to researchers** to sensitize them to the impact of our stances and practices in research, by illustrating with my own data how they can lead to tell diverse stories, as presented in Chapter 4.

*Box 18 : My contributions to invite agricultural scientists to reflect on their stances and practices during this Ph.D. study*

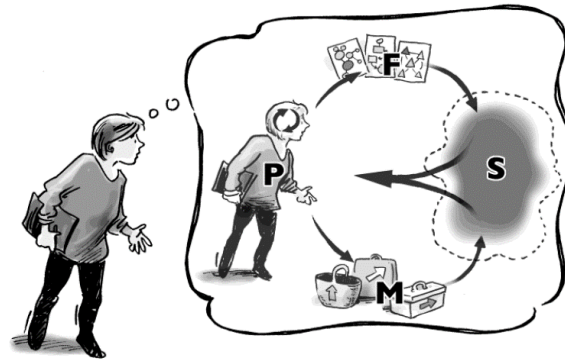


Figure 55 : Example of illustration to promote researchers' reflection on their stances and practices. Extracted from Darnhofer et al. (2012) chapter 7. Original caption: A conceptual model which can be applied to many forms of practice (e.g. researching, policy making, leading etc.) comprising a person thinking about a 'real world situation' in which a person or practitioner (P) (who may be the same as the person who is thinking) engaging with a situation (S) with a framework of ideas (F) and a method (M). I included this illustration in lectures I gave to students.

### III.7. More flexibility is needed in the research funding system to study agroecological innovations in depth.

*The current research funding system does not sufficiently provide the necessary flexibility to study agroecological innovations in depth.*

**More flexibility is needed regarding project duration, which has to be adapted to the timing needed to study agroecological innovations.** Studying agroecological innovations requires time (e.g. to co-construct interdisciplinary approaches, to long-term monitor farmers' trajectories and assess the implemented agroecological innovations). On the opposite, the duration of research projects rarely exceeds 5 years, and every new project needs to come up with a brand new idea to have a chance being funded. As a consequence, most often, research projects are more pluridisciplinary than interdisciplinary. The impacts of participatory initiatives are rarely assessed. Long-term monitoring of farmers' practice changes and multiannual assessments are barely implemented, leading to knowledge gaps. **The research funding system has to give room for such approaches, through considering longer initial durations for interdisciplinary and participatory approaches, and enabling prolongations of projects or funding follow-up projects.**

**More flexibility also has to be granted regarding the project outcomes.** Task descriptions and deliverables are often defined at least one year before the project actually start, at the proposal submission stage. While they do provide an overall direction to follow, they have to be adaptable according to emerging events that may come up over the project. This is especially true for participatory projects on agroecological innovations, including diverse actors and enshrined in uncertainty and adaptability.

In agroecology, farmers are in a norm of permanent adaptation. **A research funding system promoting agroecology needs to give researchers room to adapt as well.**

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## Résumés

### Version longue

La spécialisation des fermes et des territoires et la déconnexion entre cultures et élevages engendrent de lourds impacts environnementaux à l'échelle mondiale. Pourtant, les fermes spécialisées largement dépendantes aux intrants restent le modèle dominant. A contre-courant, quelques agriculteurs pionniers réintègrent (i.e. organisent intentionnellement le retour) de l'élevage dans les fermes et territoires spécialisés en cultures. Ces initiatives, théoriquement agroécologiques, pourraient contribuer à réduire l'impact environnemental l'agriculture. Toutefois, elles restent peu étudiées.

L'objectif de ma thèse était de produire des connaissances sur pourquoi, dans quels contextes, comment et avec quels impacts les agriculteurs réintègrent l'élevage. J'ai développé une approche exploratoire, en étudiant une grande diversité de fermes françaises ayant réintégré de l'élevage sur la ferme ou par partenariat avec un éleveur (i.e. par l'accueil temporaire d'animaux sur la ferme de cultures), en incluant tout type de cultures et d'élevages. J'ai développé une approche multi-niveaux, de l'agriculteur, à la ferme et au système sociotechnique, et j'ai enquêté différents acteurs. J'ai mobilisé le cadre de la traque aux innovations pour documenter la réintégration de l'élevage comme un exemple d'innovation agroécologique.

J'ai inventorié et hiérarchisé les motivations des agriculteurs français à réintégrer de l'élevage. Ces motivations sont variées, les trois principales étant: suivre leurs valeurs éthiques et morales (e.g. protéger l'environnement, relever un challenge technique) ; bénéficier de services écosystémiques, en particulier promouvoir la biodiversité et la qualité des sols pour remplacer les intrants ; et améliorer et stabiliser le revenu en diminuant les coûts de production et en diversifiant les productions de la ferme.

