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Farmers' limited perceptions of the role of ecological processes in crop production, a potential obstacle to agroecological transition

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A R T I C L E I N F O

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A B S T R A C T

Industrialized agriculture has strong impacts on ecosystem functioning. However, despite public policies, incentives and scientific warnings, intensive agriculture remains the main model. Agroecology, as a way to produce food while relying on ecological processes and reducing negative externalities, is considered as a sustainable alternative. The literature on agroecological transitions increasingly focuses on the perceptions that farmers have of ecological processes, supposing that the more farmers perceive the interests of ecological processes for production, the more they will implement sustainable farming practices. In this research, we tested the hypothesis that an obstacle to an agroecological transition is that farmers have little awareness of the reliance of food production on the natural functions of ecosystems. We thus address three issues in this article: first, the weight farmers gave to ecological processes in farming production itself; second, the roles of on-farm experiments (OFEs) or agri-environmental schemes (AESs) as drivers of this perception of ecological processes; and third, the links between the perception of ecological processes and the definitions of agroecology given by farmers. We interviewed 78 farmers representative of an intensive cereal plain in western France about what they perceive as drivers of crop production and of soil fertility and the links they perceived between hedges and crop production. Our results show that farmers perceive climate, inputs and technical aspects of crop production as more important drivers of crop yields than ecological processes. By contrast in non-productive areas of the farm, the perception of the importance of ecological processes was greater for questions relating to hedges. A redundancy analysis (RDA) showed that AESs rather than OFEs positively affected farmers' perceptions of ecological processes in sustaining farming. Nevertheless, despite the fact that half of the farmers related agroecology to benefits in ecosystem functioning, they had limited perceptions of the positive role of ecological processes in sustaining farming. Our study therefore supports our hypothesis that limited perceptions of the role of ecosystem functions in farming could be an obstacle to an agroecological transition, as agroecology and ecological processes are seen as beneficial for ecosystems but not for farming production. Our study also suggests that open-ended and indirect questions rather than direct methodologies can bring new insights to our understanding of farmers' perceptions.

1. Introduction

Recent reports from the Intergovernmental Panel on Climate Change (IPCC) and the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services (IPBES) underline that, to sustain food security, nutrition, health and well-being, the economic sectors that exploit natural resources (fisheries, farming and aquaculture) ought to rely on the natural functioning of ecosystems (Díaz et al., 2019; Pörtner et al., 2022). Ecosystem functioning relies on various ecological processes which are the different interactions between species and between species and abiotic elements of an ecosystem (Bruins et al., 2018). These interactions can be of different types, either predation, competition, cooperation or symbiosis association for instance, they produce different functions with inputs and outputs inside an ecosystem and which the benefits that humans obtain are called ecosystem services (Blanchart and Trap, 2020; Diaz et al., 2018; Reid et al., 2005). For instance, in agriculture, insect pollination, pest control by their natural enemies and carbon sequestration ensure sustainable crop production (Dainese et al., 2019; Garibaldi et al., 2018), as well as farmers' incomes (Catarino et al., 2019a, 2019b; Perrot et al., 2018; Pywell et al., 2015). At the same

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time, several international bodies, such as the Committee on World Food Security (CFS) and the Food and Agriculture Organization of the United Nations (FAO), have promoted agroecology as a positive contribution to the eradication of hunger and of extreme poverty and a means to facilitate the transition to more productive, sustainable and inclusive food systems (Bicksler et al., 2023). Consequently, to foster agroecological transitions and the uptake of environmentally friendly measures, several tools have been implemented, such as payments for ecosystem services (Chen et al., 2017; Mouysset, 2017; Page and Bellotti, 2015); agri-environmental schemes (AESs) (Kleijn et al., 2004, 2006); or incentives to reduce pesticide use (Zhang et al., 2018), which is recognized as one the most harmful practices for biodiversity and human health (Beaumelle et al., 2023; Gaupp-Berghausen et al., 2015; Rodrigues et al., 2023). European Union through European Green deal aims to protect citizens from environmental harms and impacts, with for example a zero pollution ambition and the Farm to Fork plan for a fair, healthy and environmentally friendly food system (European Commission, 2020, 2022; Fetting, 2020). These ambitions, especially those related to the decrease of 50% of pesticides uses and increase up to 25% of organic farming in the European Union, echoes those of the French Ecophyto plan (Guichard et al., 2017). However, the current trajectory of agriculture towards intensification and industrialization does not align with the objectives of these programs, as illustrated in Europe by the stable trends of pesticide use for farming during the past 40 years (European Food Safety Authority et al., 2023; EUROSTATS, 2021; Marchand, 2023; Sharma et al., 2019). Multiple reasons have been proposed to explain this pattern. For instance, the failure to consider farmers' knowledge (Lee et al., 2019), as well as sociotechnical and cognitive lock-ins due to downstream chain demands (Guichard et al., 2017; Meynard, 2013) or social and moral concerns (Mzoughi, 2011), have been shown to contribute to the ineffectiveness of European policy instruments to reduce pesticide use.

Another possible explanation is farmers' potential lack of perception of the importance of ecological processes for food production. Perception here means the act by which the subject becomes aware of objects or concepts that have made an impression on his or her senses, and how the individual characterises these elements by assigning subjective value to them (Bennett, 2016). In this way, perceptions are based on specific knowledge, but they are different from knowledge understood as a body of scientific knowledge (Beltrán-Tolosa et al., 2020; Breeze et al., 2019). Therefore, addressing farmers' perceptions of ecological processes as drivers of crop production means investigating whether and to what extent farmers can view these ecological processes as services that benefit their production. In fact, perceptions of ecological processes have been shown to play an important role in the adoption of environmentally friendly practices (Klebl et al., 2023, 2024; Xu et al., 2023), in addition to other socio-economic factors that influence pro-environmental behaviour (Bennett, 2016; Dessart et al., 2019; Klebl et al., 2023). In fact, the adoption of more sustainable practices can result from multiple factors, such as economic, technical and social reasons, from which it is not straightforward to isolate the contribution of the perception of ecological processes. However, several studies have demonstrated that the deeper the awareness of the importance of pollination among farmers, the higher their willingness to implement measures promoting pollinator biodiversity (Hevia et al., 2020; Osterman et al., 2021). Still, few farmers perceive how ecological processes or ecosystem services relate to crop production (Lamarque et al., 2011; Smith and Sullivan, 2014). The roles that ecosystem services play in agricultural production are generally considered more important by scientists, highly educated farmers (Lamarque et al., 2011; Maas et al., 2021) and small-scale farmers (Teixeira et al., 2018) than by others. Differences in understanding of the roles of ecological processes and biodiversity may be due to information sources (e.g. technical advisors; Misganaw et al., 2017; Maas et al., 2021), to farmers' personal experiences (Osterman et al., 2021) or to differences in capital endowment (Xu et al., 2023).

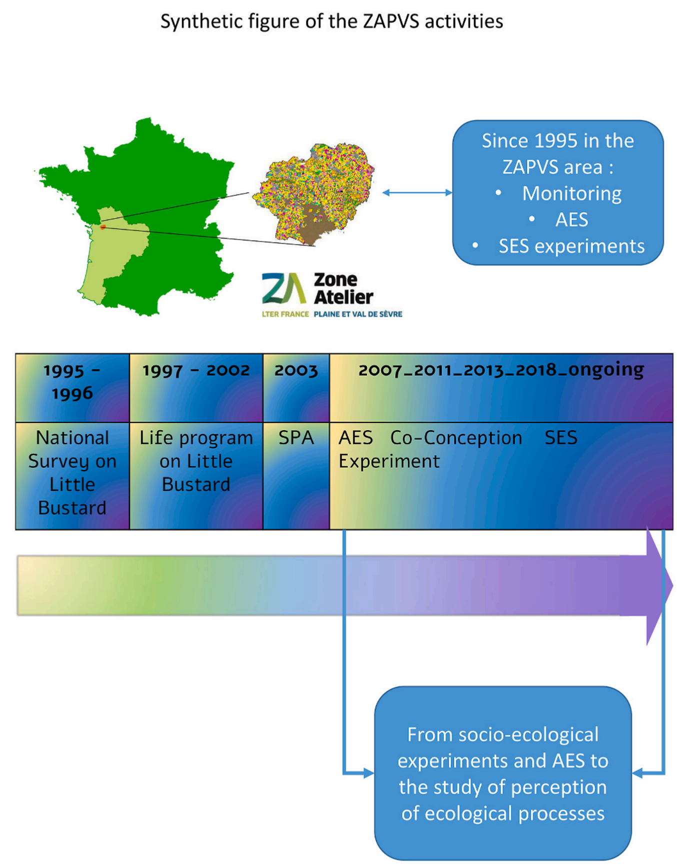

Fig. 1. Composite figure of the ZAPVS research area activities with a sustainable program for agriculture (SPA) begun in 2003 and the implementation of agri-environmental schemes (AES) led by scientists of the area. From 2013 to 2023 socio-ecological experiments (SES) have been made with farmers in the area.

