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Sara Bosshardt, Rodolphe Sabatier, Arnaud Dufils, Mireille Navarrete

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Review

Changing perspectives on chicken-pastured orchards for action: A review based on a heuristic model

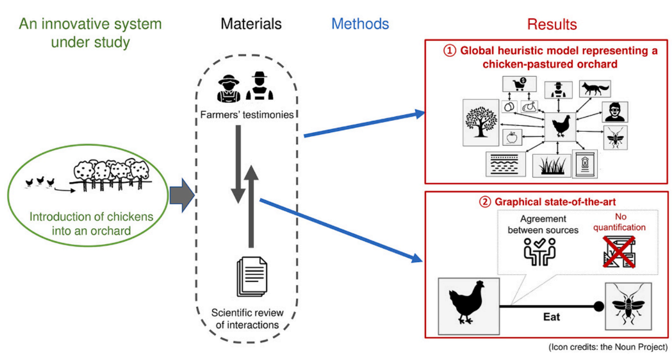
Sara Bosshardt *, Rodolphe Sabatier, Arnaud Dufils, Mireille Navarrete

INRAE, UR 767 Ecodéveloppement, 84000 Avignon, France

HIGHLIGHTS

- Chicken-pastured orchards are increasing in popularity among fruit growers involved in the agroecological transition
- These agroforestry systems are complex and a global consideration of interactions and components is needed
- We built a heuristic model of chicken-pastured orchards and compared the scientific state-of-the art to farmers' testimonies on some interactions
- We showed that the scientific literature is lacking and rarely fits farmers' expectations for numerous interactions
- More agroecological approaches are needed to study these systems and to help fruit growers design and manage chicken-pastured orchards

GRAPHICAL ABSTRACT



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ABSTRACT

CONTEXT: Agroforestry and, more precisely, the integration of animals into orchards, represent an interesting source of income diversification for fruit growers who are confronted with rising climatic and economic risks. Besides farm resilience and optimisation of land use, this association seems to provide reciprocal benefits for both trees and animals, such as: nutrient cycling, weed management, natural protection and pest control. In particular, poultry and, more specifically, chickens, have caught the attention of numerous fruit growers in search of simple and time-saving agroecological solutions to regulate pests and weeds in their orchards. Yet, whereas traditional silvopastoral systems involving livestock have been extensively studied, the advantages and disadvantages of introducing chickens into orchards have been overlooked.

OBJECTIVE: In this review, we aimed to build a heuristic representation of a chicken-pastured orchard in order to better understand this complex agroecosystem. We also compared the scientific state-of-the-art concerning some characteristics of this system to situations in the field.

METHODS: We first carried out a synthesis using an initial set of information (scientific articles, grey literature, testimonies, etc.) to build a simple heuristic representation based on compartments in interaction. We then examined the nature of information on interesting interactions by comparing 86 scientific articles to 26 farmers' testimonies.

* Corresponding author.
E-mail address: sara.bosshardt@inrae.fr (S. Bosshardt).

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RESULTS AND CONCLUSION: We show that the scientific and empirical knowledge concerning chicken-pastured orchards is uneven. More precisely, we identified four types of divergence on some characteristics of the information from different sources concerning the system. One general finding is that the absence of consensus about crucial aspects of the complex dynamic of chicken-pastured orchards and a lack of quantification approaches on several interactions are not consistent with farmers' needs. We suggest that including farmers in the scientific process as well as fostering interdisciplinary systemic approaches, notably between agronomy, animal science and ecology, could greatly benefit the study and design of agroecological integrated systems such as chicken-pastured orchards.

SIGNIFICANCE: To our knowledge, this review is the first one to present a global view of chicken-pastured orchards. The review built around the heuristic model aims at helping scientists identify knowledge gaps and new research questions. In addition, the heuristic model can also be a useful tool for designing and managing innovative systems together with the farmers concerned.

1. Introduction

Fruit growers in Europe are confronted with rising agronomic, economic and social challenges at this time. Moreover, these challenges are somewhat contradictory like, for example, the fact that consumers expect fruit growers to produce fruits using environmentally-friendly practices and, at the same time, demand higher quality fruits (Alaphilippe et al., 2021). Fruit production is also becoming more vulnerable to the consequences of climate change, such as the potential emergence of tree pests (Gomez-Zavaglia et al., 2020) and the shifts in plant phenological traits (Leolini et al., 2018; Vanalli et al., 2021) that lead to huge production losses (Agreste, 2021; Hostalnou, 2021). Recent late frosts in spring 2021 wiped out future fruit harvests in France and forced the French government to declare the event as an "agricultural disaster" in order to compensate fruit growers (France Relance, 2021).

To address these major challenges, fruit growers need to reinvent their activity. Agroforestry is one of the available and promising options (Pantera et al., 2018). This term is defined as the "collective name for land-use systems and technologies where woody perennials are deliberately used on the same land-management units as agricultural crops and/or animals in some form of spatial arrangement or temporal sequence" (Nair, 1993). More precisely, the integration of understorey crops or animals in orchards is an emerging practice for an ever-increasing number of fruit growers who hope to diversify their income sources and provide partial responses to a number of agronomical challenges (García de Jalón et al., 2018; Smith et al., 2013). These approaches that put tree products at the centre belong to what Pantera et al. (2018) calls "high value tree agroforestry".

Two different ways of orchard diversification are thus possible: intercropping and the introduction of animals. Regarding animals, different species are likely to be introduced: cattle, horse, sheep, chicken, geese, etc. (Brodt et al., 2020; López-Sánchez et al., 2020; Massaccesi et al., 2019; Orefice et al., 2017; Pantera et al., 2018). In contrast with understorey crops, the presence of animals in orchards seems less spatially constrained. Animals provide additional services in response to the diverse challenges of fruit production (Brodt et al., 2020; Corroyer, 2017; Coulon et al., 2000), such as fertilisation (Röhrig et al., 2020a; Soudet et al., 2021), weed control (Lavigne and Lavigne, 2013) and pest control (Clark and Gage, 1996; Pedersen et al., 2004). In parallel, orchards also offer partial responses to vital current issues in animal husbandry, such as animal welfare (García de Jalón et al., 2018), the management of farm effluents (Billen et al., 2021; Brodt et al., 2020) and the feed costs for animals (Meng et al., 2016; Röhrig et al., 2020a).

The advantages and drawbacks of this association strongly depend on the animal species. Compared to livestock, poultry husbandry seems to offer more flexibility to farmers, notably through an easy valorisation of the products (eggs and meat) and limited supervision, notably to avoid damage to trees (Cazaux, 2015; López-Sánchez et al., 2020). Hence, poultry represents an interesting choice for fruit growers who are usually not experienced in animal husbandry because investments in terms of money, time and knowledge are limited compared to livestock. The rising number of fruit growers currently attracted to this practice obviously reflects the interest of fruit growers in these poultry/orchard associations. More precisely, chicken (*Gallus gallus domesticus*), which designates both laying hens and broilers, is the most common poultry subspecies raised by a large number of fruit growers and that we have chosen to focus on in this article. It should be noted that chicken-pastured orchards must be distinguished from silvopastoralism with poultry, also referred to as silvopoultry, in which the types of trees (timber, fruit production, etc.) and poultry (chicken, geese, ducks, etc.) are not specified. They must also be distinguished from what we refer to as free-range chickens in wooded ranges, in which animal husbandry is the main activity on the farm. As defined, chicken-pastured orchards correspond to one type of silvopoultry system, and despite a husbandry component, the main activity is fruit production. In addition, concerning the use of semantics, the term "pastured" seems more adapted to chicken behaviour than "grazed", which refers more to systems that include sheep or other livestock.

Consequently, whereas traditional silvopastoralism with sheep or cattle has been extensively investigated, far less is known about these chicken-pastured orchard systems, even though they are promising agroecological systems for an increasing number of fruit growers. What is more, these systems raise new scientific issues on agroecological dynamics (Soudet et al., 2021). Indeed, the functioning and management of such agroecosystems are complex because they result in the integration of several interactions, feedbacks and compartments, at various temporal and spatial scales. There is thus a need to construct a global view of all those components in order to represent how this system functions. For this purpose, heuristic representations make it possible to combine and reveal diverse knowledge from a systemic point of view, and, as such, they are useful research tools to help design and manage agroecosystems (Le Page et al., 2014).

