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Exploring equipment management logics for species mixtures: insights from agronomy

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Key words

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Abstract (300 words)

Species mixtures are a key lever for the agroecological transition, as they allow to reduce environmental impacts while maintaining yields. Farmers face challenges in implementing them, however – especially technical difficulties and constraints related to cultivation and post-harvest sorting machinery. This study explores farmers' agricultural equipment fleet management logics in the context of species mixture cultivation.

Our research methodology draws on the innovation tracking approach. Data were collected through interviews with 13 farmers cultivating species mixtures across France. Using concepts from systems agronomy, we examined: (i) the characteristics and management of mixtures, as farmers consider them when selecting and using equipment, (ii) the technical features of the machinery used – including modifications and farmer-driven innovations – and (iii) farmers' overall logic for managing their machinery fleets.

Three main findings emerged. First, we identified six categories of species mixtures, characterized according to their component species' spatial arrangement and sowing depth – two aspects that, from farmers' perspective, are closely linked to machinery management strategies. For instance, in one category, species are sown in the same row and at the same depth, while in another, they are sown in alternating rows at different depths.

Second, we found that all farmers used a wide range of equipment to manage and sort the mixtures, with many having modified or improvised tools, especially for sowing. For example, one farmer adapted a seed drill to sow wheat and faba bean at two different depths.

Third, our interviews showed three contrasting machinery management logics: (i) cost minimization by reusing existing equipment, (ii) adapting sowing practices to the biological characteristics of species, and (iii) equipment choices shaped by local resources.

This study offers a new approach to understanding the role of agricultural machinery in species mixture management and provides insights that can support stakeholders in the development of this agroecological practice.

1. Introduction

Crop diversification is considered as one of the central pillars of the agroecological transition (Duru et al., 2015; Kremen et al., 2012), as it bolsters agroecosystem resilience (Tamburini et al., 2020). Among diversification levers, species mixtures – the cultivation of several species on the same plot – offer numerous advantages compared with single crop cultivation, such as: (i) improved use of abiotic resources such as light, water and nitrogen (Bedoussac & Justes, 2010a) , (ii) increased yields (Bedoussac et al., 2015) and stability (Malézieux et al., 2009) , (iii) improved cereal protein content when combined with a legume (Bedoussac et al., 2015; Bedoussac & Justes, 2010b; Naudin et al, 2010) , and (iv) greater resilience in the face of biotic risks (Bedoussac et al., 2015; Hauggaard-Nielsen et al., 2008), thus reducing pesticide use (Yan et al., 2024). Farmers cultivate a diverse array of species mixtures, both in terms of species sown and of management (Bedoussac et al., 2021; Gardarin et al., 2022; Verret et al., 2020), depending on their specific outlets and targeted objects (ecosystem services, targeted use of cultivated species...).

Despite the well-documented benefits of species mixtures, the literature highlights several challenges farmers face in implementing them. Some of these challenges, such as difficulties in marketing mixed seeds, are related to value chains (Mamine and Farès, 2020; Meynard et al., 2018). Others concern the need for new knowledge and skills, as well as the lack of locally available technical advice (Bonke et al., 2021). A further set of constraints relates specifically to agricultural equipment, including issues during sowing and harvesting (e.g., differences in seed size and maturity among species) and the quality of post-harvest seed separation, which directly affects the final product's marketability (Lemken et al., 2017). This is especially crucial for products intended for human consumption, which typically command higher prices than animal feed and therefore offer farmers the potential for improved economic performance (Meynard et al., 2018).

While several studies have shown that some farmers are already growing species mixtures (Aare et al., 2021; Verret et al., 2020), little is known about their management of their agricultural equipment in this context. To our knowledge, no study has specifically investigated the equipment used by farmers yet, even though it plays a key role in the development of species mixtures, much like it has been shown to do for other innovative practices (Salembier et al., 2020).

Agricultural equipment is often identified as a critical enabler of agroecological transitions, particularly when it allows farmers to adapt to evolving practices or supports them in adopting new ones (Bournigal et al., 2015; Machenaud et al., 2014; Piovan, 2018; Reboud et al., 2022), including the use of species mixtures (Bellon Maurel & Huyghe, 2017). However, equipment manufacturers have historically focused their design efforts on prevalent practices – namely, high-input monocultures on large fields (Reboud et al., 2022) – without necessarily accounting for the diversity of farmers' needs or for their evolutions (Bournigal et al., 2015; Machenaud et al., 2014).

In contrast, some authors emphasize farmer empowerment through tinkering and self-building (Guenin, 2009), and open-source and low-tech approaches (Giotitsas, 2019), highlighting these strategies' potential in enabling

agroecological transitions. Other studies have explored farmers' ways of innovating and tinkering with existing equipment to implement new practices (Kefi et al., 2022; Salembier et al., 2020).

Species mixtures management and harvest sorting thus raises specific questions that are directly linked to agricultural equipment that remains designed for monospecific crops: how should they be sown, given the physiological specificities of each species? How to harvest them? How to sort them?

This study therefore addresses the question: 'what are farmers' agricultural equipment fleet management logics in implementing species mixtures on their farms?' In the following section, we lay out the conceptual framework we used to characterize farmers' agricultural equipment fleets and action logics. We then detail our method and the cases we studied. Finally, in the last section, we present and discuss our findings.

2. Theoretical framework of the study

Our work falls within the field of systems agronomy, specifically focusing on farmers' practices. Within this framework, we primarily mobilize two key concepts – technical itinerary and logic of action – and two main study objects: species mixtures and the agricultural machinery fleet. It is important to note that we consider only species mixtures in which at least one component crop is harvested for grain. This excludes multiservice cover crops, which involve fewer constraints regarding machinery management as they do not entail grain harvesting and sorting operations. The concepts used in this study are illustrated in Figure 1.

A **technical itinerary** (Sébillotte, 1990) is defined as a '*logical and ordered combination of techniques implemented on a plot of land to obtain production*' (Sébillotte, 1974, 1978). This concept provides a framework for analyzing agricultural practices, including operations such as sowing, fertilizing, harvesting, and sorting.

The concept of **action logic** (Malanski et al., submitted; Meynard et al., 2001; Quinio et al., 2022; Salembier et al., 2021; Sébillotte, 1990) serves to examine the meaning farmers attribute to their actions within their specific situations. This includes their motivations, the effects and performance of their actions, the outcomes achieved, and their degree of satisfaction. It also considers the conditions under which actions are implemented and effective, as well as how farmers interpret the outcomes of their actions.

The **agricultural equipment machinery fleet** encompasses all agricultural equipment used for agricultural production. In this study, our focus is only on the equipment employed in managing species mixtures – whether it is owned by the farmer, shared through machinery cooperatives (CUMA), or provided by agricultural service companies. A wide range of machinery is currently available, reflecting the diversity of cropping systems, farming practices, tasks, and farm structures. In this study, agricultural equipment is characterized (Atelier Paysan, 2017) according to: (i) its technical dimension (physical structure), (ii) modifications made, (iii) its functions (intended purposes), and (iv) its actual uses (how farmers operate it).

Thus, we introduce the notion of machinery management logic to refer to our specific analytical perspective on agricultural equipment and its management, from the farmers' point of view, to gain a better understanding of their practices. To investigate farmers' machinery management logics, we first analyze the technical itinerary implemented for each species mixture and the equipment it requires, and then recontextualize this technical itinerary in the farmer's action situation.

