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

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### ► To cite this version:

Sara Bosshardt, Rodolphe Sabatier, Arnaud Dufils, Mireille Navarrete. Changing perspectives on chicken-pastured orchards for action: A review based on a heuristic model. *Agricultural Systems*, 2023, 196, 10.1016/j.agsy.2021.103335 . hal-03513287v1

**HAL Id: hal-03513287**

**<https://hal.inrae.fr/hal-03513287v1>**

Submitted on 8 Jan 2024 (v1), last revised 9 Feb 2024 (v2)

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2                           review based on a heuristic model

3

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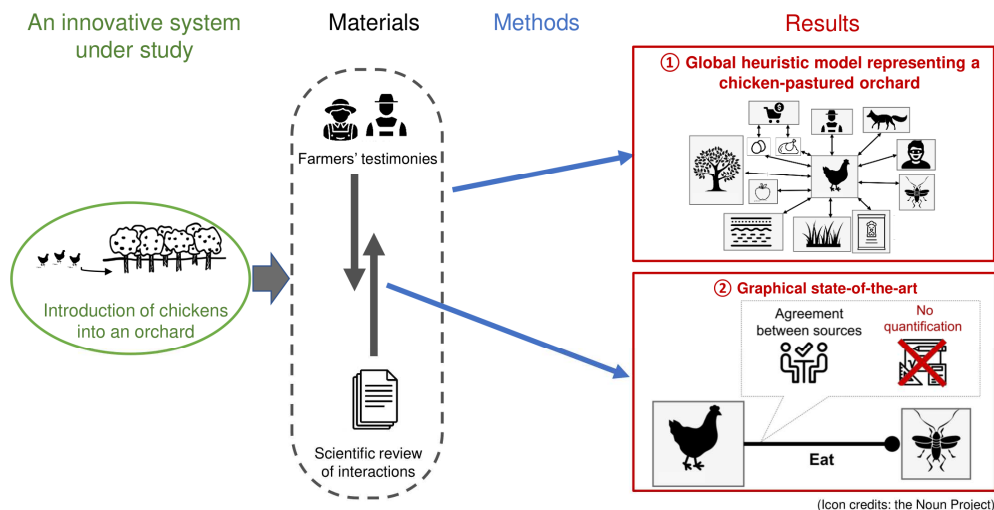
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## 10 Highlights

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

## 21 Graphical Abstract



22

## 23 Abstract

### 24 Context

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

## 34 **Objective**

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

## 38 **Methods**

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

## 43 **Results and conclusion**

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

## 52 **Significance**

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

## 57 **Keywords**

58 poultry; agroforestry; fruit grower; diversification; agroecology; ecosystem services

## 59 **1. Introduction**

60 Fruit growers in Europe are confronted with rising agronomic, economic and social challenges at  
61 this time. Moreover, these challenges are somewhat contradictory like, for example, the fact that  
62 consumers expect fruit growers to produce fruits using environmentally-friendly practices and, at the  
63 same time, demand higher quality fruits (Alaphilippe et al., 2021). Fruit production is also becoming  
64 more vulnerable to the consequences of climate change, such as the potential emergence of tree

65 pests (Gomez-Zavaglia et al., 2020) and the shifts in plant phenological traits (Leolini et al., 2018;  
66 Vanalli et al., 2021) that lead to huge production losses (Agreste, 2021; Hostalnou, 2021). Recent late  
67 frosts in spring 2021 wiped out future fruit harvests in France and forced the French government to  
68 declare the event as an “agricultural disaster” in order to compensate fruit growers (France Relance,  
69 2021).

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

79 Two different ways of orchard diversification are thus possible: intercropping and the  
80 introduction of animals. Regarding animals, different species are likely to be introduced: cattle,  
81 horse, sheep, chicken, geese, etc. (Brodt et al., 2020; López-Sánchez et al., 2020; Massaccesi et al.,  
82 2019; Orefice et al., 2017; Pantera et al., 2018). In contrast with understorey crops, the presence of  
83 animals in orchards seems less spatially constrained. Animals provide additional services in response  
84 to the diverse challenges of fruit production (Brodt et al., 2020; Corroyer, 2017; Coulon et al., 2000),  
85 such as fertilisation (Röhrig et al., 2020a; Soudet et al., 2021), weed control (Lavigne and Lavigne,  
86 2013) and pest control (Clark and Gage, 1996; Pedersen et al., 2004). In parallel, orchards also offer  
87 partial responses to vital current issues in animal husbandry, such as animal welfare (García de Jalón  
88 et al., 2018), the management of farm effluents (Billen et al., 2021; Brodt et al., 2020) and the feed  
89 costs for animals (Meng et al., 2016; Röhrig et al., 2020a).

90 The advantages and drawbacks of this association strongly depend on the animal species.  
91 Compared to livestock, poultry husbandry seems to offer more flexibility to farmers, notably through  
92 an easy valorisation of the products (eggs and meat) and limited supervision, notably to avoid  
93 damage to trees (Cazaux, 2015; López-Sánchez et al., 2020). Hence, poultry represents an interesting  
94 choice for fruit growers who are usually not experienced in animal husbandry because investments in  
95 terms of money, time and knowledge are limited compared to livestock. The rising number of fruit  
96 growers currently attracted to this practice obviously reflects the interest of fruit growers in these  
97 poultry/orchard associations. More precisely, chicken (*Gallus gallus domesticus*), which designates

98 both laying hens and broilers, is the most common poultry subspecies raised by a large number of  
99 fruit growers and that we have chosen to focus on in this article. It should be noted that chicken-  
100 pastured orchards must be distinguished from silvopastoralism with poultry, also referred to as  
101 silvopoultry, in which the types of trees (timber, fruit production, etc.) and poultry (chicken, geese,  
102 ducks, etc.) are not specified. They must also be distinguished from what we refer to as free-range  
103 chickens in wooded ranges, in which animal husbandry is the main activity on the farm. As defined,  
104 chicken-pastured orchards correspond to one type of silvopoultry system, and despite a husbandry  
105 component, the main activity is fruit production. In addition, concerning the use of semantics, the  
106 term “pastured” seems more adapted to chicken behaviour than “grazed”, which refers more to  
107 systems that include sheep or other livestock.