Few studies have investigated farmers' perceptions of the contribution of ecological processes to crop production. Furthermore, in such studies, farmers' perceptions of ecosystem services, biodiversity or ecological processes were mainly assessed by directly questioning farmers on the benefits of biodiversity for production (Maas et al., 2021; Martínez-Sastre, 2020; Omokaro et al., 2023). Revealing *a priori* the study purpose to the interviewees, here measuring farmers' awareness that agricultural production depends on ecological processes and biodiversity, can strongly bias the results towards a higher detection of ecological awareness. To our knowledge, only Blanco et al. (2020) used an indirect way to examine farmers' perceptions of ecosystem services, that is, without explicitly linking them to the support of production, and highlighted that farmers perceived biodiversity and regulating services as both beneficial and unfavourable to crop production.

In this study, we tested the hypothesis that an obstacle to an agroecological transition is that farmers have little awareness of the reliance of food production on the natural functions of ecosystems. First, following Blanco et al. (2020), we indirectly studied farmers' perceptions of the contribution of ecological processes to farming by assessing the drivers they believed were most important for farming. This was captured through three dimensions of farming: yields of both insect pollination–independent and dependent crops; soil fertility, especially in regard to organic matter recycling; and the role of hedgerows as a symbol of agroecological infrastructure. We then assessed the drivers of farmers' perceptions of ecological processes.

While the effects of socio-economic factors (e.g. gender, age, level of income or level of education) on farmers' perceptions of ecological processes have already been accounted for in other studies (Hevia et al., 2020; Maas et al., 2021; Xu et al., 2023), the extent to which AESs or on-farm experiment (OFE) programs can strengthen ecological awareness still needs to be assessed. As our research was conducted at a long-term socio-ecological research (LTSER) site (Bretagnolle et al., 2018), where scientists were in charge of the AES program (Berthet et al., 2022) and implemented OFEs with farmers to foster agroecological transitions (Gaba and Bretagnolle, 2020), we could assess the role that AES or OFE implementation plays in farmers' perceptions of ecological processes, in addition to socio-economic drivers.

Finally, because we hypothesized that a lack of ecological awareness was an obstacle to an agroecological transition, we explored the links between farmers' definitions of agroecology and their perceptions of the role of ecological processes. We postulated that agroecology is a multifaceted term that farmers do not often link with the roles that biodiversity and ecological processes play in farming. We expected different responses for the perceived drivers that farmers believed were most important for farming and their definitions of agroecology. To our knowledge, such a comparison has never been studied in the literature on farmers' perceptions and agroecological perspectives.

To answer these three questions, we conducted a survey based on a representative sample of farmers in the study area, some of whom had either implemented AESs, participated in OFEs, done both or done neither. The farmers were sampled while accounting for their farms' levels of management intensity, defined here by farm size and diversity of crops.

2. Materials and methods

2.1. Study area

The study was conducted in the Nouvelle Aquitaine Region, in the western part of France (Fig. 1), in the Zone Atelier Plaine & Val de Sèvre (hereafter ZA-PVS), an LTSER site that is part of the French Zone Atelier network (Bretagnolle et al., 2018). This territory of 450 km^2 is dominated by agriculture and includes arable land, grasslands and areas for dairy and livestock production. It encompasses 411 farms that display a range of agricultural systems (e.g. organic farming, soil conservation and conventional).

The total cultivated area in the ZA-PVS varies from 0.07 ha to 724.76 ha, with an average of 132.1 ha (±SD = 93.8). Most of the farms (252 farms) produce arable crops, while 159 farms produce both livestock (dairy cows, cattle, sheep and goats) and crops. Among the 411 farms, 100 are organic; these represent 24.33% of the cultivated area, which is higher than the average percentage in France (https://www.data.gouv.fr).

Throughout its research programs conducted over the past 30 years, the research team overseeing the ZA-PVS LTSER site, which is composed of ecologists and social scientists, has collaborated with local farmers (Berthet et al., 2022). This collaboration includes interventions in farmers' fields to protect bird nests, the monitoring of biodiversity and ecological functions in farmers' fields, interviews with farmers on their agricultural practices (Berthet et al., 2022; Bretagnolle et al., 2018) and socio-ecological experiments that involve farmers in the research process (Gaba and Bretagnolle, 2020). In this study site, the research team has been working with farmers since 1994 through different types of interventions: contracting agri-environmental schemes (until 2022), experimenting alternative farming practices with farmers in their fields (since 2013), and monitoring biodiversity on their farm (since 1994), but see Berthet et al., (2022) for details.

2.2. Interviewee selection

We developed a robust sampling strategy to ensure informed coverage of the farmer population of the ZA-PVS. We targeted 20% of the population of interest to obtain a representative sample. We excluded 39 farms smaller than 20 ha to focus on market farms.

Table 1
Respondents' characteristics.

		All	Conventional	Organic
		n = 78	*n = 56*	*n = 22*
Age	from 25 to 39	13	9	4
	from 40 to 54	25	20	5
	from 55 to 64	32	21	11
	from 64 to 89	6	4	2
Gender	male	76	55	21
	female	2	1	1
Primary entreprise	grain	45	29	16
	mixed-farming	33	27	6
Farm structure	total in ha (mean ± sd)	158 ± 109	165 ± 122	139 ± 65
	ha within the study site in ha	108 ± 102	109 ± 117	105 ± 47
	nb animal (mean ± sd)	65.6 ± 56.2	61.1 ± 59.8	85.8 ± 32.1
Link with the research team	Yes	72	51	22
	AES	19	11	8
	Bird nest protection	49	37	12
	Biodiversity monitoring	58	38	20
	Experimentations	25	16	9

We selected farmers according to two proxies of management intensity, namely, crop diversity and farm size (Hall et al., 2020; Tuck et al., 2014), to obtain a sample representative of the study area. Using the data from the RPG Database[1] (https://www.data.gouv.fr), we estimated crop diversity by computing the Shannon–Wiener index of each farm using the 'vegan' package of the software R (Grosjean et al., 2019). We divided the farm size distribution into quartiles. We then randomly sampled farms in each of the four subsamples (20% of the subsample sizes). This produced a first list of farmers we contacted by phone to have the decision-maker of the farm as registered in official administrative documents. When a farmer did not respond or declined to participate (see below), we sampled another farm in the same subsample to ensure representativeness of our sample.

2.3. Interviewee description

We conducted 78 interviews by phone from November 2022 to February 2023. A total of 167 farmers were called for surveys: 84 did not respond and five declined, for a response rate of 50% of the farmers contacted and 94% of those who responded. The interviews lasted between 10 and 50 min, with an average of 25 min (±10.1 min), and were conducted in French. The interviews were performed after ethical clearances were obtained and prior consent was provided.

The profiles of the interviewees are summarized in Table 1. Our sample was heavily biased towards men (with only two women), and a majority of farmers (65%) were older than 50 years. Only 13 farmers were under 40 years old, and six respondents were older than 64 years. More than one-quarter of farmers (22 of 78) participated in organic farming, which represented 17.74% of the cultivated area of all farms sampled, and 33 farmers of 78 (42.3%) produced both livestock and cereals, which agrees with the proportion observed in the study area (38.74% of the farmers of the ZA-PVS area, according to RPG Database). The average farm size was 159 ± 109 ha. Conventional farmers had larger farms and more animals than organic farmers. Only four farmers had never interacted with the ZA-PVS research team. Most of the interactions between farmers and the research team were for authorization for bird nest protections and/or biodiversity monitoring in their

[1] https://www.data.gouv.fr/fr/datasets/registre-parcellaire-graphique-rpg-contours-des-parcelles-et-ilots-culturaux-et-leur-groupe-de-cultures-majoritaire/.

Table 2
Main categories and sub-categories used for recoding the interviews for the four questions (i.e. drivers of yields, of mass-flowering crop yields, of soil fertility or the links between hedges and yield). Examples of responses are given in italics, for some responses such as the responses to question II.1 asking for the 5 drivers of yields, farmers could have given either a sentence or some keywords only. Questions can be found in Appendix A1.