In addition, several authors have highlighted the fact that farmers are part of these agroecosystems and build agroecological knowledge through their action on these systems. The integration of farmers' knowledge into research approaches is therefore considered as essential to build an exhaustive overview of the functioning of agroecological systems, as well as to become involved in an effective agroecological transition (Altieri, 2002). Action-oriented research thus makes it necessary to find a balance between scientific research and farmers' needs in the field, and to take empirical knowledge into consideration.

For these reasons, the objectives of this article are: (1) to obtain a simple heuristic representation of the components and interactions resulting from the introduction of chickens into an orchard; and (2) to draw up a scientific state-of-the-art of some of these interactions, and to compare current scientific knowledge to farmers' expectations. This analysis was based on two sets of data: an extensive review of the literature and a collection of fruit growers' testimonies about chicken-pastured orchards.

In this article, we first describe our methods (Section 2). Then, in Section 3, we present a simplified heuristic model of a chicken-pastured orchard based on a mental synthesis of information, and describe the dynamics involved. This representation is then refined and observed with a focus on the relative interest of research and farmers in each dimension of the system. Our results notably reveal several scientific gaps and a disconnection between scientific and fruit growers' concerns. This observation is finally discussed in Section 4 with a more global approach in order to identify the reasons for this situation, to draw a parallel with other domains and to develop research and operational perspectives about chicken-pastured orchards.

2. Materials and methods

Since most of the chicken-pastured orchards currently in operation belong to fruit growers who have introduced chickens into an existing orchard, chickens are at the centre of our representation. We therefore focused on the interactions between chickens and the other compartments (trees, pests, herbaceous stratum, etc.) and not between these other compartments.

2.1. Construction of a global heuristic model of the agroecosystem

To build an initial heuristic model of the "chicken-pastured orchard" agroecosystem, we used an initial set of various materials: peer-reviewed articles, grey literature (including technical literature and grey scientific literature) and farmers' testimonies taken during a field visit (FV) with fruit growers who own chicken-pastured orchards, and that were personally collected by the authors during two collective field visits.

Grey scientific literature notably includes conference proceedings, non-peer-reviewed articles, Master's or PhD theses, generally from within the French scientific community (Appendix A2). The interest of such literature is to provide an image of scientific research in the making since theses and conference proceedings often precede peer-reviewed articles. Similarly, we also used French technical literature, mainly corresponding to technical guides and technical articles written for future and current farmers (generally chicken farmers). These documents were collected using different means: (i) exchanges with experts in the domain; (ii) searches on technical institution websites (e.g., the French Technical Institute for the Poultry, Rabbit and Fish Sectors/ ITAVI and the French National Federation for Organic Agriculture/ FNAB); and (iii) specific databases (HAL, google scholar, HAL INRAE, etc.). Due to their heterogeneity and the difficulty of carrying out systematic research to find them, these articles were not included in the exhaustive review (Section 2.2.) but were used to construct an initial version of our heuristic model. It was then improved through a systematic review process of the scientific literature in order to include interactions that were missed in the first rough analysis and to obtain a final validated version of the model.

2.2. Representing the state-of-the-art of some of the interactions

2.2.1. Selection of interesting interactions

Among all the interactions represented in the global model (Fig. 1), we chose to focus more deeply on a restricted number of interactions that concern the sustainability of the association between chickens and orchards. More precisely, we selected all of the interactions emanating from the chicken compartment as being prone to impact fruit tree production (directly or indirectly). We also included other interactions that are liable to impact chicken sustainability in a way specific to orchards

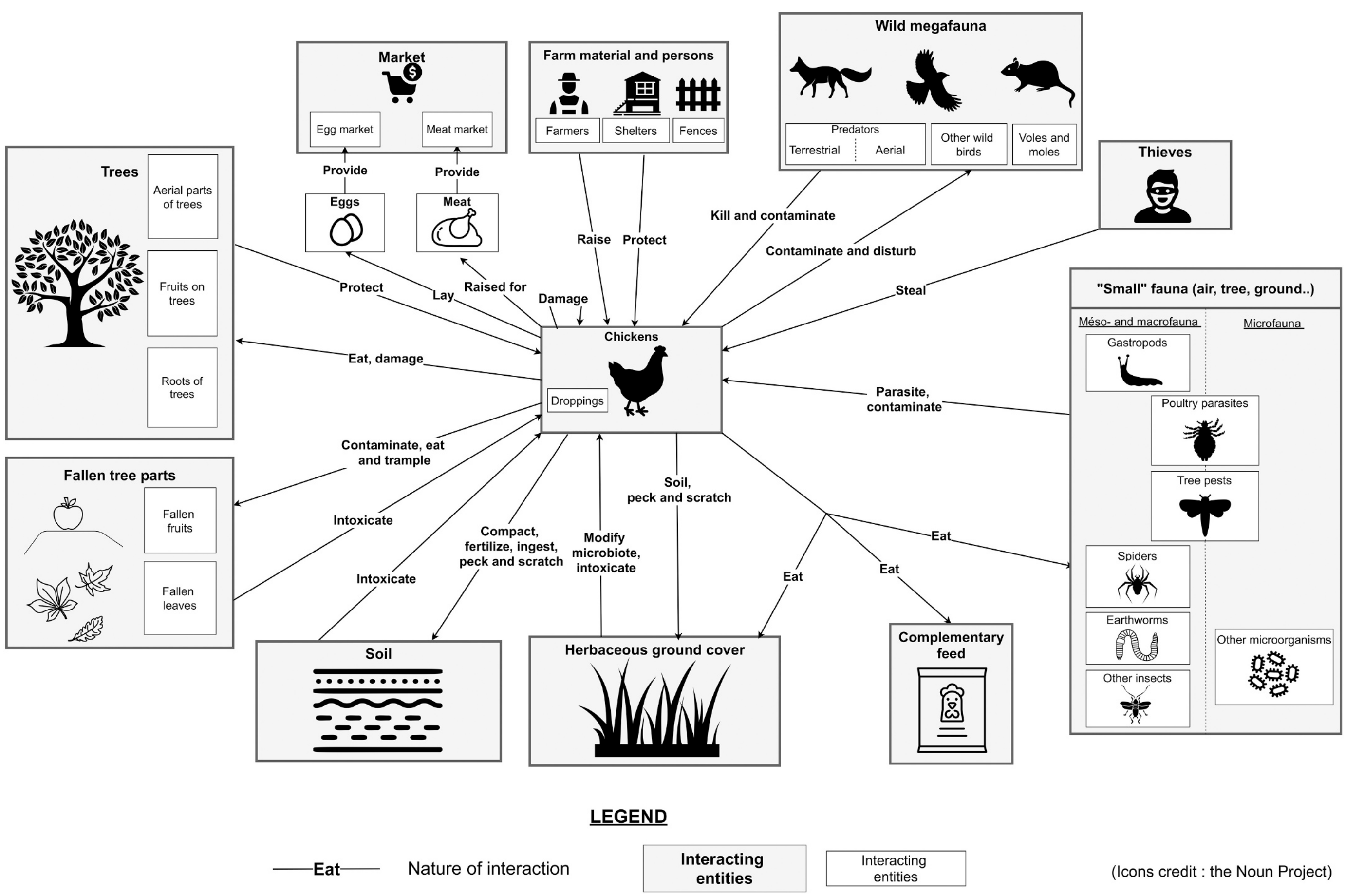

Fig. 1. Heuristic model of a chicken-pastured orchard. Only direct interactions linked to the chicken compartment are represented. The chicken compartment is connected to other compartments (represented by rectangles), with directed arrows. The nature of the interaction is given by verbs of action.

and that appeared to be significant according to farmers' testimonies, namely:

- the risks of chicken intoxication in a context of high pesticide use in orchards;
- the question of welfare and protection offered by trees to chickens;
- the question of work organisation for fruit growers who associate chickens with orchards.

Interactions concerning meteorological conditions and wild fauna were indirectly included through the question of welfare and protection provided by trees to chickens.