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

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

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

131 In this article, we first describe our methods (Section 1). Then, in Section 2, we present a  
132 simplified heuristic model of a chicken-pastured orchard based on a mental synthesis of information,  
133 and describe the dynamics involved. This representation is then refined and observed with a focus on  
134 the relative interest of research and farmers in each dimension of the system. Our results notably  
135 reveal several scientific gaps and a disconnection between scientific and fruit growers' concerns. This  
136 observation is finally discussed in Section 3 with a more global approach in order to identify the  
137 reasons for this situation, to draw a parallel with other domains and to develop research and  
138 operational perspectives about chicken-pastured orchards.

## 139 2. Materials and methods

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

### 144 2.1. Construction of a global heuristic model of the agroecosystem

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

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

164 2.2. Representing the state-of-the-art of some of the interactions

### 165 2.2.1. Selection of interesting interactions

166 Among all the interactions represented in the global model (*Figure 1*), we chose to focus more deeply  
167 on a restricted number of interactions that concern the sustainability of the association between  
168 chickens and orchards. More precisely, we selected all of the interactions emanating from the  
169 chicken compartment as being prone to impact fruit tree production (directly or indirectly). We also  
170 included other interactions that are liable to impact chicken sustainability in a way specific to  
171 orchards and that appeared to be significant according to farmers' testimonies, namely:

172 -the risks of chicken intoxication in a context of high pesticide use in orchards;

173 -the question of welfare and protection offered by trees to chickens;

174 -the question of work organisation for fruit growers who associate chickens with orchards.

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

### 177 2.2.2. Search of the scientific literature

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

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

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

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

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



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

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

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

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

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

### 213 **2.2.3. Obtaining farmers' testimonies**

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

### 224 **2.2.4. Identification of related information sources**

225 Precise examination of the literature and testimonies allowed us to improve our heuristic model and  
226 to link each article/testimony to the appropriate interactions in *Table 1*. Only primary articles in  
227 which some data were specifically acquired on this interaction (through experiments, field

228 observations, surveys, etc.) were included. Reviews and articles citing one interaction as a hypothesis  
229 were thus excluded.

### 230 **2.2.5. Representation of interactions and the nature of information**

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

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

### 240 **2.2.6. Comparison between interactions**

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

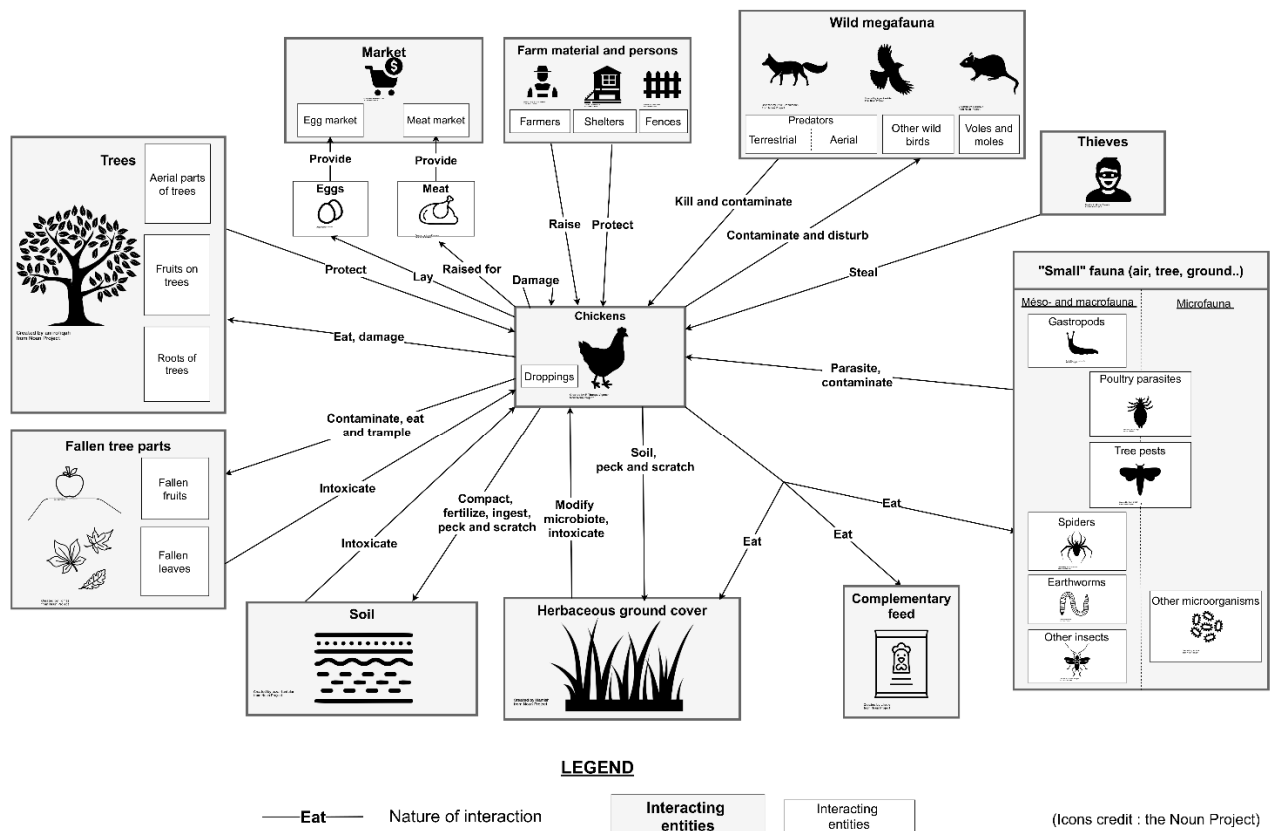
## 249 **3. Results**

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

### 254 **3.1. Nature and organisation of interactions in a chicken-pastured orchard**

255 In pastured orchards, three types of interactions were identified from the literature (*Figure 1*): (i)  
256 chickens interact directly with trees; but (ii) also interact with other biophysical components that  
257 may have an indirect impact on trees (the soil, the herbaceous ground cover, the fauna); (iii) on a  
258 broader spatial scale, there is an interaction between chickens and the socio-technical environment  
259 (farmers, farm equipment, marketing channels). Moreover, the presence of chickens involves the

260 inclusion of compartments (predators, rodents, thieves), considered as external disturbers of the  
 261 original “simple” orchard and which farmers have to deal with.