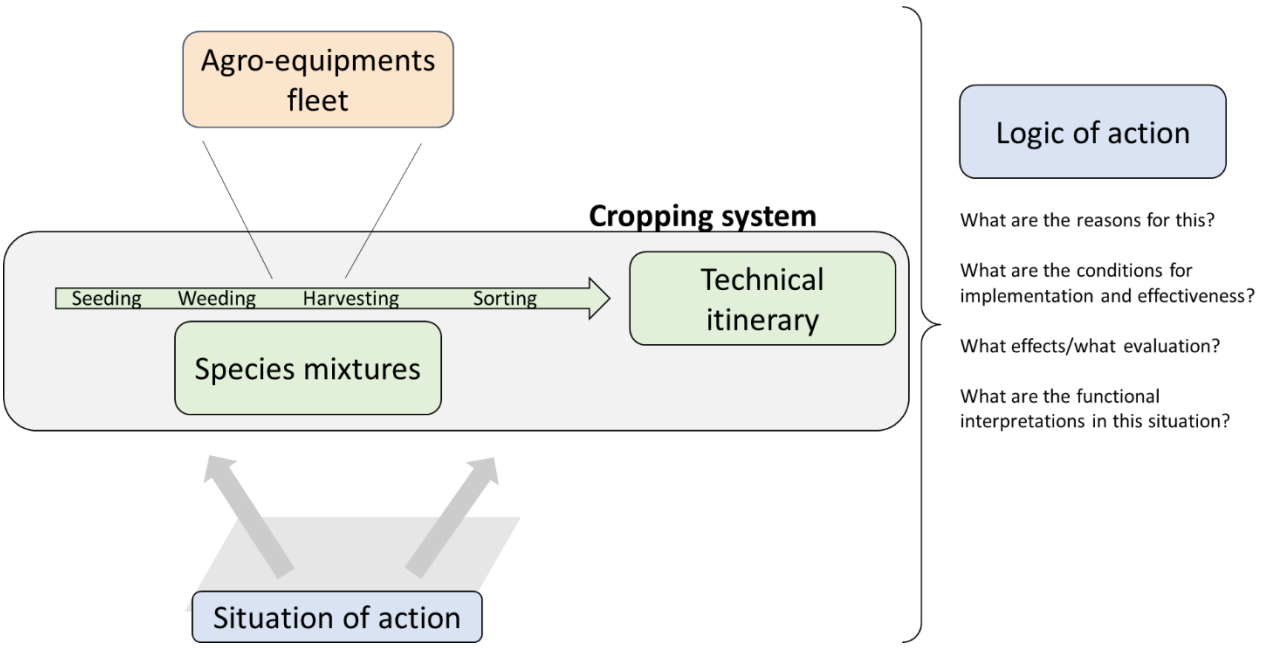


Figure 1: Conceptual framework showing the elements factored into our study of agricultural equipment management logics.

3. Methods

To identify and characterize the different ways farmers manage their agricultural machinery fleets when cultivating species mixtures, we drew inspiration from the *innovation tracking* method formalized by Salembier et al. (2021), which consists of five steps (detailed below). This study was conducted in partnership with the French national federation of agricultural equipment use cooperatives (FNCUMA – *Federation Nationale des Coopératives d'Utilisation de Matériel Agricole*).

3.1. Defining our innovation tracking project

The first of these five steps is to define the innovation tracking project itself, and in particular: (i) the geographical area of the study (here, metropolitan France), (ii) the actors involved in its implementation, and (iii) what is collectively considered as 'innovative' (and why, depending on how and by whom the findings are intended to be used).

Here, the notion of 'innovation' was defined in collaboration with members of the FNCUMA, who initiated the study and possess deep knowledge of issues related to agricultural machinery within their network. The results of this work are intended to be shared within the CUMA network, and especially with field coordinators who support farmers in adapting their practices following machinery management strategies. Accordingly, we chose to focus this innovation tracking effort on: (i) species mixtures in which at least one species is harvested for grain, to capture specific constraints related to harvesting and sorting operations – constraints that do not apply

to multiservice cover crops; and (ii) the diverse logics of machinery fleet management, as they emerge in the practices and equipment strategies adopted by farmers.

3.2. Identifying farmers growing species mixtures

To identify farmers who cultivate species mixtures, we explored several avenues. Initially, we relied on the FNCUMA's 'agricultural machinery' and 'agroecology' online forums to contact engineers and facilitators from the CUMA network who work closely with farmers in the field. Similarly, we engaged with the online forum of the French cooperative *L'Atelier Paysan*, which documents farmers' inventions and adaptations of agricultural machinery. We also reached out to researchers who have worked – or are currently working – on species mixtures, as well as to advisors from Chambers of Agriculture and 'CIVAM' local initiative collectives (Supplementary Material 1).

Finally, we established direct contact with farmers through social media, targeting French groups related to our topic (Supplementary Material 1), specifically: (i) '*Matériel agricole fabrication maison*' ('Homemade farming equipment') and '*L'Agriculture de Conservation des Sols : le semis direct, les TCS, les Couverts…*' ('Soil conservation agriculture: direct sowing, no-till, covers…') on Facebook™, and (ii) '*Couvert végétaux, gestion des intercultures*' ('Cover crops, intercrop management') and 'Plantes compagnes' ('Companion planting') on WhatsApp™.

In practical terms, we posted a message (Supplementary Material 2) on these forums and social networks. Once we had identified potential farmers, we made an initial phone call to gather information about the species mixtures they used, the equipment involved, their interest in the study, their availability for an interview, and their willingness to share their practices. We also asked whether they knew other farmers growing species mixtures and adapting their equipment. In total, we identified and contacted 30 farmers, and interviewed 13 of them for the study (Supplementary Material 3).

3.3. Discovering innovation

We conducted semi-structured interviews with each farmer, which we recorded and subsequently transcribed. Each interview took place in two phases: (i) indoors, followed by (ii) a session in front of the agricultural machinery to complete data collection with direct access to the equipment, enabling us to validate the information, observe details, and take photographs.

The interview protocol was based on the conceptual framework previously presented. It was designed to retrace the farmer's situation and the context of the farm (e.g., utilized agricultural area, labor units, farming practices), the species mixtures implemented and how they were managed during the season preceding the interview, as well as the equipment used for each technical operation. Special attention was paid to understanding the functions, uses, and potential modifications of each piece of equipment in relation to the management of species mixtures.

The interview also involved eliciting the farmer's *action logic*, through questions such as: 'Why did you choose to associate species?', 'What does this equipment allow you to do?', or 'Are you satisfied with it?'. These insights were crucial to reveal the farmer's machinery management logic for cultivating species mixtures.

3.4. Analyzing innovations

The interviews were transcribed using the *whisper* package on python. Discourse analysis was carried out inductively, using a narrative format (Salembier et al., 2021). Multi-thematic coding (Dumez, 2009) was applied, allowing us to group information into categories related to actions, equipment, and situated action logics. We then conducted a cross-case analysis of interview summaries to construct categories (Girard, 2009) based on similarities and differences between cases, following three analytical axes:

1. **Descriptions of species mixtures in relation to agricultural equipment**: looking at the characteristics of the mixtures, how they are managed, and the factors farmers take into account in their choice and use of agricultural equipment.
2. **Descriptions of the agricultural equipment** used to manage mixtures, from sowing to sorting, in terms of their functions and the modifications made to them, while acknowledging that their use depends on spatial arrangements and sowing depths.
3. **Characterizations of farmers' agricultural equipment fleet management logic** with regard to their individual situation (skills, networks, etc.), the mixtures they manage (number and types of species, choices regarding mixtures and spatial arrangement), and their machinery fleet (equipment they own, outsourced services, equipment modifications, etc.).