2.2.2. Search of the scientific literature

Based on this selection, we combined two search queries to find scientific literature related to each of these interactions on Scopus (whose results were more exhaustive than WoS). Our results focus on chickens because we could not find enough material about other poultry subspecies (geese, etc.) whose behavioural characteristics differ too much to be mixed with chickens in the model.

To compensate for the small number of research articles available, we established the working hypothesis that the type of tree did not significantly modify the nature of interactions. We therefore combined articles related to fruit trees in chicken-pastured orchards and any type of tree in silvopoultry systems with chickens.

(i) ***Final search query on silvopoultry systems on Scopus (last access: June 2021)***

((TITLE(hen$ OR chicken$ OR broiler$ OR *poultry) OR KEY (hen$ OR chicken$ OR broiler$ OR *poultry)) AND TITLE-ABS-KEY(agroforestr* OR *silvopoultry OR silvopast* OR "crop animal" OR "integrated agriculture" OR orchard OR (integration PRE/2 animal*)) AND NOT TITLE-ABS-KEY(litter OR manure)) AND (EXCLUDE(DOCTYPE, "er")) AND (LIMIT-TO(SUBJAREA, "AGRI") OR LIMIT-TO(SUBJAREA, "ENVI"))

Since we only collected 46 articles, most of which were not entirely relevant to our question, we decided to extend our search to free-range chicken systems on the basis of the hypothesis that some extrapolations could be made concerning some interactions. We thus wrote a second search query referring to the different compartments and interactions previously selected.

(ii) ***Final search string on free-range chicken systems, focusing on interactions and compartments of interest (last access: June 2021)***

((TITLE(hen$ OR chicken$ OR broiler$ OR poultry) OR (TITLE (egg$) AND TITLE-ABS-KEY(hen$))) AND KEY(pasture* OR (free AND rang*) OR grazing OR foraging) AND TITLE-ABS-KEY (orchard* OR tree* OR soil OR (grass* OR weed* OR herb* OR vegetation OR pasture) OR (biodiversit* OR insect* OR earthworm* OR (pest* AND fruit*) OR spider$) OR vole OR (gasteropod* OR snail* OR slug*) OR predation) AND NOT ALL (ducked OR prairie OR harrier$) AND NOT TITLE(*manure* OR *litter*)) AND (EXCLUDE(DOCTYPE, "er")) AND (LIMIT-TO (SUBJAREA, "AGRI") OR LIMIT-TO(SUBJAREA, "ENVI"))

A total of 155 documents were obtained with (ii) on Scopus.

We examined 195 articles from searches (i) and (ii), among which we identified 68 articles of interest for our heuristic model (Fig. 2 and Table 1). We also included 18 other articles in our model that we obtained through careful searches (other articles from known authors, references in a pertinent article, etc.).

Among the 86 articles listed, 51% concern laying hens, 30% broilers and 19% concern both. Similarly, 14% of the articles concern chicken-pastured orchards, 7% other silvopoultry systems, 71% free-range systems and 6% both chicken-pastured orchards and free-range systems.

2.2.3. Obtaining farmers' testimonies

Twenty-six testimonies from French fruit growers who raised chickens under orchards were obtained, directly or indirectly (see Appendix A). Exhaustivity is not an option in such a process and our priority was to collect testimonies from a diversity of sources and formats in order to address the entire range of possible situations. Four types of data were gathered (Table 1): field visits (FV, see 1.a), farmers' interviews (FI), videos (V) and grey literature (GL). Farmers' interviews (FI) were taken from a field survey carried out between August 2018 and June 2019 within the EIP-Agri DEPASSe (https://www.grab.fr/wp-content/uploads/2018/09/plaquette-depasse-V8.pdf). Testimonies (V) were taken from four relevant videos on the integration of chickens under orchards. We also retrieved testimonies from different French grey literature media (GL), namely, one technical guide, one technical book and three technical articles.

2.2.4. Identification of related information sources

Precise examination of the literature and testimonies allowed us to improve our heuristic model and to link each article/testimony to the appropriate interactions in Table 1. Only primary articles in which some data were specifically acquired on this interaction (through experiments, field observations, surveys, etc.) were included. Reviews and articles citing one interaction as a hypothesis were thus excluded.

2.2.5. Representation of interactions and the nature of information

Interactions were related to one of three categories: (1) chicken health and welfare; (2) chicken nutrition; and (3) the physical, biological and chemical impact of chickens. For each heuristic interaction between two compartments, we characterised and represented the nature of information according to three dimensions:

(i) the sense of the information (e.g., chickens play a role on trees or the opposite);
(ii) the existence of quantifications: depending on the type of source, the information may be qualitative (e.g., chickens eat weeds) or quantified (e.g., chickens ingest 70 g of forage/day);
(iii) the consistency of information from several sources.

2.2.6. Comparison between interactions

We then compared interactions based on some characteristics of the information to identify four categories of interactions corresponding to divergences between and within scientists and farmers. To do so, we assumed that the number of scientific articles for one interaction reflected the level of scientific interest towards a question. The interaction was considered as "quantified" as long as we could find one quantification in the scientific literature. Similarly, situations of disagreement correspond to discrepancies between quantifications (between scientific articles), or even oppositions concerning the existence or not of an interaction (within and between scientific articles and farmers' testimonies).

3. Results

First, we will describe the global model of a chicken-pastured orchard and the nature and organisation of interactions. We will then focus on some interactions that we propose to categorise, depending on some characteristics of the information, by examining the results and attention given by researchers and practitioners to each different dimension.

3.1. Nature and organisation of interactions in a chicken-pastured orchard

In pastured orchards, three types of interactions were identified from the literature (Fig. 1): (i) chickens interact directly with trees; but (ii) also interact with other biophysical components that may have an indirect impact on trees (the soil, the herbaceous ground cover, the fauna); (iii) on a broader spatial scale, there is an interaction between chickens and the socio-technical environment (farmers, farm equipment, marketing channels). Moreover, the presence of chickens involves the inclusion of compartments (predators, rodents, thieves), considered as external disturbers of the original "simple" orchard and which farmers have to deal with.

3.1.1. Interactions with trees

The association of chickens and trees results in some beneficial direct interactions. Trees buffer meteorological conditions by creating a suitable microclimate that protects chickens against wind, extreme temperature and sun (Jones et al., 2007). In return, chickens create a healthier telluric environment for trees by cleaning tree residues (fallen leaves and fruits) (Timmermans and Bestman, 2016). However, this association is not always a win-win partnership. Chickens can also damage trees and fruits (Hilaire et al., 2001), particularly by eating them, and contaminate fallen fruits as well (Coisne, 2020). Correspondingly, feeding on fallen tree elements can result in a higher risk of intoxication, particularly in the case of a chemically-treated orchard (ADABio, 2020).

3.1.2. Interactions with the biophysical components of an orchard

However, besides these direct effects, most interactions occur indirectly through other compartments of the system.

First of all, some elements from the agroecosystem represent complementary nutritional resources for chickens. Chickens naturally consume grass from the herbaceous stratum (Antell and Ciszuk, 2006) and feed on different types of arthropods that live in the trees, the air and the herbaceous stratum (Clark and Gage, 1996). Depending on the intensity of ingestion and the nature of the arthropods impacted (tree pests, auxiliary fauna, etc.), chickens can improve or impair tree health (ADABio, 2020). Spontaneous intake of elements from the agroecosystem can also impact chicken health. Ground ingestion (Jurjanz et al., 2015), for example, is not considered as a source of nutriments and potentially limits the ingestion of other elements. Contaminated soil and herbaceous ground cover (resulting from orchard treatment, for example) can also result in some intoxication of chickens (De Vries et al., 2006). To maintain chickens in a good health and at a sufficient production level, farmers complement this spontaneous intake with feed available in various forms (pellets, whole grains, etc.) (Bryden et al., 2021).

Chickens can also alter the physical structure of the soil and herbaceous stratum by compacting (Su et al., 2018), pecking and scratching them (Breitsameter et al., 2014). They also induce changes in the chemical composition of the soil (Hilimire et al., 2013) through fertilising effects with droppings that can benefit trees, but that can also result in soil pollution and the soiling of the herbaceous ground cover.