262  
 263 *Figure 1: Heuristic model of a chicken-pastured orchard. Only direct interactions linked to the chicken*  
 264 *compartment are represented. The chicken compartment is connected to other compartments*  
 265 *(represented by rectangles), with directed arrows. The nature of the interaction is given by verbs of*  
 266 *action.*

267 **3.1.1. Interactions with trees**

268 The association of chickens and trees results in some beneficial direct interactions. Trees buffer  
 269 meteorological conditions by creating a suitable microclimate that protects chickens against wind,  
 270 extreme temperature and sun (Jones et al., 2007). In return, chickens create a healthier telluric  
 271 environment for trees by cleaning tree residues (fallen leaves and fruits) (Timmermans and Bestman,  
 272 2016). However, this association is not always a win-win partnership. Chickens can also damage trees  
 273 and fruits (Hilaire et al., 2001), particularly by eating them, and contaminate fallen fruits as well  
 274 (Coisne, 2020). Correspondingly, feeding on fallen tree elements can result in a higher risk of  
 275 intoxication, particularly in the case of a chemically-treated orchard (ADABio, 2020).

### 276 **3.1.2. Interactions with the biophysical components of an orchard**

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

279 First of all, some elements from the agroecosystem represent complementary nutritional resources  
280 for chickens. Chickens naturally consume grass from the herbaceous stratum (Antell and Ciszuk,  
281 2006) and feed on different types of arthropods that live in the trees, the air and the herbaceous  
282 stratum (Clark and Gage, 1996). Depending on the intensity of ingestion and the nature of the  
283 arthropods impacted (tree pests, auxiliary fauna, etc.), chickens can improve or impair tree health  
284 (ADABio, 2020). Spontaneous intake of elements from the agroecosystem can also impact chicken  
285 health. Ground ingestion (Jurjanz et al., 2015), for example, is not considered as a source of  
286 nutriment and potentially limits the ingestion of other elements. Contaminated soil and herbaceous  
287 ground cover (resulting from orchard treatment, for example) can also result in some intoxication of  
288 chickens (Vries et al., 2006). To maintain chickens in a good health and at a sufficient production  
289 level, farmers complement this spontaneous intake with feed available in various forms (pellets,  
290 whole grains, etc.) (Bryden et al., 2021).

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

### 296 **3.1.3. Other global interactions**

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

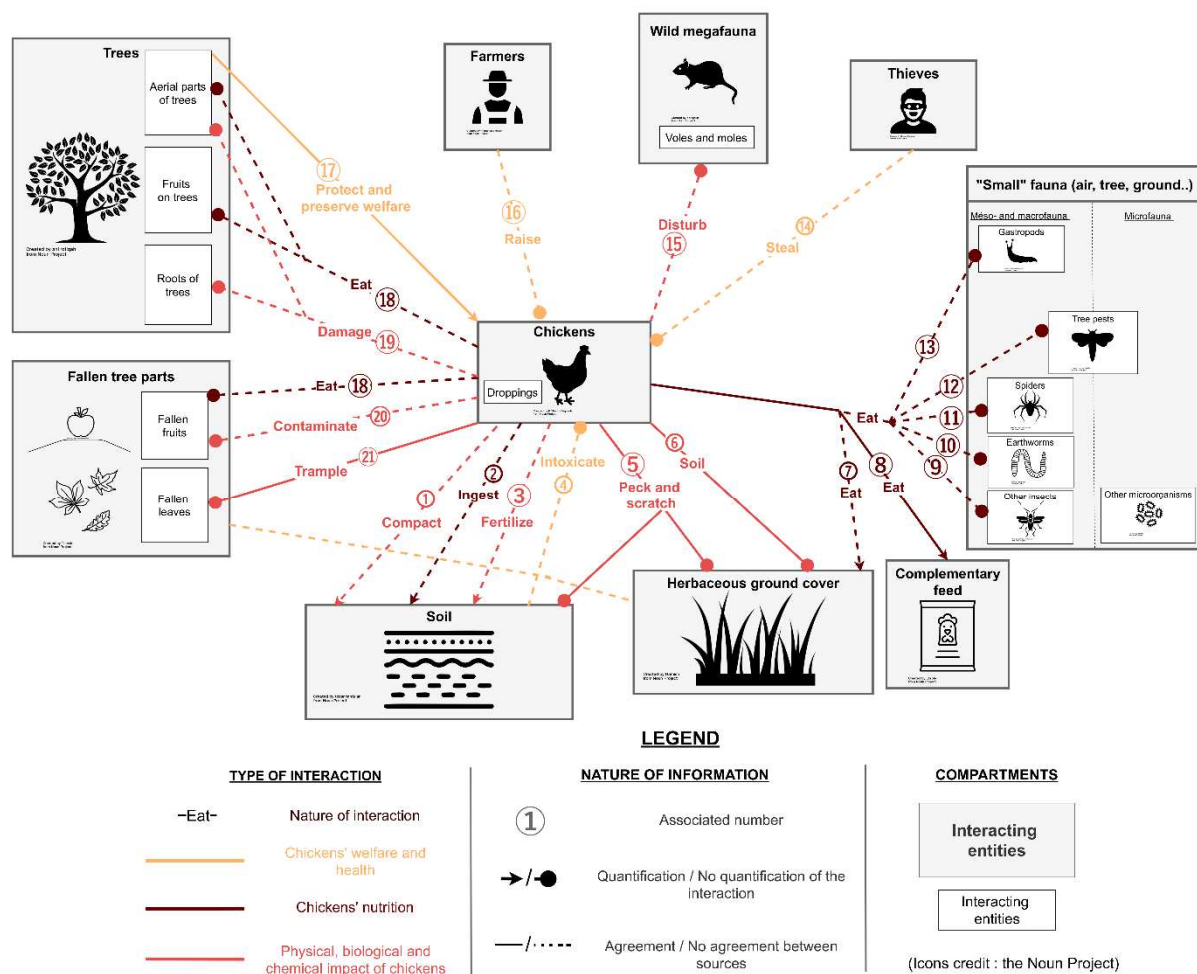
300 Finally, the presence of chickens attracts other animals that farmers have to learn how to deal with.  
301 Aerial (such as buzzards) and terrestrial predators (particularly foxes) (Bestman and Bikker-Ouwejan,  
302 2020) and chicken thieves act as external disturbers of the agroecosystem by killing and stealing  
303 chickens, respectively. Moles and voles do not directly impact chickens but potentially damage trees,  
304 plots and poultry infrastructures (Coisne, 2020). These interactions have to be considered because  
305 they may deeply impact the sustainability of the introduction of chickens into orchards.