4. Results

11 of the 13 farmers surveyed were organic farmers. During the crop year analyzed, four farmers had grown a single species mixture, three had grown two and six had grown three or more. We identified a total of 21 different species mixtures (combinations of species – see Table 1). Of these 21 mixtures, 18 combined cereals and legumes, and five combined C3 or C4 plants with service plants. The most commonly grown mix was wheat with faba bean (eight out of 13 farmers), followed by the triticale–pea mix (four farmers) and rapeseed–faba bean and sunflower–service plant mixtures (three farmers). 15 other mixtures had only been grown by a single farmer.

4.1. Characteristics of species mixtures from an agricultural equipment perspective

All the farmers we surveyed emphasized sowing, harvesting and sorting as key moments during which they adopted different agricultural equipment fleet management logics, consistent with the way they manage their species mixtures. In this section, we characterize species mixtures through the prism of the agricultural equipment used at these key moments. In other words, we look at the characteristics of mixtures and their management based on information put forward by farmers to explain how they manage their agricultural equipment fleets.

4.1.1. Mixture seeding through the lens of agricultural equipment: seeding depth and spatial layout

Our analysis of the species mixtures grown sheds light on sowing characteristics linked to spatial arrangement (alternating rows, species mixtures on the same row or at least one species broadcast seeded) and depth (either identical or different between species). This allowed us to classify the 21 species mixtures into six categories (**Category 1 to 6**; Figure 2 Left; Table 1).

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207 *Table 1: number of farmers growing the different species mixtures identified and categorization of these mixtures according to spatial arrangement and sowing depth*
208 *(Categories 1 to 6) and according to mixture harvesting and sorting (Categories A to D). * indicates that a species is a service crop*

Species mixtures (nb of farmers cultivating the mixture)	Category based on sowing						Category based on harvest and sorting			
	Same depth			Different depths			2 species harvested			
	Cat. 1 same row	Cat. 2 alternate rows	Cat. 3 broadcast	Cat.4 same row	Cat. 5 alternate rows	Cat. 6 row and broadcast	Cat. A no sorting	Cat. B easy sorting	Cat. C difficult sorting	Cat. D no sorting
Wheat - Faba bean (8)	3 AGC1, AGC6 AGC7	1 AGC3	1 AGC12		1 AGC10	2 AGC4, AGC5		2 AGC1,AGC12	4 AGC4,AGC5 AGC7,AGC10	2 AGC3,AGC6
Wheat - Clover* (1)						1 AGC1	1 AGC1			
Wheat - Pea (1)	1 AGC5									1 AGC5
Wheat - Faba bean - Pea (1)			1 AGC12					1 AGC12		
Wheat* - Lentil (1)	1 AGC2						1 AGC2			
Triticale - Pea (4)	3 AGC1,AGC7 AGC13	1 AGC10						1 AGC1	1 AGC7	2 AGC10 AGC13
Triticale - Faba bean (1)	1 AGC13									1 AGC13
Barley - Pea (2)	1 AGC11	1 AGC10								2 AGC10, AGC11
Barley - Faba bean (1)	1 AGC6						1 AGC6			
Barley - Lentil (2)	1 AGC12	1 AGC10						1 AGC12		1 AGC10
Barley - Clover* - Alfafa* (1)						1 AGC1	1 AGC1			
Rapeseed – Cover crops* (4)		1 AGC9		1 AGC8		2 AGC1, AGC6	4 AGC1,AGC6,AGC8,AGC9			
Spelt - Lentil (1)	1 AGC11								1 AGC11	
Oat - Vetch (1)						1 AGC6				1 AGC6
Buckwheat - Clover* (1)	1 AGC12						1 AGC12			
Rye - Faba bean (1)	1 AGC13									1 AGC13
Rye - Lentil (1)	1 AGC1								1 AGC13	
Khorasan wheat - Faba bean (1)	1 AGC12							1 AGC12		
Sunflower - Cover crop* (3)						3 AGC5, AGC6 AGC12	3 AGC5, AGC6, AGC12			
Maize - Soybean - Clover* (1)						1 AGC6	1 AGC6			
Number of species mixtures (out of 20)	**14**	**5**	**2**	**1**	**1**	**7**	**8**	**5**	**4**	**9**
Number of farmers (out of 13)	**8**	**3**	**1**	**1**	**1**	**5**	**7**	**5**	**3**	**6**

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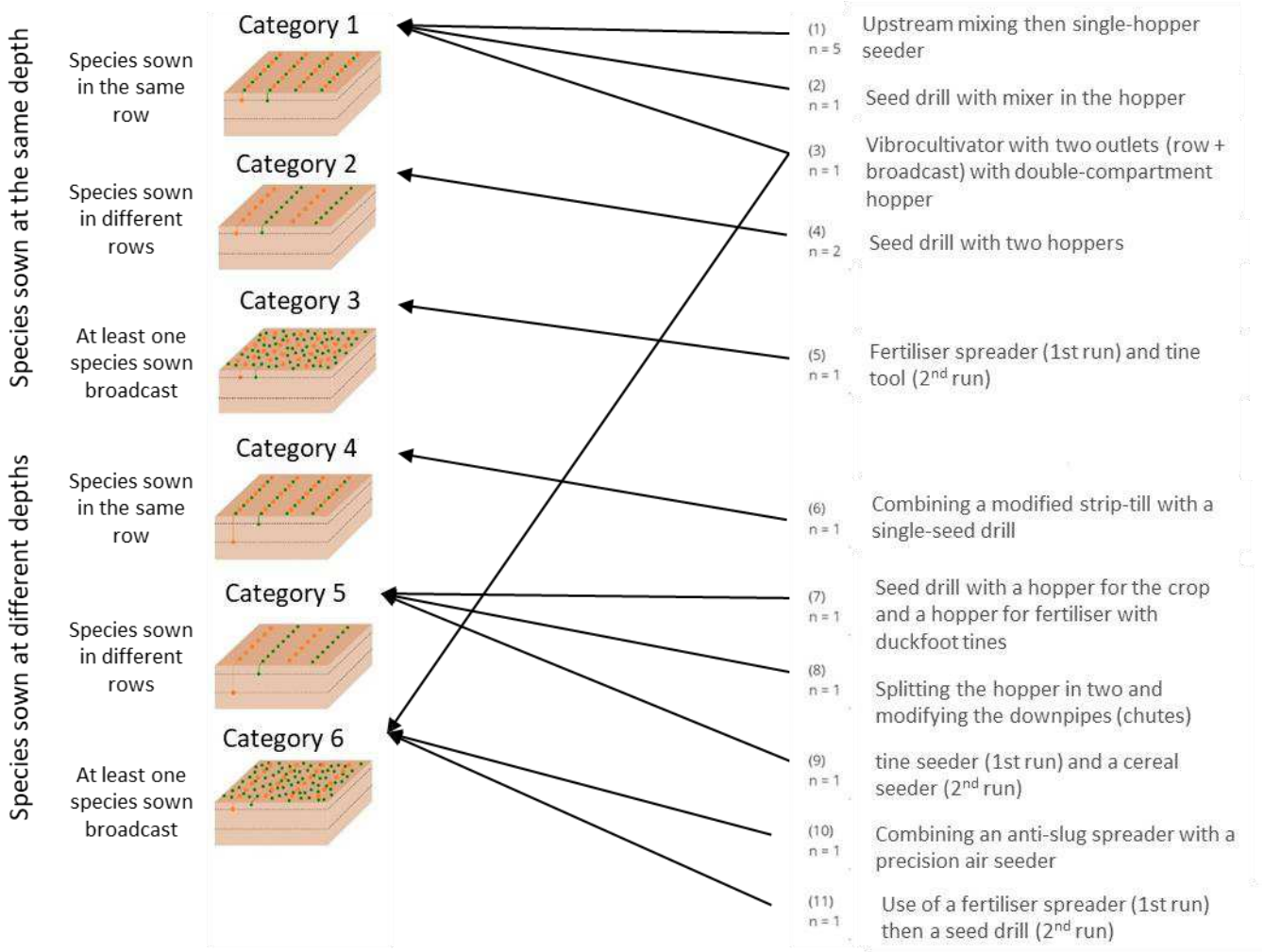


Figure 2: Schematic representation of the six categories of mixtures identified according to seeding depth and spatial arrangement of associated species (Left); Tools and number of farmers using them (n=) for the different mixture categories (Right).