3.1.3. Other global interactions

Introducing chickens into orchards often implies a modification of agricultural practices involving poultry-dedicated infrastructures, equipment and work organisation to supply specific marketing channels (García de Jalón et al., 2018).

Finally, the presence of chickens attracts other animals that farmers have to learn how to deal with. Aerial (such as buzzards) and terrestrial predators (particularly foxes) (Bestman and Bikker-Ouwejan, 2020) and chicken thieves act as external disturbers of the agroecosystem by killing and stealing chickens, respectively. Moles and voles do not directly impact chickens but potentially damage trees, plots and poultry infrastructures (Coisne, 2020). These interactions have to be considered because they may deeply impact the sustainability of the introduction of chickens into orchards.

3.2. Characteristics of the information from different sources

In the previous model (Fig. 1), all interactions were represented in the same way, regardless of the nature of the information. To deepen our understanding of the state-of-the-art of this system, we will now examine the different natures of knowledge that supports these interactions. Fig. 2, using the same model representation as in Fig. 1, thus represents some interesting characteristics of the information (quantifications, consistency between sources, etc.) by focusing on a limited number of interactions of interest. To study the level of exhaustivity of the information, we also summarized scientific references and testimonies associated with selected interactions in Table 1.

Through a global analysis of these characteristics of the information found in the literature and in testimonies, we identified four different situations of divergence within and between scientists and farmers to which we could link the interactions in Fig. 2. These situations are presented successively. First, we show that some quantifications of interactions strongly differ between scientific studies. Second, we show divergences between scientists' and farmers' interests in terms of information, that we describe in terms of knowledge gaps on two dimensions: on specific mechanisms and, more generally, on chicken-pastured orchards. Third, we identify strong divergences that occur between farmers for some interactions.

3.2.1. Divergence of quantifications between scientists

A first type of divergence corresponds to interactions for which scientific quantifications do not always match one another despite extensive studies (interactions ②, ⑦ in Fig. 2 and Table 1).

As an example, the spontaneous intake of herbaceous stratum by chickens (interaction ⑦) covers a wide range of values in the scientific literature identified: from 0.7 g of dry matter (DM) forage /day/chicken (Jurjanz et al., 2015), to 72 g of DM forage/day/chicken (Horsted et al., 2007b). In reality, these differences mask the variability concerning experimental conditions, quantification methods and systems under study.

First, as regards experimental conditions, Horsted et al. (2007b) obtained huge differences in forage intake depending on the nature of the complementary chicken feed and pasture. For example, wheat-fed chickens each ingested around 19.6 g DM forage on grass/clover pastures, but up to 49.5 g DM forage on chicory pastures. Genotype, broiler age, time of day, climatic conditions (summer/winter) and type of ranges (grass or tree-covered) were also identified as factors likely to make daily forage intake vary as much as ten times the minimal intake (Almeida et al., 2012; Jurjanz et al., 2015).

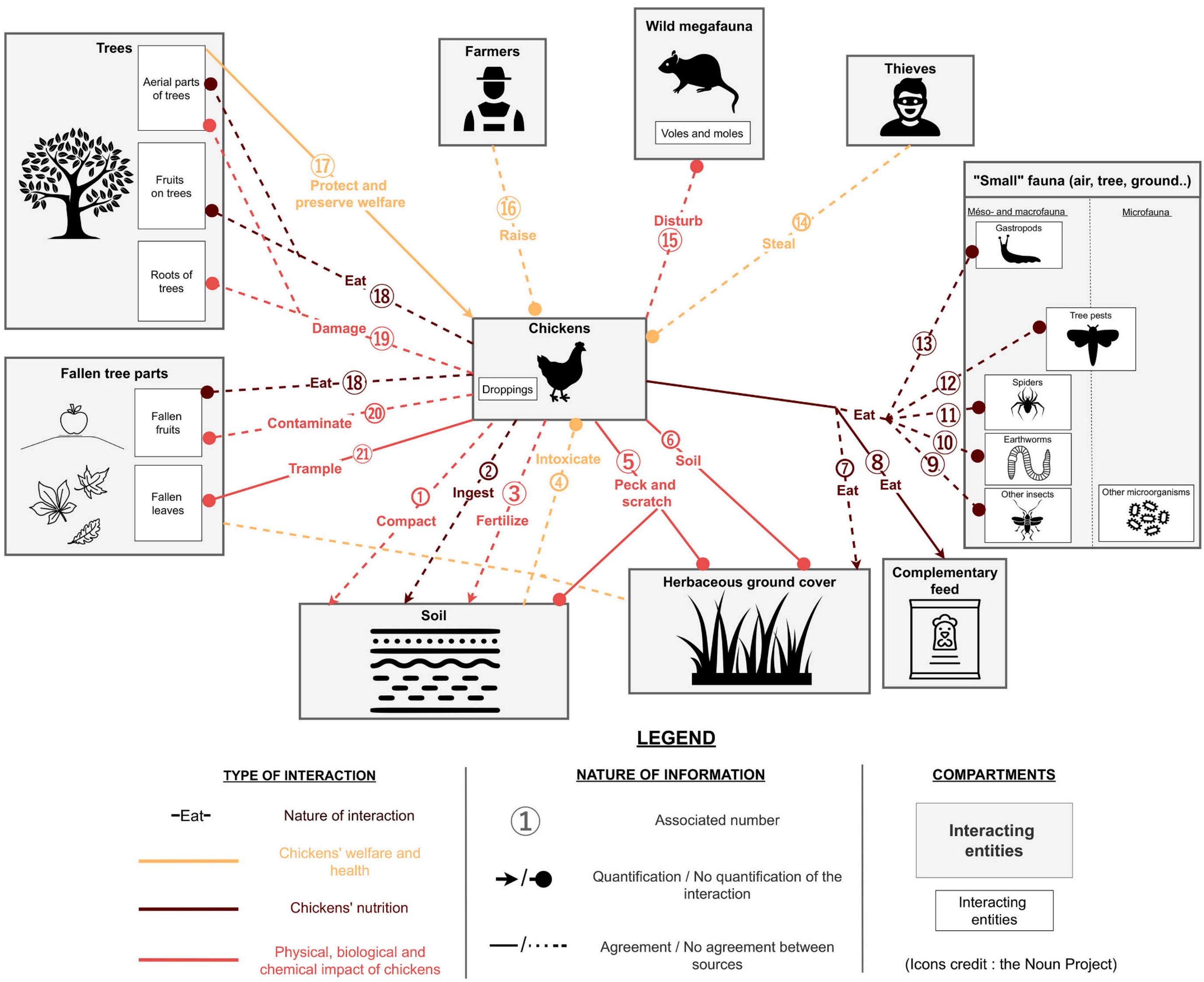

Fig. 2. Graphical state-of-the-art concerning interesting interactions in a chicken-pastured orchard. Interactions are categorised into three groups with arrows coloured accordingly: chicken welfare and health (orange); chicken nutrition (dark red); and the impacts of chickens on the rest of the system (light red). The existence of quantitative data in the literature is represented by the way the line ends: pointed if quantitative data exist; rounded otherwise. The consistency between sources is represented with the type of line for the arrow: solid in the case of relative agreement; dotted otherwise. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Table 1
Scientific references and testimonies associated with the interactions represented in Fig. 2.