### 306 **3.2. Characteristics of the information from different sources**

307 In the previous model (*Figure 1*), all interactions were represented in the same way, regardless of the  
308 nature of the information. To deepen our understanding of the state-of-the-art of this system, we

309 will now examine the different natures of knowledge that supports these interactions. *Figure 2*, using  
 310 the same model representation as in *Figure 1*, thus represents some interesting characteristics of the  
 311 information (quantifications, consistency between sources, etc.) by focusing on a limited number of  
 312 interactions of interest. To study the level of exhaustivity of the information, we also summarized  
 313 scientific references and testimonies associated with selected interactions in *Table 1*.

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



322  
 323 *Figure 2: Graphical state-of-the-art concerning interesting interactions in a chicken-pastured orchard.*  
 324 *Interactions are categorised into three groups with arrows coloured accordingly: chicken welfare and*

325 health (orange); chicken nutrition (dark red); and the impacts of chickens on the rest of the system  
 326 (light red). The existence of quantitative data in the literature is represented by the way the line ends:  
 327 pointed if quantitative data exist; rounded otherwise. The consistency between sources is represented  
 328 with the type of line for the arrow: solid in the case of relative agreement; dotted otherwise.

329

330 Table 1: Scientific references and testimonies associated with the interactions represented in Figure 2.

Compartment <sup>a</sup>	Interaction <sup>a</sup>	Precisions on interaction	Scientific references	Farmers' testimonies <sup>b</sup>
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	F11, FV2b, F14, F15
		② Evaluation of soil intake	No quantification	Almeida et al., 2012; Antell and Ciszuk, 2006
	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	F11, FV1, FV2a, FV2b, F13, F16, F17, GL1, GL2, GL7, GL8, V1, V3, SA2
		Integration of chickens with crops or valued pastures	Glatz et al., 2005b, 2005a; 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	No data	FV2a, FV2b, F14

		chickens			
<b>Herbaceous ground cover</b>	④ <b>Damage (without specifying the mechanisms)</b>	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 <b>Damage due to soiling</b>	Estimation of amount of droppings in different zones of the range	Lolli et al., 2019 No data	
		⑦ <b>Damage due to chicken intake</b>	No quantification	Clark and Gage, 1996; Mayton et al., 1945	
			Quantification using the sward cutting technique	Dal Bosco et al., 2014; Mugnai et al., 2014; Rivera-Ferre et al., 2007	FV1, FV2a, FI1, FI2, FI5, V1, V2, GL10
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				
<b>Soil and herbaceous ground cover</b>	⑤ <b>Damage caused by pecking and scratching</b>	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		
<b>Complementary feed</b>	⑧ <b>Evaluation of chicken intake</b>	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 Steinfeldt, 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	
<b>Small fauna</b>	⑨ <b>General impact on populations (no</b>	Gastropods	Glatz et al., 2005b	No data	
		Tree pests	Clark and Gage, 1996	FV1, FV2b, FI1,	

	<b>mechanisms studied)</b>			FI2, FI3, FI4, FI5, FI8, GL1, GL2, GL9, V2, V3, SA1, SA2
		Spiders	Clark and Gage, 1997	No data
		Earthworms		
		Other pests	Phillips et al., 2020; Sun et al., 2014; Xu et al., 2014	No data
		Insects (beside pests)	Clark and Gage, 1997	GL2
	<b>Presence of small fauna in the diet (9, 10, 11, 12, 13)</b>	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	Almeida et al., 2012; Amaka Lomu et al., 2004; Clark and Gage, 1996; Horsted et al., 2007b; Horsted and Hermansen, 2007	No data
		Insects (beside pests)	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
<b>Thieves</b>	<b>14 Thefts of chickens</b>	Farmers affected differently	No data	FV1, FI1, FI2, FI3, FI4, FI5, FI6, FI7, FI8
<b>Moles and voles</b>	<b>15 Impact on mole or vole populations</b>	Contrasted farmers' observations	No data	FV2a, FI3, GL9
<b>Farmer</b>	<b>16 Farmers' management of chicken husbandry</b>	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	Brannan and Anderson, 2021; Castellini et al., 2012; Hilimire, 2012; Xu et al., 2014	No data



		(besides chicken-pastured orchards)	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
<b>Trees</b>	<b>⑰ Welfare and protection by trees for chickens</b>	Welfare (without specifying mechanisms)	Abouelezz et al., 2014; Larsen et al., 2017		
		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	F11, F15, F16, F17, F18, V4, GL8, SA2	
		Protection against predators	Bestman and Bikker-Ouwejan, 2020		
	<b>⑱ Chickens appetite for fruits and leaves on trees and on the ground</b>	No quantification (observations by farmers)	No data		FV1, F11, F12, F13, V1, V4, GL10
	<b>⑲ Damage to tree roots, trunk and branches</b>	No quantification of damage	Jones et al., 2007; Larsen et al., 2017; Stadig et al., 2018; Yu et al., 2020		FV2a, F12, F14, GL8, GL10
<b>Fallen tree parts</b>	<b>⑳ Biological contamination of fallen fruits by chickens</b>	Evaluation of a potential risk	Theofel et al., 2020		GL10
	<b>㉑ Mechanical effects on leaves by trampling</b>	Degradation of leaves due to trampling effect	Item reported in the grey literature (Bestman, 2017; Timmermans and Bestman, 2016)		No data

331 Notes:

332 <sup>a</sup> Interaction numbers and compartment names (column 2) correspond to Figure 2. (X), (Y) correspond to interesting interactions for fruit growers that cannot  
333 appear in Figure 2 because the mechanisms were not specified.