Categories 1, 2 and 3 are all sown at the same depth, but they differ in terms of spatial arrangement. Species mixtures in **Category 1** are sown on the same row; species mixtures in **Category 2** are sown on alternate rows; while in **Category 3,** all species are broadcast (Figure 2, Left). 15 mixtures, grown by eight farmers (Table 1), are in **Category 1** (*e.g.* wheat – faba bean, triticale – pea, and rye – lentil). **Category 2** only contains one mixture (wheat – faba bean, grown by a single farmer) and **Category 3** contains two (wheat – faba bean and wheat – faba bean – pea, both grown by the same farmer)

Species in **Categories 4, 5 and 6** mixtures are sown at different depths, with, as before, a distinction based on spatial arrangement (**Category 4** in the row, **Category 5** in alternate rows and **Category 6** with at least one species broadcast; Figure 2, Left). It should be noted that in **Category 6**, row seeding is systematically deeper than broadcast seeding. **Category 4** only contains one species mixture (rapeseed – faba bean grown by a single farmer), while **Category 5** encompasses five mixtures (*e.g.* wheat – faba bean, triticale – pea, and barley – lentil), grown by three different farmers, and **Category 6** covers six mixtures (*e.g.* barley – clover – alfalfa and wheat – clover) grown by four farmers (Table 1).

Different farmers' ways to grow a given species mixture can fall into different categories (Table 1). This is the case for the wheat – faba bean mixture, which is grown in all categories except **Category 4**, and the rapeseed – faba bean mixture, which is grown by three farmers, each in a different category (**Categories 2, 4 and 6**). Similarly, a farmer may use different categories depending on the nature of the associated species. Thus, of the nine farmers who cultivated at least two species mixtures, three used two different categories of sowing arrangements (**Categories 1 and 6**).

4.1.2. Mixture harvesting and sorting through the lens of agricultural equipment: nature of the species associated and product outlets

Characteristics linked to harvesting and sorting emerged in our analysis of species mixtures, leading us to propose a second categorization (**Categories A to D**). These categories are based on the number of species harvested, the outlet for the harvested product and its effect on the farmer's sorting operations and their perceived complexity. The variables retained for this second categorization are: (i) the number of species harvested (0, 1 or 2), (ii) whether or not the farmer sorts the species harvested, and (iii) the ease of sorting according to species grain size (similar or different).

- **Category A**: species mixtures in which only one species is harvested and which therefore do not require sorting. 8 mixtures, grown by 7 farmers, fall in this category. This is the case, for example, with the wheat – clover mixture, where the clover is sown into the wheat in the spring to provide soil cover after the wheat harvest (AGC1), or the rapeseed – faba bean mixture, where the legume is destroyed by frost during cultivation (AGC8).
- **Category B**: mixtures in which at least two species are harvested and sorted, and in which sorting is presented as 'easy' in farmers' accounts due to contrasting seed sizes (*e.g.* wheat – faba bean, triticale – pea, or barley – lentil). This category encompasses 5 mixtures and 5 farmers. In this case, a cleaner-separator, used by three farmers (AGC4, AGC5 and AGC10), appears to be sufficient.
- **Category C**: species mixtures in which at least two species are harvested and then sorted, but for which sorting is considered 'difficult', especially due to similar seed sizes, requiring several runs through the cleaner-separator or the successive use of different sorters (*e.g.* AGC7 sorted his wheat – faba bean mixture by running it through a rotary sorter first, followed by an aerodynamic sorter). In addition to sorting constraints, farmers also mention harvesting difficulties, as in the case of the triticale-pea mix, which AGC5 stopped growing because he could not find a satisfactory combination of settings to properly thresh the triticale without breaking the pea grains.
- **Category D**: mixtures in which at least two species are harvested without the harvest being sorted before marketing. This is the case for AGC5's wheat – pea mix, which he sells directly to a livestock breeder, and AGC13's rye – faba bean mix, which he sells to winegrowers as cover crop seeds. In other cases, due to sorting difficulties or organizational hurdles, sorting is carried out by the cooperative or by contractors. This is the case, for example, with AGC13's triticale – pea mix and AGC3's wheat – faba bean mix, which are sorted by their cooperative.

As with our categorization based on species mixtures sowing methods (**Categories 1 to 6**), some mixtures fall into several of our harvesting and sorting categories (**Categories A to D)**. Farmers who grow mixtures with wheat may harvest only the wheat (**Category A**), whereas farmers who grow mixtures with lentil harvest both species (Table 1), with various degrees of sorting constraints (barley – lentil, **Category B** for AGC12, rye –

lentil, **Category C** for AGC1, and spelt – lentil, **Category C** for AGC11). This operation is sometimes outsourced (barley – lentil, **Category D** for AGC10). Similarly, AGC4 sorts his **Category C** wheat – faba bean mixture using a Marot rotary cleaner-separator, while AGC3 does so through his cooperative (**Category D**) and AGC12 through a sorting farm he has set up with other farmers (**Category B**). It thus appears that mixture sorting logics vary according to the resources available locally, such as the presence of agricultural contracting companies, cooperatives, or collective investments in sorting machinery. Finally, for the nine farmers growing several mixtures, we noted, as for sowing categories, that mixtures belonging to different categories could be grown on the same farm (*e.g.* AGC10 grows a **Category D** triticale – pea mixture and a **Category B** wheat – faba bean mixture), depending on the characteristics of the species associated and the targeted outlets' potential sorting requirements.

4.2. Agricultural equipment portfolio and its management in mixed species cultivation

The farmers surveyed use a very diverse range of agricultural equipment to manage species mixtures, which we present in this section. While some pieces of equipment are purchased and used as intended by their manufacturers, others are modified, diverted, or self-built, and different piece are sometimes used in combination. In the following sections, we present the agricultural equipment used by the farmers for each action associated with the management of species associations, from sowing to sorting.