Type of Drivers	Main categories	Sub-categories	Description and Examples of verbatim related to these main categories
External	Climate	Climate Weather conditions	Response related to the impact of weather conditions or climate as climatic change meaning or every particularity of microclimate conditions. "*They (the hedges) are very important for maintaining a certain microclimate around the plots and a hygrometry that is favourable to the crops.*" Example of a response given to question IV.2 (Female mixed farmer between 50 and 55 years old, in organic farming system and involved with research team only for monitoring in the fields).
	Stochasticity	Chance	Response related to the luck as a driver yield in general when asking to farmers the five drivers of yields according to them. "*1- Weather* *2- Effluent management* *3- Luck* *4- Crop management (sense of timing)* *5- Crop monitoring (plot observations)*." One of the fifth responses given to question II.1. (Male mixed-farmer between 60 and 65 years old in organic farming system and involved with research team for monitoring in the fields and agri-environmental schemes measures)
	Socio-economic and politic conditions	Economic sector Geopolitic events Public policies	Response related to the impact of public policies, of economic sector, of geopolical events "*Yes, because from a regulatory point of view it (the hedges) already allows us to meet the EIS conditions for the CAP and also because it's important for the environment in general by serving as firewood or to combat erosion.*" Example of a response given to question IV.2 (Male grain farmer between 50 and 55 years old in conventional farming system and involved with research team for monitoring, experiments and agri-environmental schemes measures)
Internal	Ecological processes	Natural biological control Insect-pollination Recycling of organic matter Complementarity in ecological niches Pests, diseases and resource competition	Response related to ecological processes identified as a support of farming production such as pollination, biological control, the recycling of organic matter or the complementarity between different ecological niches. Ecological process that has negative impact on farming production such as pest, diseases and competition to crops is also included in this main category. "*These (the drivers of mass-flowering crop yields) are the same factors, even if the presence of pollinating insects is important for the flowering of rapeseed and sunflower, as much as these crops are linked to the climate.*" Example of a response given to question II.2 (Male grain farmer under 40 years old in organic farming system and involved with research team for monitoring, agri-environmental schemes measures and experiments)
	Inputs	Feeds Irrigation NPK Pest and weed control	Responses related to the use of chemical or organic inputs such as fertilizers, weed and pest control inputs. This also includes irrigation and feeds for the livestock. "*It (the fertility of soils) depends on the amount of fertiliser we use and the manure and digestats we add.*" Example of a response given to question III.1 (Male mixed-farmer between 40 and 50 years old in conventional farming system and involved with research team for monitoring and experiments)
	Pedoclimatic conditions & landscape features	Farm environment Soil conditions	Responses related to farm location, farm soil types or more generally the environment of the farm such the depth of soils or the landscape surrounding the farm. "*1- Water, both rainfall and irrigation, which account for 60% of our yields.* *2- The soil, the types of soil and their depths, as well as the fact that they are rich in organic matter.* *3- Winter, which is getting less cold.*

(*continued on next page*)

Table 2 (*continued*)

Type of Drivers	Main categories	Sub-categories	Description and Examples of verbatim related to these main categories
			4- Fertiliser inputs for fertilisation. *5- Plant protection products."* One of the fifth responses given to question II.1 (Male grain farmer under 40 years old in conventional farming system and involved with research team only for monitoring)
	Farm socio-economic conditions	Social networks Working conditions	Responses related the labour conditions on the farm or the impact of peers, siblings and colleagues whom compose the social networks of farmers. "*Yes, the hedges will reduce the yield. Now the real issue is the maintenance of the hedges and their installation in such a way that they don't hinder the passage of machinery. There's an interest in the environment in general, but from a personal point of view and from my farm, I'd say that it pleases a certain category of people but that it doesn't change anything for our agricultural production.* " Example of a response given to question IV.2 (Male grain farmer between 55 and 60 years old in conventional farming system and involved with research team for monitoring and experiments)
	Farmers' technicity	Crop diversity Knowledge Mechanical work Species selection Timing of interventions	Response related to the technicity of the farmer such as the mechanical work, the timing of the interventions in the fields, the species selection or crop diversity in the farm as well as the farmers' knowledge. "*1- Climate* *2- Technical skills* *3- Availability to monitor the fields when you also have animals to manage.* *4- Crop management* *5- The price of fertiliser, which can lead you to do without fertiliser.* " Three of the fifth responses given to question II.1 (Male mixed-farmer between 60 and 65 years old in conventional farming system and involved with research team for monitoring only)
Others	Others	No difference, no idea, no links …	'I don't know', …

fields (Table 1). Nineteen farmers (24%) signed AES contracts when the research team was the AES operator, and 25 (16 conventional farmers and nine organic farmers) participated in experiments with the research team.

2.4. Data collection

We designed semi-structured interviews with open-ended questions organized around the following themes: (1) yields of insect pollination–independent (winter cereal) and (2) insect pollination–dependent (mass flowering crops such as oilseed rape and sunflower) crops, (3) soil fertility drivers and (4) links between hedgerows and yields (Appendix 1, A1 – questions II.1, II.2, III.1, IV.2).

While the latter question refers to landscape management, the three first ones are related to crop production at the field scale. We chose open-ended questions rather than Likert scales or multiple choice questions, so as not to influence farmers by pre-selecting answers and allow farmers to express their opinions freely.

The interview was designed to collect relevant information on how farmers related biodiversity to crop production through ecological processes (such as pollination, natural pest control or organic matter recycling) without a direct mention of biodiversity or ecological functions by the interviewer. Therefore, our understanding of the role of biodiversity in crop production and our interests did not shape farmers' responses. We also asked direct questions on the relationships between farmers' practices and the relevant themes. Those were not analysed in the present study. The interviews ended with two open-ended questions on farmers' definitions of agroecology and on the actions they could implement on their farms according to their vision of agroecology.

The guide used during the interviews is presented in Appendix 1.

2.5. Data treatment and analyses

2.5.1. Recoding

The researcher who conducted the interviews transcribed them verbatim and then sent the transcription to farmers so they could check its accuracy. The verbatim of responses to each question were summarized in a database using keywords and notes, and then manually coded using an inductive coding process. The responses were coded as 25 subcategories embedded in seven categories related to the factors influencing crop production (Table 2). During the inductive coding process, we identified common topics across questions. These were mainly related to two drivers of crop production: those that are intrinsic to the farm, such as local soil conditions and landscape features, inputs and farmers' technicity and socio-economic characteristics, and external drivers, such as climate, luck and socio-economic and political contexts (Fig. A1). At the same time, deductive coding was used to identify farmers' responses related to biodiversity and ecological processes that are beneficial to crop production (insect pollination, natural pest control, ecological niche complementarity and recycling of organic matter) and those that are negatively associated to crop production (pests, diseases and competition with crop plants) (Fig. A1).

We used an inductive coding process for the responses regarding the definition of agroecology from the farmers' perspective. We first looked for key phrases (Table A1), which allowed us to identify 17 subcategories that can be grouped into four main categories, namely (1) the fact that agroecology depends on different agricultural practices, (2) that agroecology requires a redefinition of the human–nature relationship, (3) the risks that agroecological transition may pose to farmers, and (4) the respondents' opinions on this issue (Table A1). For each farmer, we then counted the number of sentences related to each of the subcategories.

2.5.2. Statistical analysis

We first analysed the definitions that farmers gave for agroecology. Then, to test the effects of farmers' socio-economic characteristics and relationships to the research team, we used a redundancy analysis (RDA) with Monte Carlo permutation tests (999 permutations) with the definition of agroecology as a predictor. We included as covariables the farmer's age (four classes), whether they used organic farming (yes or no), the type of production (cereal vs mixed), farm crop diversity (estimated by the Shannon index), farm size and farmers' participation in experiments with the research team (yes or no) and AESs (yes or no). Farm crop diversity and farm size were standardized, and a Hellinger transformation was applied to the predictor (i.e. farmers' responses).