334 <sup>b</sup> Letters reflect the origin of the testimony: Farmers' interviews (FI), Farm visit (FV), Video (V), Grey Literature (GL), SA (Scientific Article). Each number  
335 indicates one farmer. Testimonies have been aggregated to correspond to the interaction level (column 2) and not to the precision level (column 3), except  
336 when it was relevant with respect to farmers' testimonies ((3), (4), (Y), (9), (10), (11), (12), (13), (16)).

### 337 3.2.1. Divergence of quantifications between scientists

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

340 As an example, the spontaneous intake of herbaceous stratum by chickens (interaction (7)) covers a  
341 wide range of values in the scientific literature identified: from 0.7 g of dry matter (DM) forage

342 /day/chicken (Jurjanz et al., 2015), to 72 g of DM forage/day/chicken (Horsted et al., 2007b). In  
 343 reality, these differences mask the variability concerning experimental conditions, quantification  
 344 methods and systems under study.

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

351 Second, values of forage intakes vary because quantification methods differ and do not consider the  
 352 same bias (see *Table 1-Interaction* ⑦). Three collected studies (Dal Bosco et al., 2014; Mugnai et al.,  
 353 2014; Rivera-Ferre et al., 2007) relied on the sward cutting method, which underestimates trampling  
 354 by chickens (Jurjanz et al., 2015). Eight other studies (Abouelezz et al., 2013; Almeida et al., 2012;  
 355 Amaka Lomu et al., 2004; Antell and Ciszuk, 2006; Horsted et al., 2007b; Lorenz et al., 2013; Ponte et  
 356 al., 2008b) used dissection (crop and/or gizzards) combined with an equation from Antell and Ciszuk  
 357 (2006) to calculate daily intake. One drawback of this method is that it is not repeatable on the same  
 358 individual (Singh et al., 2016). More recently, studies focused on n-alkane analysis, which seems  
 359 reliable to estimate forage intake but is harder to conduct (Jurjanz et al., 2015; Singh et al., 2016).

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

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

<b>System characteristics</b>	<b>Examples of modality</b>	<b>Examples in the literature</b>
Outdoor stocking densities	110 chickens/ha	Amaka Lomu et al., 2004
	2,500 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

363

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

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

### 369 3.2.2. Divergence of interest within and between scientists and farmers

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

#### 373 Concerning mechanisms:

374 We first identified some knowledge gaps concerning basic mechanisms of interactions in this  
 375 agroecosystem, which are mainly detrimental for scientific purposes (interactions ⑤ and ⑥ in  
 376 *Figure 2* and *Table 1*). Although studies concerning the degradation of herbaceous ground cover by  
 377 chickens do exist (⊗ in *Table 1*), studies about precise mechanisms are rare and especially concern  
 378 the quantification of the physical impact of chickens by pecking and scratching or soiling. Except for  
 379 one study (Breitsameter et al., 2014), pecking and scratching the ground is principally studied  
 380 through the prism of ethology in the other studies (see *Table 1*). However, data concerning time  
 381 spent by chickens pecking and scratching are not sufficient to construct scientific mechanistic models  
 382 of the impact of chickens on this agroecosystem. Evaluation of pecking and scratching in terms of  
 383 weed biomass or its effect on the herbaceous stratum structure would, for example, be necessary.  
 384 This lack of knowledge is not only deleterious for scientific purposes but also for the practitioners

385 insofar as this knowledge is needed to help them design and/or manage innovative agricultural  
386 systems. Indeed, 20 farmers declared in their testimonies to be highly concerned by the effects of  
387 chickens on grass cover, and some of them reported the lack of information concerning the  
388 appropriate chicken stocking density or the appropriate dynamic management necessary to preserve  
389 the quality of the herbaceous stratum.

390

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

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

418 In addition to this direct impact, chickens also indirectly impact pest regulation by impacting the  
419 dynamics of the whole agroecosystem, including auxiliary fauna (earthworms, spiders and other  
420 insects). Even though we listed a certain number of articles dealing with the impacts on fauna  
421 (interactions ⑨, ⑩, ⑪, ⑫ in *Figure 2* and *Table 1*), very few authors carried out sufficient in-  
422 depth analyses to draw significant conclusions. For instance, among all the listed studies dealing with  
423 the impact on insects (beside pests) or ingestion of insects (besides pests), only two (Clark and Gage  
424 1996; 1997) actually gave the names of the insect species impacted by chickens. All the other studies  
425 just used the term insects in general, neglecting the diversity of species and functions. Regardless, in  
426 all of those cases, scientific evidence would be valuable in order to (i) confirm the robustness of  
427 farmers' observations (FI1, FI2, FI3, GL1, GL7, V1, V2, V3), and (ii) identify levers to help farmers to  
428 manage the association.

#### 429 Concerning systems:

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

439 These lacks can be illustrated through the example of work management (interaction ⑯),  
440 which represents a great challenge in chicken-pastured orchards. Indeed, several farmers'  
441 testimonies highlighted difficulties for farmers confronted with heavier workloads, more time spent  
442 on the farm due to animal presence, and conflicts in terms of space and time between the two  
443 activities (FI4, FI5, FI6, FI7, FI8, FV2b, GL3). More precisely, the long-term sustainability of farms  
444 depends on the compatibility and even complementarity of both activities. Despite this, we identified  
445 only five articles that include a social perspective and not just economic or environmental  
446 approaches to evaluate the sustainability of chicken-pastured orchards (Elkhouraibi et al., 2017; García  
447 de Jalón et al., 2018; Rocchi et al., 2019; Röhrig et al., 2020a, 2020b). Moreover, these studies focus  
448 on slightly different objects than those we identified in the testimonies. Elkhouraibi (2017) identified  
449 major challenges in poultry farming, but from US farmers who were initially chicken producers. As for  
450 Rocchi (2019), the social evaluation was limited to labour safety, animal welfare and farm integration

451 in the landscape. However, Röhrig (2020a, 2020b) and García de Jalón et al. (2018) quickly examined  
452 trade-offs related to tree/chicken associations. Röhrig (2020a) raises the question of conflicts  
453 between both activities, the extreme complexity of management, and the need for additional  
454 external work (Röhrig et al., 2020b). García de Jalón (2018) also put forward these issues of  
455 management complexity and labour burden in the perception of agroforestry farmers. However, this  
456 approach does not specifically focus on chicken-pastured orchards and does not make it possible to  
457 draw conclusions about this specific system. Hence, there is a need for quantitative approaches to  
458 study trade-offs between both activities and the organisation of choices and adaptations made by  
459 farmers.