4.2.1. What agricultural equipment is needed to mix seeds before sowing?

Three farmers do not mix seeds prior to sowing, as they use a seed drill with a double-compartment hopper or sowed in several runs. The other farmers, who sow in a single run and with a non-compartmentalized hopper, emphasized the need to choose species with relatively similar seed sizes to avoid, as AGC1 puts it*, 'unmixing during sowing due to vibrations'*. Two farmers (AGC1 and AGC8) use a pressurized hopper to mitigate this. We identified four seed mixture preparation practices:

- **Seed drill hopper.** The farmer mixes seeds directly in the seed drill hopper. This is what AGC5 does for the wheat – faba bean mixture, using a seed drill hopper equipped with paddles. While these paddles' initial function is to prevent the outlets from clogging, here, they serve to mix the seeds and mitigate unmixing during sowing.
- **Concrete or mud mixers**. Six farmers use these tools to prepare large volumes (up to 300L with a mud mixer and up to 800L with a concrete mixer). As AGC11 emphasized, this operation is time-consuming, as it generally requires several runs to obtain the quantity of seed needed to sow a plot: *'It's hellish because the concrete mixer is a batch of, let's say, 100 kilos, 150 kilos. When I have two tons to prepare, I'd have to do 20 batches in the concrete mixer'*. Several farmers pointed out that it is easier to mix seeds with similar thousand-kernel weights in this way. This is the case of AGC6, for example, who prepares the soybean – maize mix in a concrete mixer, which he then sows with a single-seed drill.
- **Hopper and chute**. Three farmers use these tools. AGC2, for example, uses them to prepare the wheat – lentil. He places a conical hopper containing the lentil above an empty conical hopper intended to contain the seed mix. Upon opening the lentil hopper door, he shovels wheat into the second hopper as it fills with lentil seed. In this case, it is necessary to have precisely calculated the quantity of seed of each species to achieve the targeted sowing density. Once the first mix is complete, AGC2 transfers

it twice from one hopper to the other to homogenize the batch. AGC13 alternates a layer of each species in a hopper, which he empties and fills several times until a homogeneous mix is obtained.

- **Auger conveyor.** AGC11 is the only one to use this tool to prepare a large volume of seeds in a single operation. He places the seeds of the two species together on the ground and feeds them into the bottom of the conveyor (400 mm diameter), where they are mechanically mixed along the entire length of the auger (5 m long). He did not consider this mixing process to be optimized yet, as it takes time to fill the auger with the different seeds, but it is less time-consuming than using a concrete mixer. As he explained: *'I put my seeds, my different seeds in there. Over 5 meters, it has time to mix well'*. AGC6, for his part, stopped using an auger conveyor because he felt it damaged the seeds.

4.2.2. What agricultural equipment is needed to sow mixed species?

Sowing the species mixtures is a decisive operation. Here again, we saw farmers use a diverse range of agricultural equipment (Figure 2 Right), depending on which **1 to 6 Category** their mixtures fell into.

When seeds are mixed before being introduced into the seed hopper, farmers do not adapt their equipment in any particular way. This is the case for all **Category 1** mixtures (same row, same depth).

The use of a seed drill with two hoppers or a compartmentalized hopper allows farmers to sow **Category 2** mixtures (alternating rows at the same depth). This is the case for AGC10, who hires a farm contractor to sow a wheat – faba bean mix, and for whom what matters most is to sow in alternating rows to limit the spread of diseases by creating a barrier effect*: 'We're going to create plant panels that will limit the distribution of disease through contact. When you have a curtain of wheat, a curtain of faba beans. The wheat curtains on either side can't touch... As a result, there's less contact with disease. There's less transmission'*.

AGC12 was the only one to grow **Category 3** mixtures (broadcast sowing of the mixture), i.e. wheat – faba bean and wheat – faba bean – pea. He does so using a fertilizer spreader (DP12) followed by a tine stubble cultivator to bury the seeds. This strategy gives him a high work rate, and therefore more time for sowing. As he explained: *'the big advantage is that I spread 24 meters wide and drive at 25 km per hour. I drive at 25 km/h. So in terms of work rate, I'm unbeatable. As I'm on my own and have a lot to do, it suits me just fine'*. To compensate for emergence losses due to poorly buried seeds, he increases seeding densities.

AGC8, on the other hand, was alone in cultivating a **Category 4** mixture (same row and different depths): rapeseed – faba bean. To this end, he has combined a strip-till, modified by the manufacturer with the addition of downpipes, and a single-seed drill. This solution allows him to sow the mixture in a single run, while respecting 'the physiology of the species, with rape sown on the surface and faba beans deep down' (excerpt from AGC8 interview). Strip-tilling allows to cut furrows at a depth of 10 cm for sowing the faba beans, while also preparing the seedbed for sowing the rapeseed with a precision drill, at a depth of 1.5 to 2 cm.

Three farmers planted **Category 5** mixtures (alternating rows and different depths) in one run (AGC3 and AGC10) or in two runs (AGC9):

- AGC3 has modified a no-till drill originally equipped with two distributor heads, a hopper and a double row of discs with a right/left separation at the distributor heads, to (i) add a removable partition in the hopper, and (ii) modify the chutes so that one compartment of the hopper fed the front discs (for deep seeding of faba beans) and the other the rear discs (for shallower seeding of wheat).

- AGC10, for his part, has repurposed a seed drill originally equipped with two hoppers connected to ploughshares on which are mounted two outlets, one of which was intended for depositing fertilizers or insecticides on either side of the sowing row and a centimetre deeper than it, but which he uses to sow the cereal in his mixtures (barley–pea, triticale–pea, and barley–lentil).
- AGC9 combines two implements to sow a rapeseed – faba bean mix in two runs (each at a different angle), first sowing the faba bean deeply with a tine drill, then sowing the rapeseed with a precision drill combined with a strip-till. As he explained, *'Actually, I go at an angle to sow my oilseed rape with my tine seeder, and I go into the field at an angle to sow the faba beans. And then I don't run the strip-till in same direction again. Precisely because I know that the strip-till tine blows away part of the grain, the faba bean. And so, this year, it worked very well. I've got my beans in the inter-row, but not in the row.'* It should be noted that sowing rapeseed can have an impact on the sowing of faba beans, which is not a problem, as the latter is destroyed during the crop (either by frost or chemically) and only the rapeseed is to be harvested.

Four farmers sowed **Category 6** mixtures (different depths and at least one species broadcast):

- Three farmers (AGC1, AGC5 and AGC6) sow these mixtures (*e.g.* wheat – faba bean, or sunflower – clover) in a single run, first broadcasting with a fertilizer spreader and then sowing in rows with a cereal drill to control sowing depth.
- Four farmers (AGC1, AGC4, AGC5) use a two-run system (*e.g.* wheat – faba bean), combining a drill (single-seed, tine or disc) for row seeding followed by a fertilizer or slug pellet spreader for broadcast seeding. It should be noted that two of these systems make use of the micro-granulator hoppers originally fitted to single-seed planters.