Compartment [a]	Interaction [a]	Precisions on interaction	Scientific references	Farmers' testimonies [b]
Soil	① Physical impact of chickens on soil structure	Bulk density evaluation	Glatz et al., 2005a; Hilimire et al., 2013; Liu et al., 2013; Miao et al., 2005; Su et al., 2018; Xu et al., 2014	FI1, FV2b, FI4, FI5
	② Evaluation of soil intake	No quantification	Almeida et al., 2012; Antell and Ciszuk, 2006	No data
		Partial intake quantification (through crop content)	Amaka Lomu et al., 2004; Horsted et al., 2007b; Horsted and Hermansen, 2007	No data
		Daily intake quantification	Jurjanz et al., 2015	No data
	③ Chemical enrichment of the range by chickens, notably by droppings	Integration of chickens with trees	Clark and Gage, 1997; Gai et al., 2021; Stadig et al., 2018	FI1, FV1, FV2a, FV2b, FI3, FI6, FI7, GL1, GL2, GL7, GL8, V1, V3, SA2
		Integration of chickens with crops or valued pastures	Glatz et al., 2005a, 2005b; Hilimire et al., 2013; Liu et al., 2013; Miao et al., 2005; Skřivan et al., 2015; Su et al., 2018; Xu et al., 2014; Yu et al., 2020; Zhang et al., 2020	No data
		"Classical" chicken range	Dekker et al., 2012; Maurer et al., 2013; Wiedemann et al., 2018	No data
Soil, herbaceous ground cover, fallen leaves	④ Intoxication of chickens	By general chemicals (dioxins, furans, DDT, etc.)	Bouwman et al., 2015; Covaci et al., 2009; Hsu et al., 2010; Kudryavtseva et al., 2020; Lin et al., 2012; Piskorska-Pliszczynska et al., 2014; Polder et al., 2016; Stephens et al., 1995; Strankowski and Stanley, 1981; Van Overmeire et al., 2009; Waegeneers et al., 2009; Zafeiraki et al., 2016	No data
		Questions about orchard treatments on chickens	No data	FV2a, FV2b, FI4
Herbaceous ground cover	ⓦ Damage (without specifying the mechanisms)	Impact on vegetation biomass or species diversity of chickens	Almeida et al., 2012; Clark et al., 1995; Cosentino, 2020; Cosentino et al., 2020; Glatz et al., 2005a, 2005b; Horsted et al., 2006; Jones et al., 2007; Miao et al., 2005; Skřivan et al., 2015; Westaway et al., 2018; Xu et al., 2014; Yu et al., 2020	FV1, FV2a, FV2b, FI1, FI2, FI4, FI5, FI6, FI7, FI8, GL3, GL4, GL8, GL9, GL10, V1, V2, V3, SA1, SA2
	⑥ Damage due to soiling	Estimation of amount of droppings in different zones of the range	Lolli et al., 2019	No data
	⑦ Damage due to chicken intake	No quantification	Clark and Gage, 1996; Mayton et al., 1945	FV1, FV2a, FI1, FI2, FI5, V1, V2, GL10
		Quantification using the sward cutting technique	Dal Bosco et al., 2014; Mugnai et al., 2014; Rivera-Ferre et al., 2007	
		Quantification using dissection (crop, gizzard)	Abouelezz et al., 2013; Almeida et al., 2012; Amaka Lomu et al., 2004; Antell and Ciszuk, 2006; Horsted et al., 2007b; Lorenz et al., 2013; Ponte et al., 2008b	
		Quantification using physico-chemical analysis	Horsted et al., 2007a; Jurjanz et al., 2015; Singh et al., 2016; Skřivan and Englmaierová, 2014	
Soil and herbaceous ground cover	⑤ Damage caused by pecking and scratching	Scales of sward degradation	Breitsameter et al., 2014	FV1, FV2a, FV2c, FI2, FI4, GL6, GL7, V2, SA2
		Ethology studies (behavioural time budget)	Abouelezz et al., 2014; Amaka Lomu et al., 2004; Breitsameter et al., 2014; Chielo et al., 2016; Kruschwitz et al., 2008; Larsen et al., 2017; Mayton et al., 1945; Phillips et al., 2020; Phillips and Heins, 2021; Zeltner and Hirt, 2008	
Complementary feed	⑧ Evaluation of chicken intake	Quantification of spontaneous intake in free-range contexts	Abouelezz et al., 2013; Almeida et al., 2012; Antell and Ciszuk, 2006; Dal Bosco et al., 2014, 2010; Fanatico et al., 2013; Hammershøj and Steenfeldt, 2012; Hermansen et al., 2004; Horsted et al., 2006; Horsted and Hermansen, 2007; Ipek and Sozcu, 2017; Jurjanz et al., 2015; Lorenz et al., 2013; Meng et al., 2016; Mugnai et al., 2014; Ponte et al., 2008a, 2008b; Rivera-Ferre et al., 2007; Singh et al., 2017; Skřivan et al., 2015; Yu et al., 2020	FV1, FV2a, FV2b, FI2, FI3, FI6, FI8, GL1, GL3, GL4, GL5, GL9, SA2
Small fauna	ⓨ General impact on populations (no mechanisms studied)	Gastropods	Glatz et al., 2005b	No data
		Tree pests	Clark and Gage, 1996	FV1, FV2b, FI1, FI2, FI3, FI4, FI5, FI8, GL1, GL2, GL9, V2, V3, SA1, SA2
		Spiders	Clark and Gage, 1997	No data
		Earthworms	No data	
		Other pests	Phillips et al., 2020; Sun et al., 2014; Xu et al., 2014	No data
		Insects (beside pests)	Clark and Gage, 1997	GL2
	Presence of small fauna in the diet (⑨, ⑩, ⑪, ⑫, ⑬)	Gastropods	Abouelezz et al., 2013; Clark and Gage, 1996	No data
		Tree pests	Clark and Gage, 1996	FI1, FI3, FV1, FV2b, GL1, GL3, GL7, V2, V3
		Spiders	Clark and Gage, 1996)	No data
		Earthworms		No data

(continued on next page)

Table 1 (*continued*)

Compartment [a]	Interaction [a]	Precisions on interaction	Scientific references	Farmers' testimonies [b]
		Insects (beside pests)	Almeida et al., 2012; Amaka Lomu et al., 2004; Clark and Gage, 1996; Horsted et al., 2007b; Horsted and Hermansen, 2007 Abouelezz et al., 2013; Almeida et al., 2012; Amaka Lomu et al., 2004; Clark and Gage, 1996; Horsted et al., 2007b; Horsted and Hermansen, 2007; Lorenz et al., 2013; Phillips et al., 2020; Singh et al., 2017	FI1, FI2, FI3, GL1, GL7, V1, V2, V3
Thieves	⑭ Thefts of chickens	Farmers affected differently	No data	FV1, FI1, FI2, FI3, FI4, FI5, FI6, FI7, FI8
Moles and voles	⑮ Impact on mole or vole populations	Contrasted farmers' observations	No data	FV2a, FI3, GL9
Farmer	⑯ Farmers' management of chicken husbandry	Work organisation in chicken-pastured orchards	Elkhoraibi et al., 2017; García de Jalón et al., 2018; Rocchi et al., 2019; Röhrig et al., 2020a, 2020b	FV2b, FI1, FI2, FI4, FI5, FI6, FI7, FI8, GL1, GL3, GL8,
		Environmental or economic evaluation of chicken-pastured orchards	García de Jalón et al., 2018; Paolotti et al., 2016; Qingyan et al., 2012; Rocchi et al., 2019; Röhrig et al., 2020a, 2020b; Zhang et al., 2013	FV1, FV2a, FV2b, FI1, FI2, FI4, FI5, FI6, FI8, GL1, GL3, GL8, GL9
		Work organisation in chicken husbandry (besides chicken-pastured orchards)	Brannan and Anderson, 2021; Castellini et al., 2012; Hilimire, 2012; Xu et al., 2014	No data
		Environmental or economic evaluation of chicken husbandry (besides chicken-pastured orchards)	Brannan and Anderson, 2021; Castellini et al., 2012; Hilimire, 2012; Liu et al., 2013; Martinelli et al., 2020; Xu et al., 2014; Yates et al., 2006; Zhang et al., 2020	No data
Trees	⑰ Welfare and protection by trees for chickens	Welfare (without specifying mechanisms)	Abouelezz et al., 2014; Larsen et al., 2017	FI1, FI5, FI6, FI7, FI8, V4, GL8, SA2
		Protection against meteorological conditions	Dal Bosco et al., 2014; Jones et al., 2007; Nagle and Glatz, 2012; Stadig et al., 2017; Zeltner and Hirt, 2008	
		Protection against predators	Bestman and Bikker-Ouwejan, 2020	
	⑱ Chickens appetence for fruits and leaves on trees and on the ground	No quantification (observations by farmers)	No data	FV1, FI1, FI2, FI3, V1, V4, GL10
	⑲ Damage to tree roots, trunk and branches	No quantification of damage	Jones et al., 2007; Larsen et al., 2017; Stadig et al., 2018; Yu et al., 2020	FV2a, FI2, FI4, GL8, GL10
Fallen tree parts	⑳ Biological contamination of fallen fruits by chickens	Evaluation of a potential risk	Theofel et al., 2020	GL10
	㉑ Mechanical effects on leaves by trampling	Degradation of leaves due to trampling effect	Item reported in the grey literature (Bestman, 2017; Timmermans and Bestman, 2016)	No data

Notes

[a] Interaction numbers and compartment names (column 2) correspond to Fig. 2. ⓧ, ⓨ correspond to interesting interactions for fruit growers that cannot appear in Fig. 2 because the mechanisms were not specified.