Au-delà des motivations, d'autres déterminants conditionnent la réintégration de l'élevage. Par une analyse transversale des freins et leviers sociotechniques à la réintégration de l'élevage dans trois régions du monde, j'ai montré que les principaux freins à cette réintégration sont le manque de connaissances spécifiques de tous les acteurs du système sociotechnique et la disparition des services liés à l'élevage (e.g. abattoirs) dans les territoires spécialisés en cultures. Des actions collectives sont nécessaires pour surmonter ces freins.

Pour contribuer à combler ce manque de connaissances et déterminer les réels bénéfices à attendre de la réintégration de l'élevage, je me suis re-focalisée sur les fermes françaises pour caractériser les changements de pratiques liés à la réintégration de l'élevage et évaluer leurs impacts agroenvironnementaux, en accord avec les motivations des agriculteurs. La réintégration de l'élevage peut être durable, si et seulement si elle s'accompagne d'adaptations systémiques favorisant les interactions entre cultures et élevages et réduisant l'usage d'intrants.

La réintégration de l'élevage étant un processus de changement, j'ai souhaité créer une typologie de trajectoires menant les agriculteurs à cette réintégration. Mon échantillon très diversifié ne m'a pas

permis d'y parvenir. Cet échec m'a questionnée sur l'impact de mes choix de chercheuse sur mes résultats. J'ai partagé cette réflexion épistémologique en invitant mes collègues agronomes à réfléchir sur leurs postures et pratiques de recherche.

Dans ma thèse, je propose un premier aperçu de la réintégration de l'élevage, au travers d'un panorama des déterminants menant à cette réintégration, des changements de pratiques induits et de leurs impacts. J'identifie des formes durables de réintégration de l'élevage à étudier en priorité et les conditions nécessaires pour soutenir leur développement. Je contribue à enrichir le cadre de la traque aux innovations par une analyse multi-niveaux des déterminants menant à des innovations agroécologiques et une évaluation objective de leur durabilité agroenvironnementale.

### Version courte vulgarisée

En France, des agriculteurs pionniers réintègrent (i.e. organisent intentionnellement le retour) de l'élevage dans des fermes et territoires de cultures. Ils vont à contre-courant de la tendance de spécialisation. Ces initiatives agroécologiques innovantes sont encore peu étudiées. Ma thèse vise à produire des connaissances sur cette réintégration, pour déterminer si son développement doit être soutenu et comment. Je propose une approche exploratoire incluant une diversité de fermes ayant réintégré de l'élevage, et multi-niveaux, de l'agriculteur, à la ferme et au territoire. J'offre un premier aperçu de la réintégration de l'élevage, en construisant un panorama des motivations des agriculteurs et des contextes menant à cette réintégration, ainsi que des changements de pratiques induits et de leurs impacts. J'identifie les formes de réintégration de l'élevage durables à étudier en priorité. L'originalité de ma thèse réside dans son objet d'étude et dans son approche multi-niveaux.

Mots-clés: Intégration cultures-élevages, agroécologie, motivations, contexte sociotechnique, durabilité des fermes, traque aux innovations

## Abstracts

### Full version

The specialization of farms and regions toward either crop or livestock production leads to high environmental impacts worldwide. Yet, high-input specialized farming systems remain the mainstream. Opposing this trend, a few pioneer farmers are reintegrating (i.e. intentionally organizing the return of) livestock in specialized crop farms and regions. Such farming systems theoretically match the principles of agroecology, and may contribute to improve the environmental impacts of agricultural production. Yet, they have been understudied to date.

In this Ph.D. work, I aimed to produce knowledge on why, in which contexts, how and with what impacts farmers are reintegrating livestock. To do so, I relied on an exploratory approach. I studied a wide diversity of French farms having reintegrated livestock on the farm or through partnership with a livestock farmer (i.e. with the crop farmer hosting livestock temporarily) including all crop and livestock production. I relied on a multi-level approach from the farmer, to the farm and the sociotechnical system, and interviewed diverse actors. I built on the innovation-tracking framework to unearth and document livestock reintegration as an example of agroecological innovation.

I inventoried and ranked French farmers' motivations for reintegrating livestock. Such motivations are diverse, the three main ones being: following personal ethical and moral values (e.g. aligning with environmental stewardship, undertaking a technical challenge) ; benefiting from ecosystem services, particularly soil quality and biodiversity promotion, to substitute input ; and improving and stabilizing income due to decreasing production costs and diversifying farm production.

Beyond motivations, other determinants condition livestock reintegration. Through a transversal analysis of sociotechnical barriers and levers to reintegrating livestock in three regions of the world, I showed that such reintegration is particularly hindered by the lack of specific knowledge from all actors of the sociotechnical system and by the disappearance of livestock-related services (e.g. slaughterhouses) in specialized crop regions. Such barriers require collective actions to be raised.