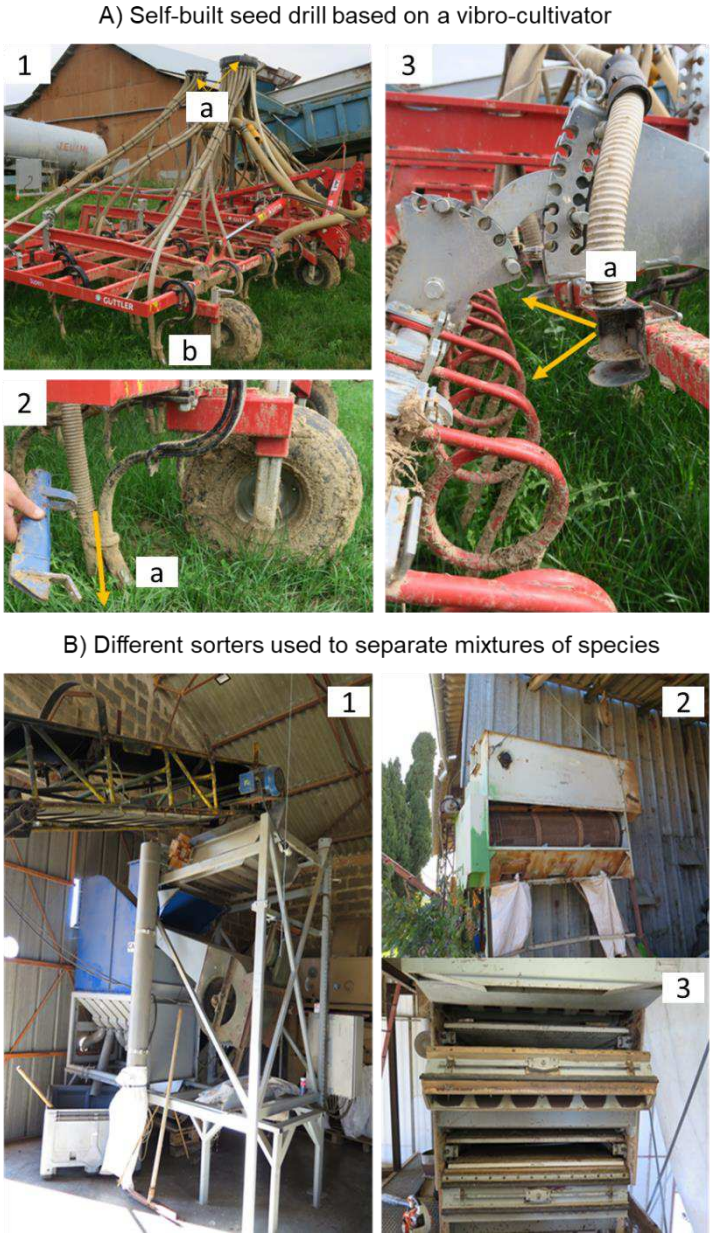


Figure 3: A) Self-built seed drill based on a vibrocultivator for sowing species mixtures with Category 1 and Category 6 arrangements with the integration of two distribution heads (A-1a), an outlet for deep seeding (A-1b and A-2a) and an outlet for broadcast sowing of seeds (A-3a); B) Different sorters used to separate species mixtures on the farm, namely aerodynamic sorter (B-1), rotary cleaner-separator (B-2) and flat cleaner-separator (B-3).

Farmer AGC1 has self-built a seed drill that enables him to sow six mixtures of species belonging to **Categories 1** and **6**. This self-built seeder is based on a vibrocultivator (Figure 3A) and comprises : (i) a double-compartment hopper that avoids having to prepare the mixture in advance, (ii) two distribution heads (Figure 3A-1a), (iii) outlets located at the level of certain vibrocultivator tines for deep seeding (Figure 3A-2a), (iv) outlets positioned after the last row of vibrocultivator tines for broadcast seeding (Figure 3A-3a), and (v) combs located at the rear end of the tool to cover the seed. For seeding **Category 1** mixtures (*e.g.* wheat –

peas), each species is placed in a separate compartment of the hopper, then both are sent to the distribution head connected to the outlets located at the level of the vibrocultivator tines (Figure 3A-2a). For sowing **Category 6** mixtures (*e.g.* wheat – clover), each species is also placed in a separate compartment of the hopper, but they are sent to two different distribution heads: (i) the one connected to the outlets located at vibrocultivator tine level for wheat sowing (Figure 3A-2a), and (ii) the other feeding the outlets positioned after the last row of vibrocultivator tines for clover sowing (Figure 3A-3a). It should be noted that the farmer uses this tool for tillage, independently of its function as a seed drill.

4.2.3. What agricultural equipment is needed to harvest species mixtures?

There are three types of combine harvesters: (i) **conventional**, based on a rotating cylindrical threshing drum surrounded by a static concave to extract the grain, which is then run through a system of shakers to separate it from the straw and cleared of light impurities by an air blower system; (ii) **axial**, which uses a single rotor for threshing, separation and grain cleaning; and (iii) **hybrid**, in which the threshing elements of conventional models are combined with an axial grain separation system. AGC2 was the only farmer who had modified his conventional combine harvester. He grows lentils alongside wheat but tops the wheat rather than harvesting it. By adding sieves to the threshing unit to filter out the largest waste while allowing small seeds to pass through, he is able to pre-sort these lentils.

Of the eight farmers who harvested at least two species, all own a combine harvester (two conventional and six axial), four also hire a farm machinery contractor (type unknown) and AGC11 also uses the CUMA's (a hybrid model with pre-recorded settings for the different mixtures). As soon as they start harvesting two or more species, farmers and agricultural contractors seek a compromise between optimal settings for each species in the mix. In particular, they adapt the beater's rotation speed and the spacing between the beater and concave to ensure that the mixture is properly threshed on the one hand while, on the other, keeping the largest or most fragile seeds from being broken in the process. As AGC11 pointed out when discussing the triticale – faba bean mix, such a compromise can be difficult, if not impossible, to find: *'Last year, I did triticale – faba bean and I couldn't manage... Triticale is very hard to beat. The grains stick to the stalks and if I go too hard, it breaks my faba beans'*. This is why, like AGC5, he gave up on growing this mixture.

For a given mix, farmers found that harvest quality depends on the type of combine and the settings chosen. However, due to their cost, farmers rarely have access to different combine models, so they default to the one available, regardless of the species in their mixtures. Only AGC12, who has access to several models of combine harvesters, chooses the most suitable one according to the specifics of his species mix (Axial for the barley – lentil mix and pick-up with a conveyor belt after mowing for the sunflower – service plant mix).

4.2.4. What agricultural equipment is used to sort species?

Farmers use various types of sorters, alone or in succession, to separate species mixtures (Figure 3B): (i) **aerodynamic sorter** (Figure 3B-1), which separates materials according to their lift in an air flow; (ii) **rotary cleaner-separator** (Figure 3B-2) consisting of a succession of rotating drums with holes of different shapes and sizes, and equipped with a blower to suck up light waste; (iii) **flat cleaner-separator** (Figure 3B-3) operating on the same principle as the rotary cleaner-separator, but with a superposition of vibrating perforated grids; (iv) **indented cylinder separator,** consisting of a rotating cylinder with cells of varying widths and depths that block certain seeds; (v) **helical sorters,** using inclined ramps on which the grains accelerate to varying

degrees and are either ejected or not; (vi) **densimetric tables,** using vibrations and an air flow to separate particles of the same size but different densities; or (vii) **optical sorters** using visible light cameras to eliminate waste according to shape and colour, and infrared cameras to eliminate mineral or organic matter.

Seven of the 13 farmers are equipped with a rotary cleaner-separator. Six of them have acquired theirs before they started mixing species, mostly to prepare their farm-saved seed. Two farmers have an indented cylinder separator (AGC7 and AGC12), only one has an aerodynamic sorter (AGC7), one has a helical sorter (AGC2) and one has an optical sorter (AGC12). It should be noted that this optical sorter is part of a complete sorting chain (cleaner-separator, indented cylinder, densimetric table, optical sorter) purchased collectively to share investment costs, which farmers also use to provide sorting, hulling and bagging services.

Four farmers (AGC2, AGC6, AGC7 and AGC12) have more than one sorter. AGC7 first uses his aerodynamic sorter to pre-sort his wheat – faba bean mixture, then feeds the part of his harvest it could not sort through his rotary cleaner-separator. It should be noted that he also uses this aerodynamic sorter to separate wheat grains according to specific weight.