[b] Letters reflect the origin of the testimony: Farmers' interviews (FI), Farm visit (FV), Video (V), Grey Literature (GL), SA (Scientific Article). More precisions can be found in Appendix A. Each number indicates one farmer. Testimonies have been aggregated to correspond to the interaction level (column 2) and not to the precision level (column 3), except when it was relevant with respect to farmers' testimonies (③, ④, ⓨ, ⑨, ⑩, ⑪, ⑫, ⑬, ⑯).

Second, values of forage intakes vary because quantification methods differ and do not consider the same bias (see Table 1-Interaction ⑦). Three collected studies (Dal Bosco et al., 2014; Mugnai et al., 2014; Rivera-Ferre et al., 2007) relied on the sward cutting method, which underestimates trampling by chickens (Jurjanz et al., 2015). Eight other studies (Abouelezz et al., 2013; Almeida et al., 2012; Amaka Lomu et al., 2004; Antell and Ciszuk, 2006; Horsted et al., 2007b; Lorenz et al., 2013; Ponte et al., 2008b) used dissection (crop and/or gizzards) combined with an equation from Antell and Ciszuk (2006) to calculate daily intake. One drawback of this method is that it is not repeatable on the same individual (Singh et al., 2016). More recently, studies focused on n-alkane analysis, which seems reliable to estimate forage intake but is harder to conduct (Jurjanz et al., 2015; Singh et al., 2016).

Third, comparison is also difficult between disparate experimental systems *(*Table 2*)* whose diversity reflects the heterogeneity of chicken rearing conditions in real systems.

Except for one reference (Dal Bosco et al., 2014), all experiments were conducted on experimental farms at research centres, in a diversity of countries and climates (Denmark, Australia, Mexico, Sweden, Italy, Portugal, the Netherlands, France, Czech Republic).

As is the case with weed intake, quantifications of soil (interaction ②) vary between scientific studies.

3.2.2. *Divergence of interest within and between scientists and farmers*

The interactions presented in our model also differ by the level of interest they generate for scientists and farmers. More specifically, we identified two types of scientific knowledge gaps: the first concerning mechanisms and the second concerning systems in general.

3.2.2.1. Concerning mechanisms. We first identified some knowledge gaps concerning basic mechanisms of interactions in this agroecosystem, which are mainly detrimental for scientific purposes (interactions ⑤ and ⑥ in Fig. 2 and Table 1). Although studies concerning the degradation of herbaceous ground cover by chickens do exist (ⓧ in Table 1), studies about precise mechanisms are rare and especially concern the quantification of the physical impact of chickens by pecking and scratching or soiling. Except for one study (Breitsameter et al., 2014), pecking and scratching the ground is principally studied through the prism of

Table 2
Diversity of experimental systems used in scientific articles about interaction ⑦.

System characteristics	Examples of modality	Examples in the literature
Outdoor stocking densities	110 chickens/ha	Amaka Lomu et al., 2004
	2500 chickens/ha	Almeida et al., 2012; Dal Bosco et al., 2014; Lorenz et al., 2013; Rivera-Ferre et al., 2007
	≈ 40,000 chickens/ha	Ponte et al., 2008b
Access to range	Restricted in space with floorless portable metal outdoor pens	Ponte et al., 2008a
	Restricted in time	Singh et al., 2016
Type of range	Spontaneous pasture	Abouelezz et al., 2013; Lorenz et al., 2013; Singh et al., 2016
	Sown pastures	Horsted et al., 2007a; Rivera-Ferre et al., 2007
Shelters on range	No shelter	Almeida et al., 2012; Horsted et al., 2007b; Skřivan and Englmaierová, 2014
	Artificial shelter	Amaka Lomu et al., 2004
	Trees and bushes	Clark and Gage, 1996; Dal Bosco et al., 2014; Jurjanz et al., 2015; Mugnai et al., 2014

ethology in the other studies (see Table 1). However, data concerning time spent by chickens pecking and scratching are not sufficient to construct scientific mechanistic models of the impact of chickens on this agroecosystem. Evaluation of pecking and scratching in terms of weed biomass or its effect on the herbaceous stratum structure would, for example, be necessary. This lack of knowledge is not only deleterious for scientific purposes but also for the practitioners insofar as this knowledge is needed to help them design and/or manage innovative agricultural systems. Indeed, 20 farmers declared in their testimonies to be highly concerned by the effects of chickens on grass cover, and some of them reported the lack of information concerning the appropriate chicken stocking density or the appropriate dynamic management necessary to preserve the quality of the herbaceous stratum.

Similarly, we identified mechanisms observed by farmers in the field that have never or only rarely been studied by scientists. The mechanisms concerned by this lack are related to the impact of chickens on fauna (⑨, ⑩, ⑪, ⑫, ⑬ in Fig. 2 and Table 1). For example, the introduction of chickens into orchards is often seen by farmers as a way to control crop pests. Among the set of collected testimonies, 11 farmers reported regulation effects on apple sawfly populations *(Hoplocampa testudinea)* (GL2, GL9), apple blossom weevil *(Anthonomus pomorum)* (V3, FV2b, GL9), codling moth (*Cydia pomonella*) (FV2b, GL2, FI2), spotted wing drosophila *(Drosophila suzukii)* (FV1), olive fly *(Bactrocera oleae)* (GL1), peach fruit fly *(Bactroceraspp.zonata)* (FI1), and a diversity of other pests (V4, FI3, FI4). Two other farmers did not observe any effect on pests but mentioned that pest pressure in their orchards was originally not very high (FI5, FI8). Such observations have also been made in contexts other than French chicken-pastured orchards. A survey conducted among 18 Californian pastured-chicken producers revealed that 17% of them cited chickens as a way to control pests, and that for 6% of them, pest control was even their initial motivation to raise pastured poultry (Hilimire, 2012). In another survey concerning nine mixed farms in Italy, the three farmers who owned poultry-pastured orchards observed reduced tree pests/diseases compared to before the chickens were introduced (Röhrig et al., 2020a). The main mechanism of regulation mentioned on nine of our testimonies (FI1, FI3, FV1, FV2b, GL1, GL3, GL7, V2, V3) is ingestion of tree pests by chickens, directly or through the intake of damaged fruits.

Nevertheless, despite farmers' interest for this ecosystem service, scientific concern about it is low and the results are incomplete. We collected only one scientific article (Clark and Gage, 1996), one conference proceeding (Pedersen et al., 2004) and two grey literature articles (Hilaire et al., 2001; Lavigne and Lavigne, 2013) that studied the regulation of fruit tree pests by chickens. For all of them, the results were mitigated and the underlying mechanisms were unclear or not studied. For example, Pedersen et al. (2004) compared damage on apples and pears caused by several pests, with or without broilers under trees, but found significant effects of broilers only for capsid bug and pear midge. That may be one of the reasons for such apparent disinterest: unclear or unstable results are difficult to publish.

In addition to this direct impact, chickens also indirectly impact pest regulation by impacting the dynamics of the whole agroecosystem, including auxiliary fauna (earthworms, spiders and other insects). Even though we listed a certain number of articles dealing with the impacts on fauna (interactions ⑨, ⑩, ⑪, ⑫ in Fig. 2 and Table 1), very few authors carried out sufficient in-depth analyses to draw significant conclusions. For instance, among all the listed studies dealing with the impact on insects (beside pests) or ingestion of insects (besides pests), only two (Clark and Gage, 1996, 1997) actually gave the names of the insect species impacted by chickens. All the other studies just used the term insects in general, neglecting the diversity of species and functions. Regardless, in all of those cases, scientific evidence would be valuable in order to (i) confirm the robustness of farmers' observations (FI1, FI2, FI3, GL1, GL7, V1, V2, V3), and (ii) identify levers to help farmers to manage the association.