### 460 **3.2.3. Strong divergence of observations between farmers that cannot be explained by scientific** 461 **literature**

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

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

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

483 a major challenge to study these interactions in order to find the eventual management levels  
 484 necessary to propagate the practice of association.

485 4. Discussion

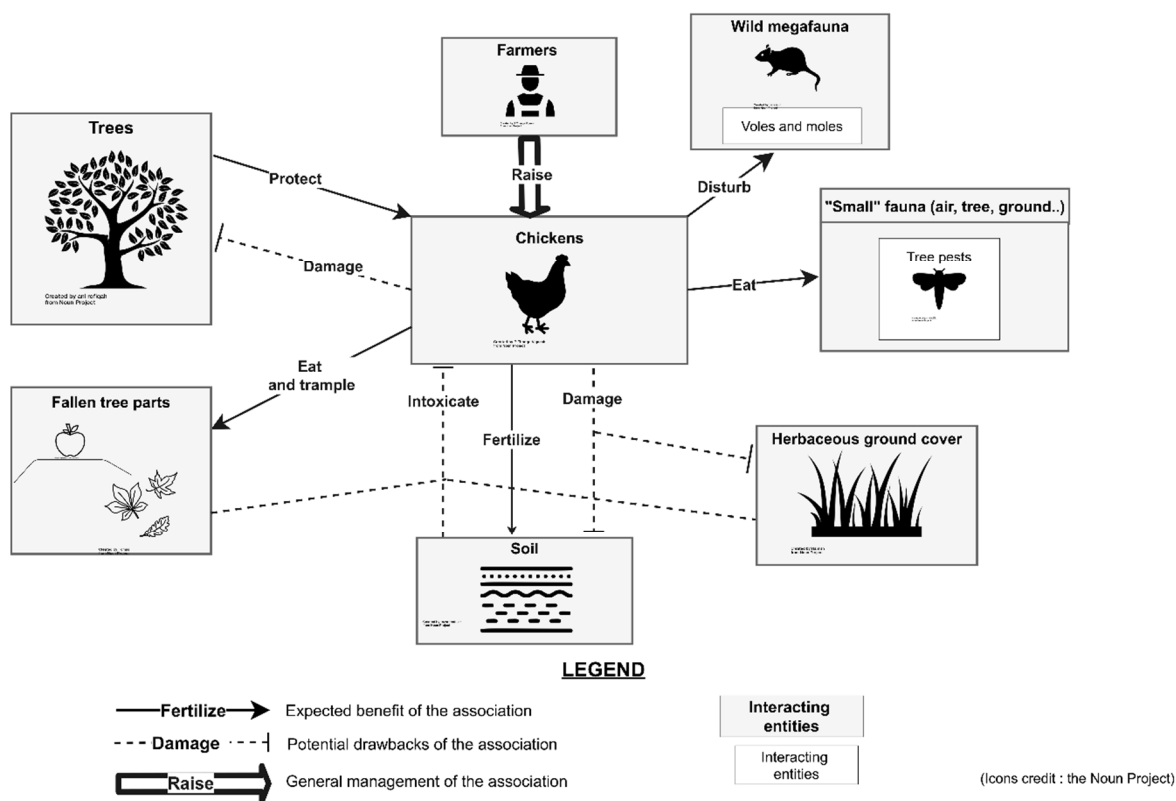
486

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

492

493 4.1. Key interactions in the heuristic model

494 To summarise the conclusions of the literature review based on the heuristic model, we propose  
 495 here a simplified version of the model (Figure 1). This representation highlights the key interactions  
 496 considered to be central in chicken-pastured orchards and for which information is lacking.



497

498 Figure 1: Simplified heuristic model based on Figure 1, presenting key interactions on which research questions should focus.

499 These interactions can be classified into three categories: interactions concerning (i) expected  
 500 benefits of the chicken-tree association; (ii) potential drawbacks of the association; and (iii) general

501 management of the association. We claim that these interactions should constitute priority research  
502 questions because their knowledge is essential to design efficient chicken-pastured orchards.

503 Expected benefits of the association have been reported by several farmers, but in order for these  
504 practices to be disseminated, proof should be reinforced to convince new audiences. Hence, the  
505 potential regulation and sanitation effects of chickens on the orchard (on tree pests, on moles and  
506 voles, and on fallen tree parts) need to be confirmed by scientific approaches and quantified. The  
507 other beneficial effects (protection of chickens by trees and soil fertilisation) have been partly  
508 studied but the specificities of chicken-orchard associations (for example, fertilisation with regard to  
509 fruit tree needs) should be more precisely considered. Drawbacks of the association should also be  
510 more deeply studied in order to tackle farmers' challenges and to improve already-existing chicken-  
511 pastured orchards. Hence, the general damage of chickens on orchards is known, but quantification  
512 concerning the intensity of damage is often lacking. Similarly, studying potential intoxications of  
513 chickens by orchard treatments is all the more essential when considering a dissemination of these  
514 systems towards more treatment-intensive orchards. Finally, farmers' management of the  
515 association and their ways to deal with complex trade-offs between those benefits and drawbacks  
516 need to be assessed and considered. More broadly speaking, this topic could contribute and bring  
517 new perspectives to the study of diversified agroecosystems and their specificities in terms of  
518 management complexity.