Two farmers (AGC1 and AGC13) call on agricultural contractors to sort their mixtures for direct sale. AGC1 rents a rotary cleaner-separator, usually for one or two days, to sort his grain himself on his farm.

Lastly, six farmers do not sort their mixtures (**Category D**), due to a lack of time, skills, or agricultural equipment. In this case, they deliver the mix directly to the buyer, who may or may not then carry out a sorting operation (cooperative for AGC3's wheat – faba bean mix, breeder for AGC5's wheat – pea mix and winegrower for AGC13's rye – faba bean mix).

Table 2: descriptive variables used to characterize the archetypes of agricultural equipment management logics. These variables concern: (i) the farmer's situation, (ii) species mixtures (number of mixtures grown, number of categories, choice of spatial arrangement, harvesting, sorting and integration into the crop rotation), and (iii) their agricultural equipment fleet (types of modification for mixture management and adaptability of mixtures and/or agricultural equipment).

Action logics	**Key elements of the farmer's situation**	**Mixed species**					**Agricultural equipment fleet**	
		Nb of species mixtures / Nb of mixture categories	**Choice of spatial layout**	**Harvesting equipment**	**Sorting equipment**	**Integration into the crop rotation**	**Type of modification to agricultural equipment for mixture management**	**Adaptability of combinations and/or agricultural equipment**
A: minimizing mechanization costs by using the agricultural equipment already available on the farm.	A large and often aging stock of agricultural equipment	1 to 5 / 1 to 3	To make the most of the agricultural equipment already present on the farm and to respect the physiology of the species	Owned by the farmer	Owned by the farmer or sorting outsourced	Fixed rotation	Repurposing / Combination / Modification of physical structure	Adaptable species mixtures
B: sowing mixtures according to the characteristics of the species by adapting agricultural equipment	variable investment capacity / DIY skills and knowledge of agricultural equipment	1 to 5 / 1 or 2	Goal-oriented (respecting the physiology of species, fostering a barrier effect, etc.)	Owned by the farmer	Owned by the farmer or sorting outsourced	Semi-fixed rotation: various degrees of flexibility, adjustments according to weed prevalence on the plots.	Purchase / Modification of physical structure / Self-build	Adaptable associations and agricultural equipment for single crop and species mixtures cultivation
C: choosing species mixtures and agricultural equipment based on available resources	Presence of a farm contractor in the area / Changing mixtures year on year	2 to 6 / 1 or 2	Profitability and other farmer-specific goals	Owned by the farmer or harvest outsourced	Owned by the farmer or a group or sorting outsourced	No fixed rotation, with decisions based on plot conditions (weeds), the market and the economic interest of the crops.	Repurposing / contractors	Adaptable agricultural equipment

4.3. Agricultural equipment management logics for mixed species management

The cross-sectional analysis enabled us to identify three agricultural equipment fleet management logics for species mixtures. These are described below, and Table 2 presents the archetypal categories we drew according to the factual variables based on which these logics were characterized.

4.3.1. Management Logic A: minimizing mechanization costs by using the agricultural equipment already present on the farm.

Four farmers (AGC2, AGC4, AGC5 and AGC6) had adopted **Management Logic A: mobilizing a large fleet of old agricultural equipment to minimize costs**. On the one hand, this allows them to grow a diversity of mixtures (2 to 5) during most of their crop rotation but, on the other, they have to adapt the spatial arrangement of the mixtures (1 to 3 categories) according to the available machinery's technical possibilities, just as they adapt harvesting and sorting logics according to the outlets available to them.

For example, AGC5 owns a large fleet of second-hand agricultural equipment, which he has adapted at little cost to the particularities of the species he sows and associates. *'And by trying to adapt the farm's equipment a little'*, he produces various mixtures (oat – vetch, wheat – pea, wheat – faba bean, sunflower – service plants) either in **Category 1** or **Category 6**, depending on the specific characteristics of the associated species, with the overarching goal of limiting the use of inputs. For example, he sows his wheat–faba bean mixture (**Category 6**) in two runs spaced one to two weeks apart, first sowing the faba bean with a single-seed drill, then broadcasting the wheat with a pendulum spreader. *'What happens if we do that? What happens is the beans go under and the wheat stays on top'*. In contrast, he sows the oat-vetch mixture (**Category 1**) in a single run with a cereal drill. It bears noting that he does his best to adapt the sowing dates of his mixtures to ensure that species reach maturity synchronously, for easier harvesting. He produces his own seeds and sells as much as possible through short distribution channels. For instance, he sells his wheat–pea mix directly to a livestock farmer without prior sorting.

4.3.2. Management Logic B: sowing mixtures according to the characteristics of the species by adapting agricultural equipment.

Six farmers (AGC1, AGC3, AGC7, AGC8, AGC9 and AGC10) worked with **Management Logic B: adapting farm equipment to the services expected from the mixtures.** To this end, they repurposed, modified or purchased one or more agricultural equipment items, enabling them to cultivate 1 to 5 mixtures of species and to adapt the sowing layout either to the physiology of the species or for specific services (1 or 2 categories), while minimizing the number of runs.

For example, AGC3 grows only one mixture (wheat – faba bean), with an aim to produce high-protein wheat alongside faba bean, which he sells to the local cooperative. He has chosen: (i) to adopt a **Category 5** logic in planting this mixture, to respect the physiology of each species in terms of sowing depth (1.5 cm for wheat and 5 cm for faba beans) and alternate rows to better control competition between species; (ii) to limit the number of runs in the field to reduce working time and fuel costs, and (iii) to use the agricultural equipment available to reduce investment costs. Relying on the mechanical skills of one of a fellow farmer, these choices have led him to customize a no-till seed drill by adding a removable partition in the hopper and modifying the chutes (see 4.2.2 for details). *'We didn't want to run twice: first of all, in terms of hectares, we don't have the time. And then, financially speaking, we had to make it work. So that's why we modified the seeder'*. It is also

noteworthy that this other farmer's mechanical skills also allowed him to adapt the combine's settings to limit bean breakage while still threshing the wheat properly.

4.3.3. Management Logic C: choosing species mixtures and agricultural equipment based on locally available resources

Three farmers (AGC11, AGC12 and AGC13) followed **Management Logic C**, which involves adapting species mixtures to the year's context, using a wide range of locally available agricultural equipment (co-ownership, contractors and CUMA). These three stood out, as they grow a more diverse array of mixtures (1 to 6). Their crop rotations also vary year to year, as their choice is not constrained by potential harvesting or sorting difficulties, given the diversity of agricultural equipment available to them. It should be noted that these three farmers worked in the same region and used the same sorting farm, which appears to be a key factor in crop diversification and the development of species mixtures.

For example, AGC12 grows eight mixtures that are either **Category 1** or **3**. For those in **Category 1** (barley – faba bean, sunflower – service plant, Khorasan wheat – faba bean, barley – lentil, and barley – clover – alfalfa), he uses a single-hopper seeder, which required the seeds to be mixed beforehand. He does so by alternating a layer of each species in a hopper, which he empties in another hopper and re-fills several times until he obtains a homogeneous mix. For **Category 3** mixtures (wheat – faba bean, wheat – faba bean – pea and buckwheat – clover), he sows in two runs (one per species) with a fertilizer spreader (DP12), followed by a run with a tine stubble cultivator to bury the seeds. Harvesting is carried out by a farm contractor who owns several types of combine harvesters. The mixtures are then sorted at the sorting farm he has set up with other farmers, which is equipped with a complete sorting chain, from cleaner-separator to optical sorter. This service allows AGC12 not only to limit his investments in agricultural equipment, but also to gain access to a wide range of techniques for growing a variety of mixtures, some of which he can sell directly. As he explained: *'There are two reasons why I'm able to make these mixtures. It's because the contractor is equipped to harvest whatever I sow, and then, after that, because the sorting farm is equipped to unmix whatever I bring in'*.