3.2.2.2. Concerning systems. Beyond knowledge gaps concerning specific mechanisms, chicken-pastured orchards are under-studied systems: only 17 articles among the whole list of articles concern chicken-pastured orchards. For some interactions (chicken/soil or chicken/herbaceous stratum), extrapolations can be made through the study of free-range chicken systems. However, for many of them, issues differ between free-range and chicken-pastured orchards. Hence, the questions of fertilisation effects ③, intoxication of chickens by chemicals ④, and the work organisation of farmers ⑯ have been studied but not often in the context of chicken-pastured orchards, despite the specific issues it raises (the benefit of this fertilisation for fruit trees, the impact of fruit tree treatments on chickens, and the management of a double activity by fruit growers, respectively).

These lacks can be illustrated through the example of work management (interaction ⑯), which represents a great challenge in chicken-pastured orchards. Indeed, several farmers' testimonies highlighted difficulties for farmers confronted with heavier workloads, more time spent on the farm due to animal presence, and conflicts in terms of space and time between the two activities (FI4, FI5, FI6, FI7, FI8, FV2b, GL3). More precisely, the long-term sustainability of farms depends on the compatibility and even complementarity of both activities. Despite this, we identified only five articles that include a social perspective and not just economic or environmental approaches to evaluate the sustainability of chicken-pastured orchards (Elkhoraibi et al., 2017; García de Jalón et al., 2018; Rocchi et al., 2019; Röhrig et al., 2020a, 2020b). Moreover, these studies focus on slightly different objects than those we identified in the testimonies. Elkhoraibi et al. (2017) identified major challenges in poultry farming, but from US farmers who were initially chicken producers. As for Rocchi et al. (2019), the social evaluation was limited to labour safety, animal welfare and farm integration in the landscape. However, Röhrig et al. (2020a, 2020b) and García de Jalón et al. (2018) quickly examined trade-offs related to tree/chicken associations. Röhrig et al. (2020a) raises the question of conflicts between both activities, the extreme complexity of management, and the need for additional external work (Röhrig et al., 2020b). García de Jalón et al. (2018) also put forward these issues of management complexity and labour burden in the perception of agroforestry farmers. However, this approach does not specifically focus on chicken-pastured orchards and does not make it possible to draw conclusions about this specific system. Hence, there is a need for quantitative approaches to study trade-offs between both activities and the organisation of choices and adaptations made by farmers.

3.2.3. *Strong divergence of observations between farmers that cannot be explained by scientific literature*

The last type of divergence that we identified in the data collected concerns strong discrepancies between the farmers themselves, with farmers testifying to the existence of interactions and others negating it (interactions ①, ⑮, ⑱, ⑲ in Fig. 2 and Table 1). For instance, two farmers (FV2a, GL8) considered and observed that chickens potentially damage trees (trunks, roots or branches), whereas four others did not. Although the differences in farm situations (system, location, etc.) and observation bias could explain such discrepancies, no clear conclusion can be drawn.

Moreover, these interactions seem crucial for fruit growers: they are mentioned by a certain number of farmers (five testimonies for ①, four testimonies for ⑮, eight testimonies for ⑱, and eight testimonies for ⑲), and they concern major general challenges in orchards (integrity of trees and fruits, preservation of soil quality and management of rodents). For example, the issues of chickens eating fruits on trees and on the ground ⑱ or damaging the trees ⑲ can endanger the most fundamental activity of fruit growers and lead them to give up this association.

In all those interactions, referring to scientific literature does not make it possible to settle the question, either because scientific results are not conclusive ① or because literature is deeply lacking (⑮, ⑱, ⑲). Concerning damage to trees (interaction ⑲), four scientific articles mention the impact of chickens, but the trees correspond to coppice willows (Stadig et al., 2018), woodland (Jones et al., 2007), small trees on a natural meadow (Yu et al., 2020) and wooded areas in poultry ranges (Larsen et al., 2017) which deeply differ from orchard. Moreover, except for Jones et al. (2007), the absence of damage is stated but not quantified or tested in a dedicated experiment. Precisely, in those cases, science would be necessary to help settle a debate between practitioners. There is thus a major challenge to study these interactions in order to find the eventual management levers necessary to propagate the practice of association.

4. Discussion

The results are discussed according to four perspectives. First, we present a simplified heuristic model that highlights key interactions. Second, we identify some methodological limitations of our approach. Third, we show the scientific and operational interests in building a model that compares scientific and farmers' knowledge and, last, we call for a systemic approach that reconnects animal and plant productions.

4.1. *Key interactions in the heuristic model*

To summarise the conclusions of the literature review based on the heuristic model, we propose here a simplified version of the model (Fig. 3). This representation highlights the key interactions considered to be central in chicken-pastured orchards and for which information is lacking.

These interactions can be classified into three categories: interactions concerning (i) expected benefits of the chicken-tree association; (ii) potential drawbacks of the association; and (iii) general management of the association. We claim that these interactions should constitute priority research questions because their knowledge is essential to design efficient chicken-pastured orchards.

Expected benefits of the association have been reported by several farmers, but in order for these practices to be disseminated, proof should be reinforced to convince new audiences. Hence, the potential regulation and sanitation effects of chickens on the orchard (on tree pests, on moles and voles, and on fallen tree parts) need to be confirmed by scientific approaches and quantified. The other beneficial effects (protection of chickens by trees and soil fertilisation) have been partly studied but the specificities of chicken-orchard associations (for example, fertilisation with regard to fruit tree needs) should be more precisely

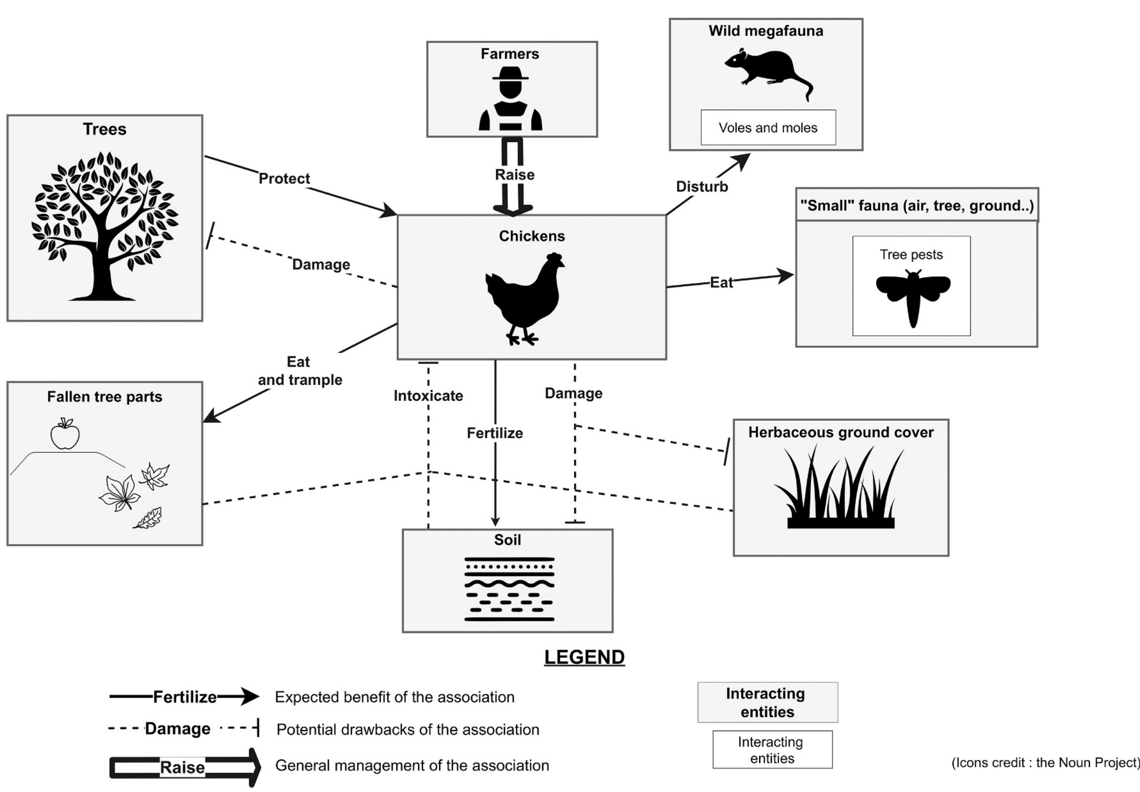

Fig. 3. Simplified heuristic model based on Fig. 1, presenting key interactions on which research questions should focus.

considered. Drawbacks of the association should also be more deeply studied in order to tackle farmers' challenges and to improve already-existing chicken-pastured orchards. Hence, the general damage of chickens on orchards is known, but quantification concerning the intensity of damage is often lacking. Similarly, studying potential intoxications of chickens by orchard treatments is all the more essential when considering a dissemination of these systems towards more treatment-intensive orchards. Finally, farmers' management of the association and their ways to deal with complex trade-offs between those benefits and drawbacks need to be assessed and considered. More broadly speaking, this topic could contribute and bring new perspectives to the study of diversified agroecosystems and their specificities in terms of management complexity.