We then examined the responses to the questions related to yield (cereal and insect-pollinated crops), soil fertility and hedges by computing the number of responses in each main category and subcategory and the mean and standard deviation for the number of responses given by farmers per subcategory. For each question, we explored the links between farmers' responses by performing a network analysis using the 'igraph' R package (Csárdi et al., 2023). We kept the links with a number of occurrences equal to or higher than the third quartile value of the distribution of the number of responses. We also ran a canonical correlation analysis (CCA) using the 'vegan' R package (Oksanen et al., 2015) to estimate the relationships between the responses to each pair of questions. All combinations were explored. To test the effects of farmers' socio-economic characteristics and relationships to the research team, we used four RDAs and assigned, for each question, the number of responses per main category to ensure sufficient statistical power. We included the same variables as for the definition of agroecology. Because of multiple zeros, we applied a Hellinger transformation to the data before conducting the CCA and RDA (Legendre and Legendre, 2012). Finally, we explored the relationship between farmers' definitions of agroecology and their perceptions of ecological processes using an RDA with the number of responses related to ecological processes benefiting production (i.e. insect pollination, natural pest control, organic matter recycling and complementarity of ecological niches) for each of the four questions as predictors and the number of definitions of agroecology related to human–nature relationships, agricultural practices, risks and other topics as variables.

All statistical analyses were performed using R software version 4.3.1 (R Core Team, 2023).

3. Results

3.1. Half of farmers linked agroecology to biodiversity

The number of responses to the definition of agroecology varied among farmers, ranging from one (49 farmers) to four (one farmer) (Table A1). The responses were generally related to agricultural practices (43 responses given by 35 farmers) and to human–nature relationships (43 responses given by 36 farmers). Seven farmers also related agroecology to risks to farmers (five) or to food security (two). Among the responses linking agroecology to agricultural practices, two concerned production modes, namely, agroforestry (10) and organic farming (eight), while eight farmers related agroecology to a decrease in the use of synthetic inputs. Almost half of the farmers (36 of the 78 farmers) associated the definition of agroecology with a redefinition of human-nature relationships, and 35 farmers with agricultural practices they had already implemented or are willing to implement. Interestingly, 10 farmers defined agroecology as a redefinition of human-nature relationships and agricultural practices. Twenty-nine farmers directly related agroecology to biodiversity either as a way to produce crops with lower negative impacts on biodiversity or as way to produce in partnership with nature. The other farmers (seven of the 78 farmers) indirectly related agroecology to biodiversity through a reduced negative impact on soil. Three farmers also associated agroecology with practices that promote the well-being of other humans.

The selection procedure of the RDA retained two variables, namely, the production mode (organic farming vs convention farming) and participation in experiments with researchers (yes or no). Those

Table 3
Redundancy Analysis exploring the links between farmers' definition of agroecology (first column) or answers to the four questions (second to fifth columns), farmers' socio-economic characteristics, and their participation to agri-environmental schemes (AES) and on-farm experiment. Significant effects are bold.

	RDA Agroecology				RDA Cereal yield				RDA Insect-pollinated crop yield				RDA Soil fertility				RDA Hedges			
	$R^2 = 16.02\%$				$R^2 = 14.75\%$				$R^2 = 15.07\%$				$R^2 = 18.39\%$				$R^2 = 11.94\%$			
	Df	Variance	F	P-value	Df	Variance	F	P-value	Df	Variance	F	P-value	Df	Variance	F	P-value	Df	Variance	F	P-value
Production Mode (OF/CF)	1	3,22%	2.80	**0.002**	1	0,75%	0.815	0.640	1	0,34%	0.302	0.978	1	1,94%	2.053	0.065	1	0,69%	0.727	0.700
Agricultural system (Grain/Mixed)	1	1,83%	1.59	0.103	1	1,06%	1.150	0.322	1	0,98%	0.880	0.471	1	1,13%	1.197	0.296	1	0,99%	1.049	0.387
Experimentation with researcher (Yes/No)	1	1,11%	0.97	0.427	1	0,68%	0.738	0.724	1	1,08%	0.968	0.382	1	1,53%	1.618	0.159	1	0,39%	0.412	0.960
AES (Yes/No)	1	0,71%	0.62	0.799	1	0,50%	0.548	0.911	1	3,18%	2.856	**0.012**	1	1,20%	1.271	0.242	1	1,08%	1.140	0.317
Farm crop diversity	1	0,44%	0.38	0.963	1	1,83%	1.992	**0.011**	1	0,84%	0.759	0.617	1	1,39%	1.469	0.181	1	0,60%	0.633	0.786
Farm size	1	1,27%	1.10	0.364	1	1,25%	1.357	0.143	1	1,50%	1.349	0.222	1	0,89%	0.946	0.454	1	0,70%	0.742	0.680
Farmers' age	4	4,42%	0.96	0.550	4	3,23%	0.8768	0.729	4	3,01%	0.676	0.872	4	4,66%	1.233	0.192	4	2,30%	0.606	0.976
Production mode x Agricultural system	1	0,60%	0.52	0.888	1	0,57%	0.617	0.863	1	1,31%	1.181	0.283	1	0,46%	0.484	0.854	1	1,22%	1.289	0.203

Table 4

Farmers' answers to the four questions. For each question, the first column "nb of answers" corresponds to the total number of answers given by the farmers, i.e. the sum of the numbers for each column for each question; the second column corresponds to the number of farmers who mentioned this sub-category in their response; and the third column indicates the average number of elements related to the sub-category mentioned by the farmers in their answer.

Drivers	Great categories	Sub-categories	Grain yield			Insect-pollinated yield			Soil fertily			Hedges presence		
			Nb of answers	Nb of farmers	Mean response per farmer (±SD)	Nb of answers	Nb of farmers	Mean response per farmer (±SD)	Nb of answers	Nb of farmers	Mean response per farmer (±SD)	Nb of answers	Nb of farmers	Mean response per farmer (±SD)
			398	78	5.1 (±0.31)	100	77	1.28 (±0.66)	141	78	2.01 (±0.87)	258	78	3.31 (±1.29)
External	Climate	Climate	24	24	1	3	2	1.50 (±0.71)	0	0		13	12	1.08 (±0.29)
		Weather conditions	65	56	1.16 (±0.46)	14	14		4	4	1	44	42	1.05 (±0,22)
	Socioeconomic and politic conditions	Economic sector	20	18	1.11 (±0,32)	1	1	1	0	0		15	15	1
		Geopolitic events	0	0		0	0		0	0		0	0	
		Public policies	8	8	1	0	0		2	2	1	3	3	1
	Stochasticity	Chance	4	4	1	0	0		0	0		0	0	
Internal	Ecological processes	Complementarity of ecological niche	1	1	1	5	5		2	2	1	10	10	1
		Insect pollination	0	0		1	1	1	0	0		5	5	1
		Natural biological control	0	0		0	0		0	0		39	36	1.08 (±0.28)
		Pests, diseases, and resource competition	26	19	1.37 (±0,68)	19	18	1.06 (±0.24)	0	0		51	49	1.04 (±0.20)
		Recycling of organic matter	5	5	1	2	2		22	22	1	0	0	
	Farm socio-economic conditions	Social networks	4	4	1	0	0		0	0		2	2	1
		Working conditions	9	9	1	3	3		0	0		11	11	1
	Farmers technicity	Crop diversity	10	10	1	9	8	1.13 (±0.35)	21	21	1	1	1	1
		Knowledge	22	21	1.05 (±0,22)	1	1	1	9	9	1	0	0	
		Mechanical work	25	25	1	2	2	1	16	16	1	10	10	1
		Species selection	29	28	1.04 (±0.19)	1	1	1	0	0		1	1	1
		Timing interventions	27	27	1	3	3	1	1	1	1	0	0	
	Inputs	Feed inputs	2	2	1	3	3	1	0	0		12	11	1.09 (±0.30)
		Irrigation	5	5	1	0	0		2	2	1	0	0	
		NPK	27	26	1.04 (±0.20)	1	1	1	39	39	1	0	0	
		Pest and weed control	19	19	1	4	4	1	0	0		0	0	
	Pedoclimatic conditions & landscape features	Farm environment	6	6	1	0	0		0	0		9	9	1
		Pedological conditions	31	30	1.03 (±0.18)	1	1	1	22	22	1	21	21	1
Others	Others	No idea	29	22	1.32 (±0.48)	0	0		1	1	1	0	0	
		No difference	0	0		27	27	1	0	0		0	0	
		No links with production	0	0		0	0		0	0		11	11	1