To contribute addressing this knowledge gap, and disentangle the benefits to expect from reintegrating livestock, I re-focused on the farm level and on French farms to characterize the changes in farming practices after reintegrating livestock and assess their agroenvironmental impacts in regard of farmers' motivations. I showed that reintegrating livestock can be environmentally sustainable only if subsequent adaptations of the farming system are made to promote interactions between crop and livestock that reduce input use.

As reintegrating livestock is a process of change by nature, I aimed at analysing the succession of events leading farmers to reintegrate livestock by providing a typology of trajectories they followed. The high diversity of my sample did not provide sufficient redundancy to do so. Yet, this failure questioned me on the way I, as a researcher, choose to emphasize or overshadow specific elements while analysing

data and on how such choices condition my research results. I shared this epistemological reflection as an invitation to agricultural scientists to reflect on their research stances and practices.

In my Ph.D. work, I provide first insights on the understudied topic of livestock reintegration by building a panorama of determinants leading to reintegrating livestock, actual changes in farming practices and their impacts. I identify sustainable forms of livestock reintegration that should be studied more in depth by research and identify conditions to support their scaling up. I contribute to enrich the innovation-tracking framework through an original approach studying across levels the determinants leading to agroecological innovations, and objectively assessing their agroenvironmental sustainability.

Keywords: Crop-livestock integration, agroecology, motivations, sociotechnical context, farm sustainability, innovation-tracking



### Short popularized version

Pioneer French farmers reintegrate (i.e. intentionally organize the return of) livestock onto crop farms and into crop regions. They are opposing the trend of specialization. These innovative agroecological farming systems have been understudied to date. My work aims at producing knowledge on such reintegration, to determine whether its scaling up should be supported and how. I rely on an exploratory approach including a wide diversity of farms having reintegrated livestock. I focus on three interconnected levels, from the farmer, to the farm and to the territory. I provide first insights on livestock reintegration, through a panorama of farmers' motivations and contextual determinants leading to reintegrating livestock, of changes in farming practices induced and of their agroenvironmental impacts. I identify sustainable forms of livestock reintegration to further study. The novelty of my work lays in its original focus and on the multi-level approach developed.



**Titre :** Réintégrer l'élevage dans les fermes et territoires de cultures: motivations des agriculteurs, contextes sociotechniques, pratiques et durabilité des fermes

**Mots clés :** Intégration cultures-élevages, Agroécologie, Motivations, Contexte sociotechnique, Durabilité des fermes, Traque aux innovations

**Résumé :** La spécialisation des fermes et des territoires et la déconnexion entre cultures et élevages engendrent de lourds impacts environnementaux à l'échelle mondiale. Pourtant, les fermes spécialisées largement dépendantes aux intrants restent le modèle dominant. A contre-courant, quelques agriculteurs pionniers réintègrent (i.e. organisent intentionnellement le retour) de l'élevage dans les fermes et territoires spécialisés en cultures. Ces initiatives, théoriquement agroécologiques, pourraient contribuer à réduire l'impact environnemental l'agriculture. Toutefois, elles ont jusqu'alors été peu étudiées. L'objectif de ma thèse était de produire des connaissances sur pourquoi, dans quels contextes, comment et avec quels impacts les agriculteurs réintègrent l'élevage. J'ai développé une approche exploratoire, en étudiant une grande diversité de fermes françaises ayant réintégré de l'élevage sur la ferme ou par partenariat avec un éleveur (i.e. par l'accueil temporaire d'animaux sur la ferme de cultures), en incluant tout type de cultures et d'élevages. J'ai développé une approche multi-niveaux, de l'agriculteur, à la ferme et au système sociotechnique, et j'ai enquêté différents acteurs. J'ai mobilisé le cadre de la traque aux innovations pour documenter la réintégration de l'élevage comme un exemple d'innovation agroécologique. J'ai inventorié et hiérarchisé les motivations des agriculteurs français à réintégrer de l'élevage. Ces motivations sont variées, les trois principales étant: suivre leurs valeurs éthiques et morales (e.g. protéger l'environnement, relever un challenge technique) ; bénéficier de services écosystémiques, en particulier promouvoir la biodiversité et la qualité des sols pour remplacer les intrants ; et améliorer et stabiliser le revenu en diminuant les coûts de production et en diversifiant les productions de la ferme. Au-delà des motivations, d'autres déterminants conditionnent la réintégration de l'élevage. Par une analyse transversale des freins et leviers sociotechniques à la réintégration de l'élevage dans trois régions du monde, j'ai montré que les principaux freins à cette réintégration sont le manque de connaissances spécifiques de tous les acteurs du système sociotechnique et la disparition des services liés à l'élevage (e.g. abattoirs) dans les territoires spécialisés en cultures. Des actions collectives sont nécessaires pour surmonter ces freins. Pour contribuer à combler ce manque de connaissances et déterminer les réels bénéfices à attendre de la réintégration de l'élevage, je me suis re-focalisée sur les fermes françaises pour caractériser les changements de pratiques liés à la réintégration de l'élevage et évaluer leurs impacts agroenvironnementaux, en accord avec les motivations des agriculteurs. La réintégration de l'élevage peut être durable, si et seulement si elle s'accompagne d'adaptations systémiques favorisant les interactions entre cultures et élevages et réduisant l'usage d'intrants. La réintégration de l'élevage étant un processus de changement, j'ai souhaité créer une typologie de trajectoires menant les agriculteurs à cette réintégration. Mon échantillon très diversifié ne m'a pas permis d'y parvenir. Cet échec m'a questionnée sur l'impact de mes choix de chercheuse sur mes résultats. J'ai partagé cette réflexion épistémologique en invitant mes collègues agronomes à réfléchir sur leurs postures et pratiques de recherche. Dans ma thèse, je propose un premier aperçu de la réintégration de l'élevage, au travers d'un panorama des déterminants menant à cette réintégration, des changements de pratiques induits et de leurs impacts. J'identifie des formes durables de réintégration de l'élevage à étudier en priorité et les conditions nécessaires pour soutenir leur développement. Je contribue à enrichir le cadre de la traque aux innovations par une analyse multi-niveaux des déterminants menant à des innovations agroécologiques et une évaluation objective de leur durabilité agroenvironnementale.