519

#### 520 4.2. Methodological limitations of our approach

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

531 The previous global analysis highlighted several gaps in the scientific literature concerning  
532 chicken-pastured orchards. We counted only 17 articles out of 195 collected dealing with those  
533 systems. Hence, to obtain a sufficient number of scientific articles, we chose to broaden our search



534 to free-range chicken husbandry. These extrapolations mainly concerned interactions between  
535 chickens and the herbaceous stratum, the soil or insects. Retrospectively, these extrapolations were  
536 interesting to obtain some range of values concerning crucial mechanisms for fruit growers, such as  
537 the ingestion of forage by chickens and the fertilisation potential of droppings. However, free-range  
538 systems deeply differ from pastured orchards. For example, the density of chickens is often much  
539 higher in free-range systems than in pastured orchards. Direct translations of the knowledge  
540 developed on free-range systems to pastured orchards are thus not always possible. Moreover, even  
541 on free-range systems, the literature collected was so disparate that even general findings about  
542 interactions were difficult to obtain and, as a consequence, interactions could only be quantified for  
543 six interactions out of 21.

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

#### 550 4.3. [A model that compares scientific and farmers' knowledge to reveal knowledge gaps](#)

551 To study complex agroecological systems, it is often necessary to combine a plurality of knowledge  
552 and, notably, to integrate farmers' points of view (Hazard et al., 2018). Hence, scientific and farmers'  
553 knowledge can interact in different ways. In our approach, farmers' knowledge was useful to  
554 complete the list of interactions and to draw a global image of the system. Reciprocally, scientific  
555 approaches made it possible to reveal and specify underlying mechanisms when farmers only  
556 observe general impacts. In other studies, some authors noted that farmers expect scientific  
557 knowledge to answer their questions or to legitimise the practical choices they made (Hazard et al.,  
558 2018). In our case, such an expectation could not be fulfilled by this incomplete scientific literature,  
559 which is, in addition, deeply disconnected from farmers' needs. However, comparing scientific state-  
560 of-the-art to field situations allowed us to identify crucial knowledge gaps and to determine the  
561 reasons for such a situation.

562 Different reasons could indeed explain these huge knowledge gaps. First, chicken-pastured  
563 orchards and, more generally, grazed or pastured orchards, are minority agricultural practices:  
564 according to den Herder et al. (2017), around 5% of permanent crops in the European Union were  
565 being grazed in 2012. Second, even though grazing animals under trees is not new (Coulon et al.,  
566 2000), the reintroduction of animals into modern orchards, particularly poultry, requires to break the

577 frontier that still persists in modernised agriculture between animal and plant production. This  
578 disconnection on farms also exists in the scientific research that is compartmentalised and  
579 reductionist. Indeed, because of their hybrid form, pastured orchards do not fit the classical  
570 conceptual frameworks of two disconnected disciplines, agronomy and animal science: for  
571 agronomy, because of the introduction of the husbandry component into the system, and for animal  
572 science, because animal products are not the principal target in these systems. This statement might  
573 explain why we observed a greater focus on classical husbandry interactions (e.g., complementary  
574 feed intake, meat and egg contamination by dioxins) by the animal sciences, which neglect to study  
575 other interactions in terms of ecosystem services provided by chickens.

#### 576 4.4. Perspectives for systemic approaches

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

597 In order to produce action-oriented knowledge, research questions also need to evolve  
598 through comparison with the field. Just as we did, other studies on agroecological practices pointed  
599 out some discrepancies between scientific knowledge and crucial needs for farmers, notably  
600 concerning practical management issues and ecosystem services (Brodt et al., 2020; Ditzler et al.,

601 2021). Yet, from an operational point of view, including farmers' points of view, it is necessary to  
602 design and manage innovative agroecological systems adapted to farmers' constraints (Demestihias  
603 et al., 2017b; Fagerholm et al., 2016). Concretely, our model, which already includes empirical  
604 knowledge, could serve as a discussion tool that farmers could compare to their own local situations.  
605 This model could also be mobilised as an intermediary object for serious games in workshops with  
606 practitioners to make them work on the design of diversified systems that associate poultry and fruit  
607 trees (Duru et al., 2015).

## 608 5. Conclusion

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

## 621 6. Appendix

622 Supplementary references of grey literature (A) and testimonies (B) on chicken-pastured orchards,  
623 and icon credits (C).

## 624 7. Conflicts of interest

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

## 627 8. Acknowledgements

628 This work was supported by a doctoral fellowship from the École Normale Supérieure de Paris  
629 attributed to S.B., by the Fondation de France and by INRAE (ACT Department). The authors also  
630 thank the stakeholders that gave their own testimonies or helped to identify grey literature.