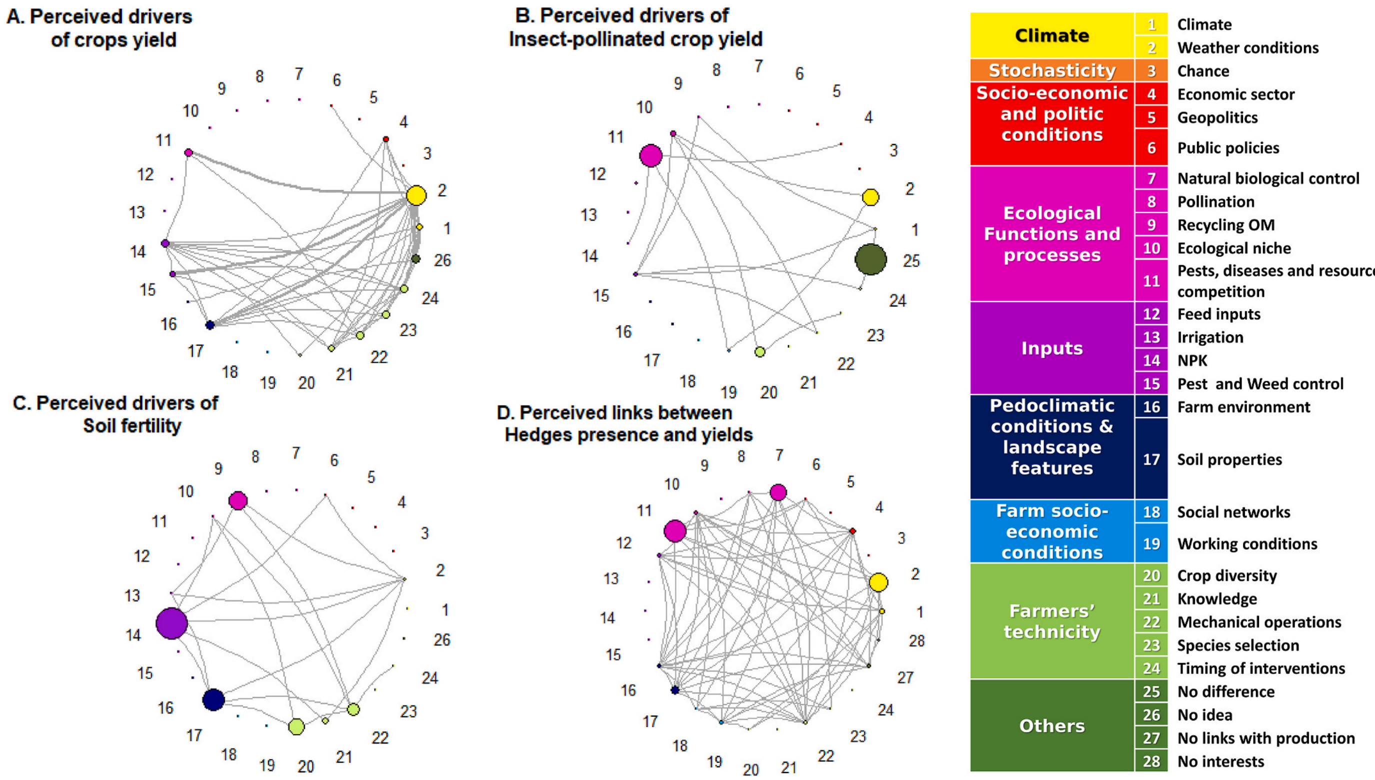

Fig. 2. Relationships between farmers' responses to the four questions. Only frequent links (i.e. observed more than the third quartile of the total number of links for each question) are presented. Colors refer to the main categories, while the nodes represent the sub-categories as detailed in the legend. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

variables explained less than 5% of the variance in farmers' responses. Organic farming had a significant effect on the responses ($F_{1,62} = 2.8$, $p = 0.0021$) and explained 3.22% of the variance in the definitions of agroecology. Organic farming was associated with responses relating agroecology to 'human well-being' (Table 3). Participation in experiments with researchers, although retained by the model selection procedure, had no significant effects on farmers' definitions of agroecology ($F_{1,62} = 0.97$, $p > 0.1$).

3.2. Farmers rarely made the link between ecological processes and agricultural production

Our analysis revealed that farmers identified a wide range of drivers influencing crop production, with 398, 100, 158 and 258 responses given to the questions concerning grain yield, insect-pollinated crop yield, soil fertility drivers and the presence of hedges, respectively. On average, farmers identified 5.1 (±0.31) drivers affecting grain yield, 1.3 (±0.7) for insect-pollinated crop yield and 2.01 (±0.87) for soil fertility and 3.31 (±1.3) responses on the effect of hedges on crop production (Table 4). Comparisons across responses to the four questions revealed repeated patterns involving the dominance of internal drivers (from 55% to 69% of the overall responses per question) over external ones (Table 4). However, the CCAs showed significant relationships only between responses to the cereal yield and insect-pollinated crop yield questions (Pillai's trace = 6.03, $p = 0.031$), as well as between responses to the insect-pollinated crop yield and hedge questions (Pillai's trace = 4.94, $p = 0.007$; see Table A2 for full results of the CCA).

3.2.1. Farmers considered climate, inputs and technicity as the main drivers of crop production

Among the main categories, 73 (94%) farmers cited climate as the main driver affecting grain yield (Table A3). More precisely, two-thirds of the respondents considered grain yield to strongly depend on weather conditions. For 61 (78%) of farmers, their technicity was also a major factor affecting grain yield. Inputs, especially the use of fertilizer (for 26 farmers) and soil conditions (for 30 farmers) were also highly important drivers. In terms of the ecological processes, 19 farmers cited the negative impacts of pests, diseases or weeds more than once (average of 1.37 ± 0.68; Table 4). We found that a high proportion of farmers (>75%; Fig. 2A) reported climate, soil properties, NPK fertilizer, pests, diseases and resource competition due to weeds as the main combination of drivers affecting grain yield. Only four of these 19 farmers also cited pest and weed control, while the 15 farmers who identified pest and weed control as a driver of grain yield did not cite pests, diseases or weeds as drivers of grain yield.

While 35% of farmers did not identify any differences in drivers of yield between grain (e.g. winter cereals) and insect-pollinated crops (e.g. mass flowering crops such as oilseed rape or sunflower), we observed a different pattern among the main categories and subcategories for the two crop types (Table 4; Fig. 2A and B). Farmers' technicity was rarely cited (17% of farmers) as a driver of insect-pollinated crop yield, and almost 20% of the answers given by farmers were related to the effects of pests, diseases or weeds on the production of these crops. Only one farmer cited insect pollination as a driver of mass flowering crop yield. Indeed, farmers almost never cited ecological processes associated with crop benefits, such as natural pest control, which was never cited as a driver of either grain or mass flowering crop yield.

3.2.2. Farmers assigned more importance to ecological processes when discussing soil fertility and hedgerows

The main drivers of soil fertility, according to the farmers surveyed, were inputs, especially NPK fertilizers (50% of respondents), followed by soil conditions (28%) together with organic matter recycling (28%) and crop diversity in space and time (27%). However, these responses were rarely given together (Fig. 2C). Sixteen farmers (20.5%) also reported that soil fertility was affected by soil mechanical operations.

Most of the responses to the question on hedgerows fell into the main category of ecological processes: hedgerows were related to natural pest

Table 5
Redundancy Analysis exploring (A) the links between farmers' definition of agroecology and the number of responses given by farmers to the fourth questions that highlight benefits of ecological processes to farming, and (B) the links between farmers' answers related to benefits from ecological processes to insect-pollinated crop yield on one hand, and farmers' socio-economic characteristics, their participation to agri-environmental schemes (AES) and on-farm experiment on the other hand. Definition of agroecology: A1 presents the output of the RDA analysis with significant effects are bold. A2 shows the correlation between the two first axes of the RDA and the definition of agroecology, while A3 shows the correlation between the two first axes of the RDA and the number of responses to the fourth questions related to benefits of ecological processes to farming. Responses to insect-pollinated crop yield: B1 presents the output of the RDA analysis with significant effects are bold; B2 the correlation between the two first axes of the RDA and farmers' socio-economic characteristics, their participation to agri-environmental schemes (AES) and on-farm experiment; and B3 the correlation between the two first axes of the RDA and the number of responses to the question about the drivers of insect-pollinated crop yield per main category.