**Title:** Reintegrating livestock in specialized crop farms and regions: farmers' motivations, sociotechnical contexts, practices and farm sustainability

**Key words:** Crop-livestock integration, Agroecology, Motivations, Sociotechnical context, Farm sustainability, Innovation-tracking

**Abstract:** The specialization of farms and regions toward either crop or livestock production leads to high environmental impacts worldwide. Yet, high-input specialized farming systems remain the mainstream. Opposing this trend, a few pioneer farmers are reintegrating (i.e. intentionally organizing the return of) livestock in specialized crop farms and regions. Such farming systems theoretically match the principles of agroecology, and may contribute to improve the environmental impacts of agricultural production. Yet, they have been understudied to date. In this Ph.D. work, I aimed to produce knowledge on why, in which contexts, how and with what impacts farmers are reintegrating livestock. To do so, I relied on an exploratory approach. I studied a wide diversity of French farms having reintegrated livestock on the farm or through partnership with a livestock farmer (i.e. with the crop farmer hosting livestock temporarily) including all crop and livestock production. I relied on a multi-level approach from the farmer, to the farm and the sociotechnical system, and interviewed diverse actors. I built on the innovation-tracking framework to unearth and document livestock reintegration as an example of agroecological innovation. I inventoried and ranked French farmers' motivations for reintegrating livestock. Such motivations are diverse, the three main ones being: following personal ethical and moral values (e.g. aligning with environmental stewardship, undertaking a technical challenge) ; benefiting from ecosystem services, particularly soil quality and biodiversity promotion, to substitute input ; and improving and stabilizing income due to decreasing production costs and diversifying farm production.

Beyond motivations, other determinants condition livestock reintegration. Through a transversal analysis of sociotechnical barriers and levers to reintegrating livestock in three regions of the world, I showed that such reintegration is particularly hindered by the lack of specific knowledge from all actors of the sociotechnical system and by the disappearance of livestock-related services (e.g. slaughterhouses) in specialized crop regions. Such barriers require collective actions to be raised. To contribute addressing this knowledge gap, and disentangle the benefits to expect from reintegrating livestock, I re-focused on the farm level and on French farms to characterize the changes in farming practices after reintegrating livestock and assess their agroenvironmental impacts in regard of farmers' motivations. I showed that reintegrating livestock can be environmentally sustainable only if subsequent adaptations of the farming system are made to promote interactions between crop and livestock that reduce input use. As reintegrating livestock is a process of change by nature, I aimed at analysing the succession of events leading farmers to reintegrate livestock by providing a typology of trajectories they followed. The high diversity of my sample did not provide sufficient redundancy to do so. Yet, this failure questioned me on the way I, as a researcher, choose to emphasize or overshadow specific elements while analysing data and on how such choices condition my research results. I shared this epistemological reflection as an invitation to agricultural scientists to reflect on their research stances and practices. In my Ph.D. work, I provide first insights on the understudied topic of livestock reintegration by building a panorama of determinants leading to reintegrating livestock, actual changes in farming practices and their impacts. I identify sustainable forms of livestock reintegration that should be studied more in depth by research and identify conditions to support their scaling up. I contribute to enrich the innovation-tracking framework through an original approach studying across levels the determinants leading to agroecological innovations, and objectively assessing their agroenvironmental sustainability.