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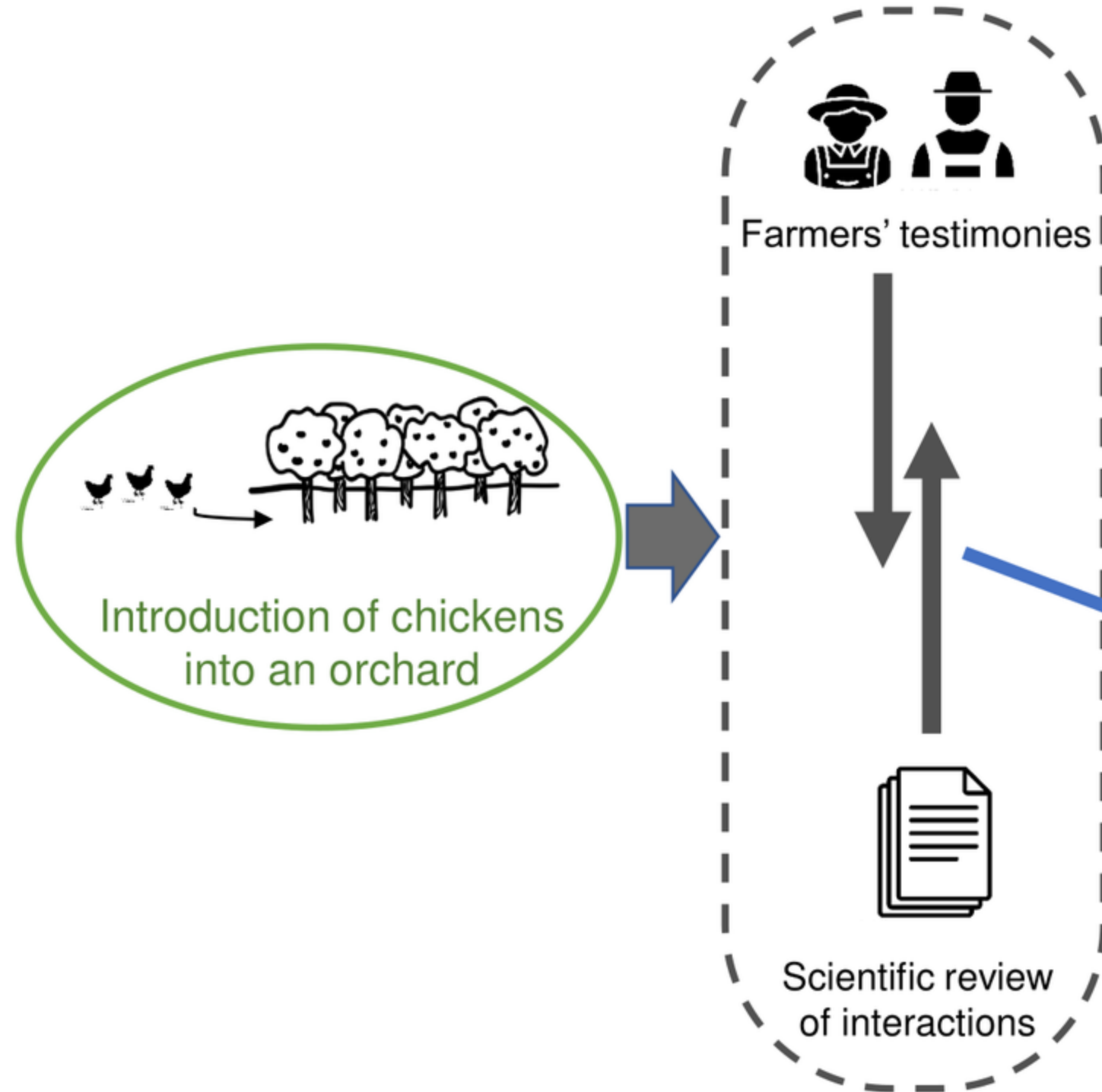


An innovative system under study

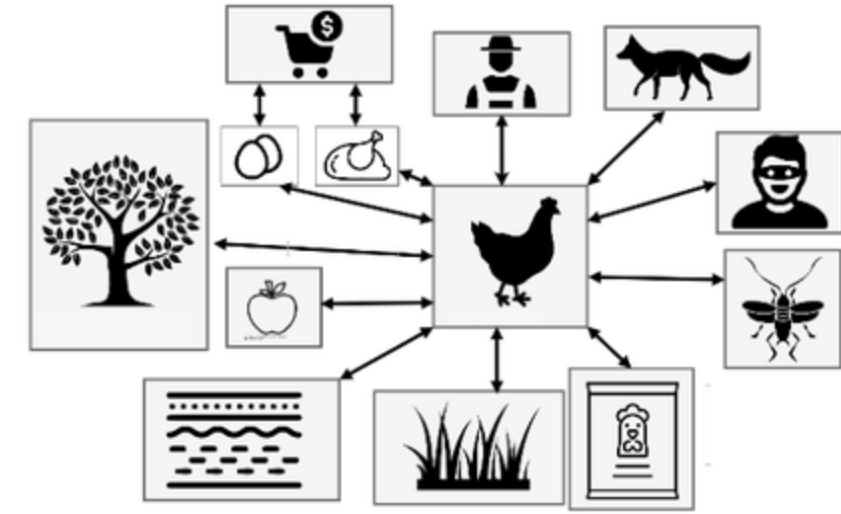
Materials

Methods

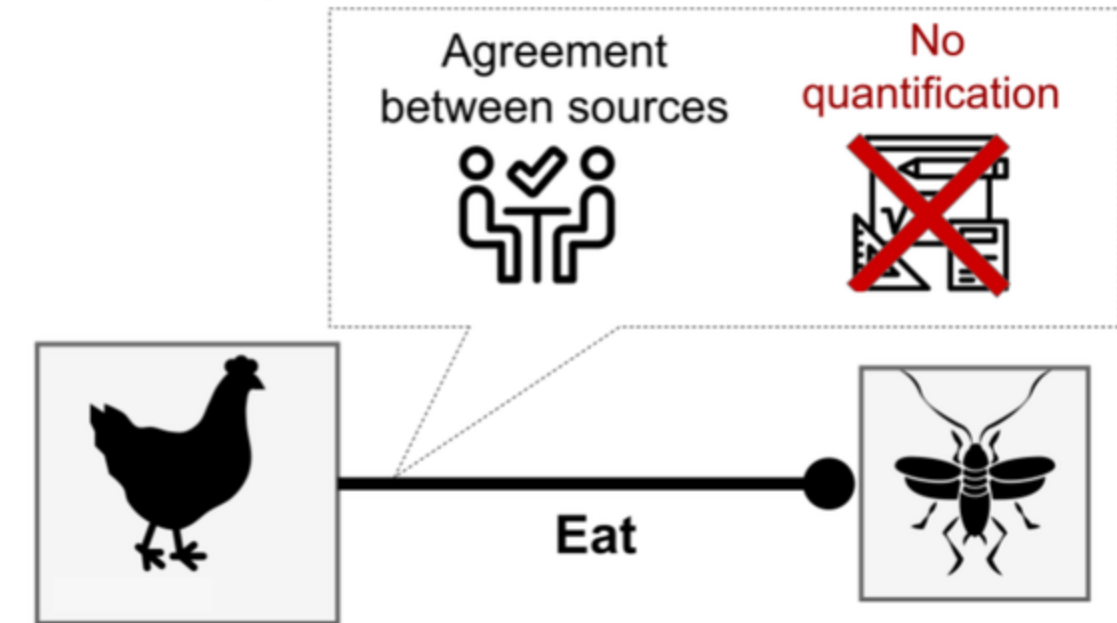
Results



① Global heuristic model representing a chicken-pastured orchard



② Graphical state-of-the-art



(Icon credits: the Noun Project)