(A1)	Df	Variance	F	Pr(>F)	(A2)	RDA1	RDA2	(A3)	RDA1	RDA2
Agricultural Practices	1	0.0039	1.2152	0.28871		0.1644	−0.0770	Nb EP + Cereal Yield	−0.1705	−1.522
Human-Nature relationships	1	0.0116	3.6203	**0.02098**		−0.2030	0.0158	Nb EP + Insect-Pollinated Yield	0.3011	−0.0009
Risks	1	0.0078	2.4894	0.08092		0.1586	0.0520	Nb EP + Soil	1.6169	0.8018
Other	1	0.0014	0.4380	0.70330		−0.0556	−0.0310	Nb EP + Hedges	−1.2929	1.2031
Residuals	72	0.2305								
(B1)	**Df**	**Variance**	**F**	**Pr(>F)**	**(B2)**	**RDA1**	**RDA2**	**(B3)**	**RDA1**	**RDA2**
Production Mode (OF/CF)	1	0.00573	0.5432	0.72827		0.0031	0.0009	Climate	−2.1312	0.5903
Agricultural system (Grain/Mixed)	1	0.01233	1.1682	0.34066		−0.0165	0.1163	Stochasticity	0.0000	0.000
Experimentation with researcher (Yes/No)	1	0.00728	0.6903	0.59041		0.0072	−0.0873	Socio-economic and politic conditions	−0.2244	−0.0099
AES (Yes/No)	1	0.02944	2.7901	**0.02897**		−0.1825	−0.0266	Ecological processes Positive effect	0.0543	−0.4005
Farm crop diversity	1	0.00733	0.6945	0.60639		0.0266	−0.0238	Ecological processes Negative effect	0.1910	−1.8991
Farm size	1	0.01560	1.4784	0.19580		−0.0957	−0.0266	Inputs	0.3222	1.2297
Residuals	67	0.70701						Pedoclimatic conditions & landscape features	0.0435	−0.0850
								Farm socio-economic conditions	0.0034	0.7868
								Farmers technicity	0.0500	−0.8535
								Others	1.6819	0.7657

control as a factor supporting crop production by 36 farmers and to resource competition with crop plants by 49 farmers (Table 4). Forty-four farmers also recognized hedgerows as protection against heavy rainfall and storms (Table 4). These responses were generally related to each other (Fig. 2D). Eleven farmers did not see any link between the presence of hedgerows and crop production.

3.2.3. Farmers who linked agroecology to human–nature relationships had greater perceptions of the benefits of ecological processes

The number of responses related to benefits from ecological processes was significantly associated with a definition of agroecology mentioning human–nature interactions (RDA: $F = 3.62$, $p = 0.02$). In particular, the RDA showed a positive correlation between farmers' responses to the hedge question that were related to the benefits of ecological processes and a definition of agroecology related to human–nature relationships (Table 5A).

3.2.4. Farmers did not consider socio-economic factors as significant drivers of crop production

Socio-economic factors had almost no significant effects on farmers' responses to the four questions. Indeed, no socio-economic factors had a significant effect on cereal production, soil fertility or hedges. Rather, we found a significant effect of AES implementation on farmers' responses to the insect-pollinated crops question ($F_{1,61} = 2.86$, $p = 0.01$), although AES explained a small amount of variance (3.18%; Table 3). Farmers who implemented AESs on their farms tended to associate insect-pollinated crop production with benefits from ecological processes, farmer technicity as well as socio-economic and political conditions (Table 5B). In contrast, farmers who did not implement AESs associated insect-pollinated crop production with inputs and socio-economic, pedoclimatic and landscape conditions of the farm.

4. Discussion

4.1. Farmers showed little awareness of the dependence of crop production on the natural functioning of ecosystems

In this study conducted in an intensive cereal plain in western France, we investigated the degree of farmers' perception of the dependence of food production on ecological processes, considering that ignoring the role of ecosystem functioning in farming could be an obstacle to agroecological transition. We surveyed 20% of the farmers of the area by telephone and found that half of them associated agroecology with human–nature relationships, either as a way of producing with a less negative impact on biodiversity or as a way of producing in partnership with nature. However, very few farmers mentioned ecological processes – other than those related to pests, diseases and weeds – as drivers of grain (winter cereal) or mass-flowering crop (oilseed or sunflower) yields (Table 4). Indeed, neither pollination nor natural pest control was mentioned by farmers as a driver of grain crop yields, and only one farmer mentioned pollinators as a driver of insect-pollinated crop yields, while natural pest control was absent from the responses (Table 4).

Almost all farmers (94%) underlined that cereal and mass-flowering crop yields were strongly influenced by weather conditions. Weather plays a dominant role in determining the timing of interventions, disease outbreaks, crop growth and yields. In recent years, agricultural production in the study area has been badly affected by weather due to recurrent water deficit, especially in 2022 (Tripathy and Mishra, 2023). These recent events and their impact on crop production, such as a loss of 20% of maize yield in 2022 in France (Pinke et al., 2024), may have had a significant influence on farmers' responses. Furthermore, climate is generally identified as the most important determinant of the future of agriculture (Altieri et al., 2015; Asrat and Simane, 2018; Pörtner et al., 2022), while biodiversity tends to lag behind, although they are related (Díaz et al., 2019; Outhwaite et al., 2022) and because the impact of biodiversity loss on agriculture is still underestimated. This may explain the higher prevalence of climate-related responses than biodiversity-related responses in this study.

Farmers also identified technical skills (78%) as important for cereal and mass-flowering crop yields. Technical skills include the ability to perform mechanical work effectively, to select appropriate species or crops (especially in mixtures) and to ensure that the 'right' tasks are performed at the right time. Technical skills are thus linked to farmers' knowledge. This finding is in line with the concept of a 'good farmer' (Burton, 2004) which is the farmer's capacity to make good management decisions that increase production (Burton, 2004; Sutherland and Burton, 2011). In our study, the answers to both questions relating to yield may suggest that producing high yields, which is a symbol of agricultural skill, requires a range of skills, such as the use of the correct species, pest control solutions and fertilizer levels; these are also characteristics of good farming described by Burton (2004). In fact, a high proportion of farmers (>75%) reported climate, soil properties, NPK fertilizer, pests, diseases and resource competition due to weeds as the main combination of drivers affecting grain yield (Table 4). This aligns with the results of previous studies that have shown that farmers perceive yield as a key indicator of farming ability that confers social status and provides a significant boost to self-esteem (Burton, 2004; Sutherland et al., 2012; Sutherland and Burton, 2011).

The recycling of organic matter was the first ecological process mentioned among the responses given to the three questions concerning crop production (questions on yield and soil fertility drivers, Table 4). The importance farmers assigned to the recycling of soil organic matter compared to other regulating services, such as pollination or natural biological control, corroborates previous studies showing that soil regulating services are more commonly perceived by farmers than natural pest control or pollination (Chisika et al., 2022; Smith and Sullivan, 2014; Teixeira et al., 2018). When we focused on the perceptions of the drivers of soil fertility, we found that responses related to soil organic matter, soil biota and soil fauna came after abiotic drivers or input-related drivers, such as soil depth, soil type and fertilizer use, which is in line with other similar studies (Kenfack Essougong et al., 2020; Kuria et al., 2019). In other words, while farmers perceive that ecological processes provided by belowground biodiversity are necessary for crop production and soil fertility, they do not mention biotic processes before technical or abiotic drivers. This might be because farmers perceive the soil as a mere object receiving inputs and fail to distinguish soil biota from other elements of their soils (Hervé et al., 2020).

4.2. *Farmers' perceptions of ecological processes seemed higher when considering the landscape scale*

Many farmers associated hedges with ecological processes that could affect crop production, either as a positive contribution to yield by improving natural pest control (36 farmers) or as a negative contribution by competing for resources with crop plants (49 farmers) (Table 4). Our results therefore show that farmers were more likely to perceive hedgerows as both harmful and beneficial to crops than to perceive them as neutral. In fact, hedgerows were perceived by 21 farmers in a dual way: on the one hand, they shelter pests' natural enemies and provide fodder for livestock and protection against erosion, leading to improved production, but, on the other hand, they are a potential cause of production losses due to competition for water, nutrients and light (Fig. 2). Such an ambivalent perception of biodiversity and ecosystem services has already been demonstrated for scavengers (Morales-Reyes et al., 2018) and trees (Blanco et al., 2020; Chisika et al., 2022) and has been called the 'Dr Jekyll and Mr Hyde' hypothesis (Morales-Reyes et al., 2018). In the case of scavengers, farmers' experience-based and local ecological knowledge was found to be associated with a positive perception (Morales-Reyes et al., 2018). In our study, we did not question farmers on their knowledge sources, but our quantitative assessment revealed that neither the experiments led by the local research team nor farmers' participation in AESs explained farmers' perceptions of hedgerows.