5. Discussion

This study aimed to identify and characterize farmers' equipment management strategies to grow species mixtures in their specific situations.

5.1. A new perspective on species mixtures through the lens of agricultural equipment

Agricultural equipment plays a critical role in shaping farming practices, especially when it comes to species mixtures management, from sowing to post-harvest sorting. While machinery is often cited as a barrier to species mixtures adoption (Bellon Maurel & Huyghe, 2017), none of the farmers interviewed in this study saw it as one. Instead, they emphasized the importance of sowing, harvesting, and sorting as key operations.

Our sowing typology (section 4.1.1) allowed us to classify mixtures using criteria that have seldom been addressed in the current literature, such as sowing depth and layout. Most previous studies have characterized mixtures based on sowing dates, duration of species cohabitation, market outlet (e.g., product vs. service), or ecosystem services delivered (Gardarin et al., 2022; Verret et al., 2020). However, layout can significantly influence the functioning of species and interactions between them (Juventia et al., 2022; Lebreton et al., 2024). Existing work tends to compare species sowing methods, between same-row sowing and sowing in alternating rows or strips (Juventia et al., 2022; Lebreton et al., 2024). Our findings contribute to this body of research by highlighting the importance of sowing depth and layout, which are strongly determined by seeder design and settings, and are central to understanding competition and complementarity among species.

Farmers across our sample had different perceptions of harvesting and sorting. Sorting was often seen as complex and even discouraging, and farmers took a pragmatic approach to it, assessing its feasibility based on their resources (time, equipment, access to external services) and on market requirements. Our analysis sheds light on a wide range of approaches – from on-farm sorting to full outsourcing through cooperatives or service providers, including collective investments.

From species selection onward, agronomic (*e.g.,* nitrogen fixation), economic (*e.g.,* seed cost), and commercial (*e.g.,* market demands) considerations intersected. Except for weeding, all technical operations were impacted. We found that the seed mixing phase, which was often carried out on-farm, could be very time-consuming, especially for farmers cultivating larger areas. Yet it remains largely underexplored, despite its strategic importance and technical complexity. Studies on the performance of species mixtures have primarily focused on yield and productivity, with less attention to the technical dimension (Bedoussac et al., 2015).

5.2. A diversity of agricultural equipment and farmer logics in different situations

Our study offers a broad overview of agricultural equipment used for various technical operations, expanding upon prior work that focused on specific agricultural equipment or operations (e.g., Ditzler et al.,2018). It reveals a nuanced spectrum of equipment use, beyond the conventional 'self-built tools' and 'new or robotic equipment' binary. Much like several previous studies (Comi, 2023; Guenin, 2009; Kefi et al., 2022; Salembier et al., 2020), ours shows farmers adapting, repurposing, and deeply modifying their equipment.

Guenin (2006) identified diverse forms of innovation in agricultural machinery, ranging from self-construction to the adaptation or repurposing of standard tools. She also emphasized that the types of innovation depend on the actors involved. When acting alone, farmers tend to repurpose old equipment; in collective settings, bolder innovations emerge. Our sample confirms this, with some farmers tinkering independently and using

old or salvaged machinery, while others are engaged in collective dynamics (*e.g.,* farmer cooperatives, equipment sharing groups) that expand their operational capacities. Across all cases, farmers demonstrate a strong commitment to working with what they already have while pursuing specific agronomic goals.

We identified three distinct archetypes of equipment management logic for implementing species mixtures. Farmers' types of intervention on machinery (repurposing, self-building, modification, or combination) were determined in part by their agronomic and economic motivations, and in part by locally available resources (e.g., cooperatives, service providers). As Lucas et al. (2019) also noted, these territorial links extended their range of possibilities. The motivation of farmers following Management Logic A was to implement mixtures without investing in new equipment, tailoring practices to what their current tools allowed. In Management Logic B, specific agronomic objectives – such as sowing at different depths – led to targeted equipment purchases or modifications. In Management Logic C, farmers selected mixtures and equipment based on locally available resources (e.g., shared services, collective dynamics). Each farmer in our sample adhered to one dominant management logic regarding species mixtures.

Our results reveal a broader spectrum of adaptation strategies than had previously been described. We observed a dual dynamic: farmers adapt equipment to the specific requirements of mixtures (*e.g.,* seed depth, size), and mixtures are, in turn, adjusted based on the technical possibilities of existing equipment. For instance, one farmer (AGC3) had modified his seeder by inserting a divider in the hopper. This equipment setup allowed him to sow faba beans deep and wheat closer to the soil surface, and factored into his decision to sow in alternating rows. These findings contrast with those of Kefi (2023), who presents equipment tinkering as a binary – either adapting practices to available tools or adapting tools to desired practices. Our study evidences a wider continuum of adaptation. Some farmers with extensive machinery fleets (Logic C) adjust both the mixture composition and its intended use to fit the capacities of their equipment. These farmers were also more likely to implement numerous mixture types (up to six). This echoes findings by Yan et al. (2025), which show a strong correlation between farmers' membership in a cooperative (like a CUMA, for instance) and their propensity to grow species mixtures. If farmers have access to suitable equipment, they are more likely to grow mixed species.

5.3. An integrated reading of practices through equipment management logics

We adapted the 'innovation tracking' method (Salembier et al., 2021), which is typically applied to innovative practices or cropping systems (Meunier et al., 2025; Périnelle et al., 2021; Salembier et al., 2016; Verret et al., 2020), to focus it specifically on the agricultural machinery used in managing species mixtures. This expanded our ability to observe agricultural innovation and allowed us to highlight technical adjustments to machinery as key indicators of farmers' courses of action.

Combining innovation tracking with the concepts of action logics and equipment management logics offered a novel methodological contribution. It allowed us to better understand how technical choices are shaped by material constraints and agronomic goals. By including variables often neglected in studies of species mixture – such as sowing depth constraints, sorting capabilities, or seeder compatibility – this approach provided a more situated understanding of practices. It also showed that species mixtures management is not a mere aggregation of technical decisions, but rather the result of coherent action logics grounded in farmers' contexts.

Conclusion

This study sheds light on the diverse logics farmers use to manage their agricultural equipment when implementing species mixtures in different farming situations. By applying the innovation tracking method, we were able to document often-overlooked practices that play a decisive role in the actual implementation of agroecological practices such as species mixtures. Three results stand out. Firstly, sowing and sorting are pivotal operations that significantly influence equipment choices and mixture implementation modalities. Secondly, farmers show high levels of technical creativity, using a wide array of strategies, from self-construction to outsourcing and including equipment modification and repurposing. Thirdly, our categorization of equipment management logics reveals context-specific trade-offs that highlight the diversity of ways in which farmers align agronomic goals, economic constraints, and available resources. By incorporating the material dimension of agricultural equipment into the analysis of farming practices, this research contributes to the broader literature on species mixtures. Future research could extend this work to other types of crops, pedoclimatic conditions, or organizational settings (*e.g.,* conservation agriculture). Further exploration of collective innovation dynamics – especially regarding shared or collectively built machinery – would also yield a deeper understanding of the social dimensions of agroecological transitions.

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