4.2. Methodological limitations of our approach

In this review, we chose to orient our approach more specifically to help the action of fruit growers introducing chickens into orchards. Hence, to study these complex systems that involve a diversity of components in interaction, we centred our heuristic model on the chicken compartment to highlight how their introduction could impact the existing tree system. Consequently, we only represented direct interactions with chickens and not interactions between other compartments, whereas, in reality, multiple interactions and retroactions do exist, for example, the structure and composition of the herbaceous stratum's impact on arthropod diversity (Demestihas et al., 2017). Indeed, in contexts other than orchards, such as pastures, sheep and cattle grazing is known to indirectly impact this species diversity (Dennis et al., 2001). These indirect effects are multiple and should be kept in mind when designing a chicken-pastured orchard.

The previous global analysis highlighted several gaps in the scientific literature concerning chicken-pastured orchards. We counted only 17 articles out of 195 collected dealing with those systems. Hence, to obtain a sufficient number of scientific articles, we chose to broaden our search to free-range chicken husbandry. These extrapolations mainly concerned interactions between chickens and the herbaceous stratum, the soil or insects. Retrospectively, these extrapolations were interesting to obtain some range of values concerning crucial mechanisms for fruit growers, such as the ingestion of forage by chickens and the fertilisation potential of droppings. However, free-range systems deeply differ from pastured orchards. For example, the density of chickens is often much higher in free-range systems than in pastured orchards. Direct translations of the knowledge developed on free-range systems to pastured orchards are thus not always possible. Moreover, even on free-range systems, the literature collected was so disparate that even general findings about interactions were difficult to obtain and, as a consequence, interactions could only be quantified for six interactions out of 21.

We also chose not to include grey literature in the literature panorama because of its heterogeneity and of the difficulty to perform an exhaustive search using keywords. Nevertheless, recent graduate theses and conference proceedings are useful since they give a precise idea of current research themes. Even though it is not included in the review, grey literature (see Appendix A) highlights the fact that research questions on this subject evolve very quickly, which demonstrates a growing interest of the scientific community in chicken-pastured orchards.

4.3. A model that compares scientific and farmers' knowledge to reveal knowledge gaps

To study complex agroecological systems, it is often necessary to combine a plurality of knowledge and, notably, to integrate farmers' points of view (Hazard et al., 2018). Hence, scientific and farmers' knowledge can interact in different ways. In our approach, farmers' knowledge was useful to complete the list of interactions and to draw a global image of the system. Reciprocally, scientific approaches made it possible to reveal and specify underlying mechanisms when farmers only observe general impacts. In other studies, some authors noted that farmers expect scientific knowledge to answer their questions or to legitimise the practical choices they made (Hazard et al., 2018). In our case, such an expectation could not be fulfilled by this incomplete scientific literature, which is, in addition, deeply disconnected from farmers' needs. However, comparing scientific state-of-the-art to field situations allowed us to identify crucial knowledge gaps and to determine the reasons for such a situation.

Different reasons could indeed explain these huge knowledge gaps. First, chicken-pastured orchards and, more generally, grazed or pastured orchards, are minority agricultural practices: according to den Herder et al. (2017), around 5% of permanent crops in the European Union were being grazed in 2012. Second, even though grazing animals under trees is not new (Coulon et al., 2000), the reintroduction of animals into modern orchards, particularly poultry, requires to break the frontier that still persists in modernised agriculture between animal and plant production. This disconnection on farms also exists in the scientific research that is compartmentalised and reductionist. Indeed, because of their hybrid form, pastured orchards do not fit the classical conceptual frameworks of two disconnected disciplines, agronomy and animal science: for agronomy, because of the introduction of the husbandry component into the system, and for animal science, because animal products are not the principal target in these systems. This statement might explain why we observed a greater focus on classical husbandry interactions (e.g., complementary feed intake, meat and egg contamination by dioxins) by the animal sciences, which neglect to study other interactions in terms of ecosystem services provided by chickens.

4.4. Perspectives for systemic approaches

However, agroecology calls for the reconnexion between animals and crops (Altieri, 2002) to close nutrient cycles or to foster biological regulation. On the basis of these statements, we suggest that a new analytical framework needs to be considered to study interactions between animal and plant productions. This need is also reinforced by the societal and environmental issues that arise, for example, because of the disconnection between animal and plant productions, such as the deterioration of water quality (Garnier et al., 2016) and the impact on biodiversity and climate in relation to animal feed production and export (Naylor, 2005). Hence, complex and multiscale integrated systems force scientific questions and approaches to evolve towards more interdisciplinary, systemic and action-oriented approaches. Research on crop-livestock systems is an example of a research domain that successfully adopted more systemic and interdisciplinary approaches to tackle those challenges (Martin et al., 2016). To our knowledge, our study is, in a similar way, the first attempt to give a broad and systemic view on chicken-pastured orchards. Through our heuristic model, we invite agronomists, ecologists, zootechnicians and others to tackle together these knowledge gaps with new common research methodologies. Moreover, we expect that the simple global representation we built could serve as a grid to read other articles dealing with ecosystem services and interactions in traditional orchards using another point of view. Indeed, it would be interesting to cross this model with extensive studies on biodiversity dynamics in orchards to make hypotheses on the indirect impacts of chicken introduction into orchards, in order to pave the way for other research questions, for example, whether chickens impact the auxiliary fauna and if so, to what extent and with what consequences on fruit production.

In order to produce action-oriented knowledge, research questions also need to evolve through comparison with the field. Just as we did, other studies on agroecological practices pointed out some discrepancies between scientific knowledge and crucial needs for farmers, notably concerning practical management issues and ecosystem services (Brodt et al., 2020; Ditzler et al., 2021). Yet, from an operational point of view, including farmers' points of view, it is necessary to design and manage innovative agroecological systems adapted to farmers' constraints (Demestihas et al., 2017; Fagerholm et al., 2016). Concretely, our model, which already includes empirical knowledge, could serve as a discussion tool that farmers could compare to their own local situations. This model could also be mobilised as an intermediary object for serious games in workshops with practitioners to make them work on the design of diversified systems that associate poultry and fruit trees (Duru et al., 2015).

5. Conclusion

Based on a literature review, we proposed a systemic heuristic model to represent the functioning of chicken-pastured orchards, and we compared the scientific state-of-the-art to farmers' needs. Chicken-pastured orchards are complex agroecosystems that have rarely been studied from a global perspective, and our study highlights several divergences of points of view within and between scientists and fruit growers. This review revealed important knowledge gaps, pointing out that research on these questions is not only compartmentalised, but also disconnected from farmers' needs. Interdisciplinary and systemic approaches are thus needed to promote the development of these innovative agroecological systems, which have also grown in popularity among consumers. A deep reorientation of scientific questions as well as political policies concerning integrated animal/plant systems is all the more urgent since animal husbandry and fruit production are both facing huge socio-environmental challenges that will require a rapid acceleration of the agroecological transition at a more global scale.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.agsy.2021.103335.

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