Furthermore, our findings showed a difference in perceptions of the contributions of natural pest control and pollination between yield-related responses and landscape-related responses. Farmers mentioned natural pest control only in their responses to the question on the role of hedgerows but never when they were asked about the drivers of crop yields or of soil fertility. This result showing that hedgerows were perceived as potential shelters for natural crop auxiliaries is in contrast to those of other studies that found that farmers do not see semi-natural habitats as a way to improve natural pest control (Brévault and Clouvel, 2019; Salliou et al., 2019). However, in our study, farmers did not link this to farming production. To our knowledge, our study is the first to reveal a dichotomy in farmers' perceptions of the role of ecological processes at the field (areas directly related to crop production) and landscape (non-productive areas) scales. This dichotomy may thus reflect a vision related to land sparing (Kremen, 2015), in which biodiversity that supports farming remains outside the field and therefore does not imply co-benefits between farming practices and biodiversity conservation at the field scale (Tittonell et al., 2016).

This dichotomy between off-field and on-field perceptions is consistent with previous studies showing that the perceptions of nature, biodiversity and ecosystem services in general positively influence the adoption of biodiversity-friendly practices (Hevia et al., 2020; Klebl et al., 2023, 2024). In Spain, farmers who perceived pollinators as important for their crops were the most likely to implement pollinator-friendly practices (Hevia et al., 2020). In our study, only one farmer out of 78 perceived pollinators as important for the yield of mass flowering crops, and five out 78 farmers mentioned pollinators when asked about their perception of hedgerows (Table 4). This highlights that maintaining or re-introducing hedgerows can foster agroecological transition by increasing farmers' perception of the importance of ecological processes for crop production.

4.3. *Drivers influencing perceptions of the roles of ecological processes and functions in farming*

In this study, we selected farmers according to two proxies of management intensity, namely, farm size and crop diversity, assuming that more intensive farmers would be less aware of the role of ecological processes in farming. No relationships were found between these proxies and farmers' perceptions of ecological processes (Table 3). Although farm size is widely used as a proxy of management intensity (Eastwood et al., 2010), this proxy may not be precise enough. For instance, Xu et al. (2023) showed that farmland area, as part of the natural capital of farmers, was, on the one hand, a driver of farmers' green behaviour but, on the other hand, was not associated with an improvement in farmers' ecological cognition. For a better understanding of this topic, further studies should include other socio-economic factors, such as income or financial capital, that were not available for this study.

Because our study was conducted in an area in which farmers could implement AESs and participate in OFEs with research teams, we investigated the role of those variables in affecting farmers' responses concerning their perceptions of ecological processes and functions. Participation in OFEs with researchers did not influence farmers' perceptions of ecological processes (Table 3). Because these experiments were designed to foster an agroecological transition by directly involving farmers in the process (but see Gaba et al., 2020), we expected the farmers who had participated in these experiments to have a greater perception of the beneficial role of ecological processes for crop production. Rather, we found that the farmers who implemented AESs cited beneficial ecological processes and functions related to insect-pollinated crops more often than the farmers who did not (Table 3). However, insect pollination as a driver of mass-flowering crop yields was mentioned by only one farmer (Table 4), suggesting that AESs are not sufficient to change farmers' perceptions of the main driver of the yields. This is further supported by our finding that participation in AESs was related to only one of the four questions (Table 3). Our results thus contrast with those of previous studies, which showed that AESs can reshape farmers' identities and their visions of good farming (Ingram et al., 2013; Riley, 2016; Teff-Seker et al., 2022). In this study we focused on OFEs and AESs because both involve changes in farmers' practices and were managed by the research team. While AES involves compensation for income forgone and contractual obligations, OFEs does not and is based on voluntary participation (but see Gaba and Bretagnolle 2020). This may partly explain our results. However, economic motives alone are not sufficient to engage farmers in AESs (Pavlis et al., 2016; Villamayor-Tomas et al., 2021) and to promote adoption of biodiversity-friendly practices in the long term (Kleijn et al., 2004, 2006). As AES have been designed and implemented by the research team over a period of more than 15 years, we can assume that our results can be explained by the interaction between researchers and farmers, as already found in Villamayor-Tomas et al. (2021).

A possible way to challenge this is to build AES programs using a systemic perspective, not only with targeted measures to protect biodiversity, as was the case until 2014 (Pavlis et al., 2016), but to reform AES programs to collective and larger scale of application measures such as landscape programmes (Groeneveld et al., 2019; McKenzie et al., 2013).

4.4. Methodological challenges addressed in this study to avoid response biases

Our results showed that farmers perceived fewer ecological processes as drivers of production than in previous studies. These studies generally used direct semi-quantitative methods such as Likert scales and asked farmers to rank how they perceived the role of pollination or natural pest control in farming (Chen et al., 2017; Cheng et al., 2023; Fruitos et al., 2019; Schmitt et al., 2021). Directly questioning farmers about the role of ecological processes may indeed influence farmers' responses. For example, Smith and Sullivan, (2014) found that 80% of farmers had no understanding of regulating ecosystem services before the interview, but a majority identified up to 12 regulating services important for crop production. Farmers' perceptions are also commonly measured using open-ended questions oriented towards nature, agroecological elements on the farm or protected areas (Blanco et al., 2020; Cáceres et al., 2015; Canova et al., 2019; Teixeira et al., 2018). Some studies even favour an ethnological approach with in-depth interviews (Blanco et al., 2020) or field observations to complete semi-structured interviews (de Oliveira and Berkes, 2014). These approaches yield more ecosystem services identified during interviews than our open-ended questions approach, especially cultural benefits from ecosystem services which were not capture in our study (Blanco et al., 2020; de Oliveira and Berkes, 2014). However, whether using Likert scales, open-ended questions or in-depth interviews and field analysis, a formulation oriented towards ecosystem services, biodiversity or nature seems to induce farmers' responses towards a greater perception of these components, therefore leading to an overweighted perception.

In our study, we examined farmers' perceptions of the role of ecological processes in farming activities without mentioning any ecological processes or biodiversity. Rather, we focused on the drivers of yield and soil fertility and the role of an agroecological infrastructure (i. e. hedges) without presenting hedges as agroecological infrastructure (A1, interview guide, Appendix 1). Only one farmer in our study cited pollination as a driver of insect-pollinated crop yield (i.e. oilseed rape and sunflower, Table 4). This strongly contrasts with studies that directly asked farmers about the importance they gave to pollination as a driver of insect-pollinated crop production (Ali et al., 2020; Christmann et al., 2022; Hevia et al., 2020; Osterman et al., 2021). For instance, Hevia et al. (2020) showed that 92.7% of farmers perceived pollinators as important for food production when asking them directly about the roles pollinators play in crop production in a narrow question. This suggests that farmers are aware of the roles of ecological processes such as pollination or natural pest control but that these roles remain disconnected from or marginally considered during their farming activities.

4.5. Disconnect between definitions of agroecology and perceptions of ecological processes

Almost half of farmers (36 of 78, Table A1), in this study, defined agroecology as being related to human–nature relationships, and we noted that these same farmers had a greater perception of ecological processes supporting farming production (35 of 78, Table A1). If it seems coherent to rethink one's own ontology towards nature (Descola, 2009; Latour, 2009) for an agroecological transition with an importance given to ecological processes in a farming system, it is paradoxical that farmers have this vision of agroecology while not citing these processes as drivers of crop yields, even insect-pollinated crop yields (Tables 4 and 5). This dichotomy illustrates an agroecological transition torn between a nature–culture dualism and a necessity for farmers to rethink agricultural systems based on the natural functioning of ecosystems. Indeed, most of the farmers who related agroecology to human–nature relationships defined agroecology as a way to reduce negative externalities on biodiversity or nature. Therefore, they did directly link biodiversity to crop production within an agroecological perspective but only through a way to conciliate both crop production and biodiversity conservation without linking biodiversity to crop production. Our study also illustrates this by the greater perception of the role of ecological processes demonstrated by the hedgerow question compared to that on yields.

This dichotomy between the definition of agroecology and the limited perception of ecological processes for crop yields might be explained by a conflict of values for farmers, depending on whether they have an anthropocentric or ecocentric philosophy associated with their perception (Gros-Désormeaux, 2021). Anthropocentric values consider biodiversity and its processes as resources for the future of humanity and ascribe to them economic values, whereas ecocentrism is less human centred and considers that protecting habitats permits humanity to live in harmony with them (Boulangeat et al., 2022; Klebl et al., 2024). These different values could strongly influence farmers' perceptions of biodiversity and the associated farm management decisions (Klebl et al., 2024). Farmers with anthropocentric values will tend to implement biodiversity conservation actions that are rather *ad hoc* and disconnected from their production practices, whereas those with a more ecocentric vision will tend to consider biodiversity protection in a more holistic way and integrate it more into their farming practices. However, the line between these two visions remains blurred. In our study, ten farmers gave a definition of agroecology that included both visions. This underlines the fact that agroecology is still a portmanteau word and that there is still little understanding of its principles, particularly the role of biodiversity and ecological processes.

5. Conclusions

In this study, we tested the hypothesis that farmers' limited perceptions of ecological functions and processes would hinder the possibility of an agroecological transition. We found that a large proportion of farmers related agroecology to human–nature relationships, with some of them defining agroecology as a way to produce by 'working with nature'. However, no farmers, even those who related agroecology to new human–nature relationships, cited any ecological processes as main beneficial drivers of crop yields. By contrast, ecological processes that have been widely studied for their benefit to crop production, that is, pollination and natural pest control, were cited by farmers only when considering the role of hedges, an off-field type of agroecological infrastructure. This highlights that a nature–culture dualism remains and that it may, as we hypothesized here, be an obstacle to an agroecological transition. This study also suggests that scientific studies in agroecology that objectivize the roles of ecological processes in crop production are still poorly known by farmers and extension services, and that these studies should be better relayed in their training courses.

This study also highlights the limited roles of OFEs and AESs as ways to improve perceptions of ecological processes and hence the design of environmentally friendly agricultural systems that produce 'with' nature and not 'against' nature. This calls into question the ability of these programs to foster agroecological transformations, especially those that would improve farmers' perceptions of the importance of ecological processes for farming. Various projects in Western Europe aim to rewild farming to restore ecological processes related to farming, such as a project to rewild agriculture in England or Paysans de Nature® in France (Mondière et al., 2022). From this perspective, it is important to analyse changes in perceptions towards biodiversity and ecological functions inside the farming process itself to determine whether farmers will reconsider their farming systems in terms of their relationships with biodiversity and ecological functions.

Declaration of competing interests

The authors have no competing interests to declare.

CRediT authorship contribution statement

Yves Cartailler: Writing – review & editing, Writing – original draft, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Elsa T. Berthet:** Writing – review & editing, Methodology, Funding acquisition, Conceptualization. **Simon Durand:** Writing – review & editing, Data curation. **Sabrina Gaba:** Writing – review & editing, Writing – original draft, Project administration, Methodology, Funding acquisition, Formal analysis, Conceptualization.

Data availability

The data that has been used is confidential.

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Appendix 1

A1- Interview guide

I. General information

Name of investigator: Date: Consent: ☐ yes ☐ no If yes, format: ☐ oral ☐ document sent by mail ☐ other (precise): Duration of the interview:

II. Farming production
   II.1. What do you think your yield generally depends on (five choices)?
   II.2. Are those factors similar for winter cereal yield and mass flowering crops? What could be different between those two crop types?
III. Soils
   III.1. In your opinion, from what does soil fertility in your farm depend on?
IV. Landscape
   IV.2. Do you think the presence of hedges has an effect on crop yields? ☐ yes ☐ no; why?

Do you see any potential benefit in the presence of hedges?

V. Agroecology
   V.1. What does the term agroecology suggest to you?
VI. Link with the research team
   VI.1. What links have you had with the research team since you first started your farm? For how many years? At which frequency?

Table A1
Number of farmers' responses to the question related to the definition of agroecology. Higher values for a given type of response are bold. No farmers give more than one response par sub-categories.

Type of response	Number of farmers	Farmers' Responses	Number of responses	Examples of verbatim for main categories
Agricultural practices	35	Agroforestry	**10**	"*I believe in it, in particular by working intercropping cover crops. At first I was doing it for regulatory reasons, but then I noticed that my soil was easier to work. I've had quite a few meetings on the subject and we can reduce the amount when we do it at the right time, depending on hygrometry and wind conditions. Today we've been able to reduce the doses by a factor of 4 when we do it at the right time.*" Example of a response given to question V.1 (Male mixed-farmer in conventional farming system, between 40 and 50 years old and involved with research team only for monitoring in the fields)
		Organic farming	7	
		Reducing the use of synthetic input	8	
		Reducing soil operations	1	
		Plant management	1	
		Change in crop rotation or intercrop	2	
		Need an increase of work load or higher technicity	5	
		His or her practices	4	
		Change compared to what is currently done	5	
Human-Nature relationships	36	Biodiversity (reducing externality on)	**17**	*"For me, the definition that emerges is to produce using nature's resources and ecological functions to the maximum, such as water, soil, hedges, air and all the natural processes that interact with our practices. So it's more a global approach to the interactions between our rotations, our practices and the ecological functions to limit chemical inputs, but it's more encompassing than that."* Example of a response given to question V.1 (Male grain farmer in conventional farming system, between 50 and 55 years old and involved with research team only for monitoring in the fields)
		Soil (reducing externality on)	9	
		Working with Nature (natural resources; biodiversity; earth)	14	
		Accounting for other human being	3	
Risk	7	For farmers	5	*"Don't know much about it. The whole environmental thing is beyond me these days, we're going to starve on it."* Example of a response given to question V.1 (Male grain farmer in conventional farming system, between 40 and 50 years old and involved with research team only for monitoring in the fields)
		For food security	2	
Opinions	19	No Idea/Polysemic	16	*"I don't really know. I don't really like the word ecology."* Example of a response given to question V.1 (Male grain farmer in conventional farming system, between 60 and 65 years old and involved with research team only for monitoring in the fields)
		Against Ecology	5	

Table A2
Canonical Correlation analysis of the association between responses to the four questions. The analysis was conducted by pair of questions.

Pair of Questions	Pllai's trace	P-value
Cereal yield & Insect-pollinated yield	6.033	0.031
Cereal yield & Soil fertility	3.400	0.793
Cereal yield & Hedges	5.1687	0.438
Insect-pollinated yield & Soil fertility	2.2690	0.998
Insect-pollinated yield & Hedges	4.9443	0.007
Soil fertility & Hedges	2.6304	0.747

Table A3
Number of farmers' responses to the four questions shown by main category. Higher values are bold. For ecological processes, values indicated between brackets correspond to the number of responses related to pests, diseases or weeds (i.e. associated with a negative impact of biodiversity).

Main categories	Grain yield	Insect-pollinated yield	Soil fertility	Hedges presence
Climate	**73**	16	**73**	45
Stochasticity	4	0	4	0
Socio-economic and politic conditions	24	1	24	17
Ecological processes (pests, diseases or weeds)	25 (19)	24 (18)	24 (0)	**71 (49)**
Inputs	42	8	**41**	11
Farm socio-economic conditions	13	3	0	12
Pedoclimatic conditions & landscape features	33	1	22	29
Farmers' technicity	**61**	13	**42**	12
Others	22	**27**	1	11

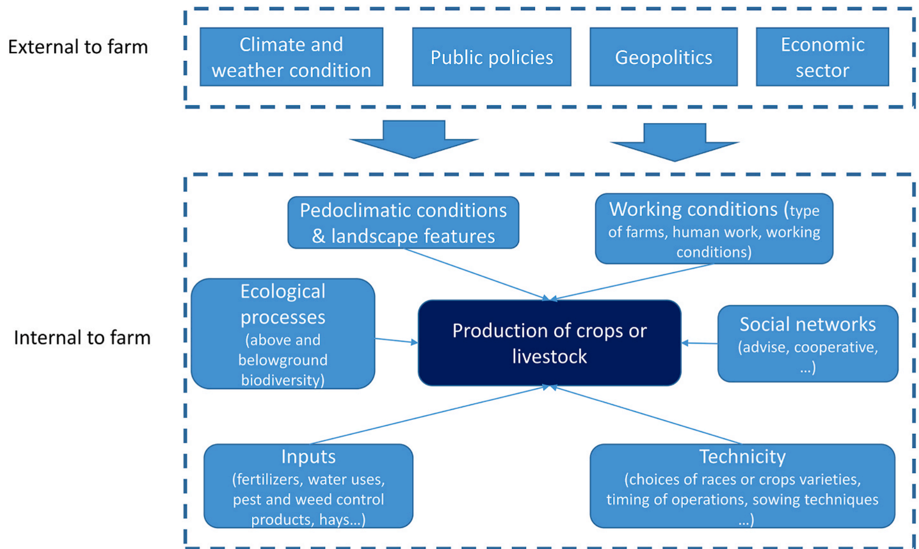

Fig. A1. Conceptual framework for abductive coding process used for 4 questions related to crop production, soil fertility drivers and hedges in order to isolate ecological processes from other perceived drivers of crop production. The external drivers were thought as drivers that farmers do not control whereas internal drivers refer to drivers that farmers can partially or completely control.

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