



**HAL**  
open science

## **Interplay: A game for the participatory design of locally adapted cereal-legume intercrops**

Clémentine Meunier, Marion Casagrande, Blandine Rosiès, Laurent Bedoussac, Cairistiona Topp, Robin Walker, Christine Watson, Guillaume G. Martin

### ► To cite this version:

Clémentine Meunier, Marion Casagrande, Blandine Rosiès, Laurent Bedoussac, Cairistiona Topp, et al.. Interplay: A game for the participatory design of locally adapted cereal-legume intercrops. *Agricultural Systems*, 2022, 201, 10.1016/j.agsy.2022.103438 . hal-03693476

**HAL Id: hal-03693476**

**<https://hal.science/hal-03693476v1>**

Submitted on 17 Jul 2023

**HAL** is a multi-disciplinary open access archive for the deposit and dissemination of scientific research documents, whether they are published or not. The documents may come from teaching and research institutions in France or abroad, or from public or private research centers.

L'archive ouverte pluridisciplinaire **HAL**, est destinée au dépôt et à la diffusion de documents scientifiques de niveau recherche, publiés ou non, émanant des établissements d'enseignement et de recherche français ou étrangers, des laboratoires publics ou privés.

# 1 **Interplay: a game for the participatory design of locally adapted cereal–legume intercrops**

2 Clémentine Meunier<sup>1</sup>, Marion Casagrande<sup>2,3</sup>, Blandine Rosiès<sup>2</sup>, Laurent Bedoussac<sup>4</sup>, Cairistiona FE  
3 Topp<sup>5</sup>, Robin L Walker<sup>6</sup>, Christine A Watson<sup>6</sup>, Guillaume Martin<sup>1</sup>

4 <sup>1</sup> AGIR, Univ Toulouse, INRAE, Castanet-Tolosan, France

5 <sup>2</sup> ITAB, F-26320, Saint-Marcel-lès-Valence, France

6 <sup>3</sup> INRAE, UR Ecodéveloppement, Avignon, France

7 <sup>4</sup> AGIR, Univ Toulouse, ENSFEA, INRAE, Castanet-Tolosan, France

8 <sup>5</sup> SRUC, West Mains Road, Edinburgh, EH9 3JG

9 <sup>6</sup> SRUC, Craibstone Estate, Aberdeen, AB21 9YA

## 10 **Abstract**

### 11 CONTEXT

12 Although cereal–legume intercropping is a recognized approach to improve crop production  
13 sustainability, its uptake on European commercial farms remains slow, due to numerous questions  
14 raised by the introduction of intercrops in a cropping system. Co-design workshops allow multiple  
15 scenarios to be explored without risks. They favor identification of consistent answers to complex  
16 problems, considering local conditions and constraints.

### 17 OBJECTIVE

18 We present Interplay, the serious game we created to support players' exploration of intercrops by  
19 designing a wide-range of cereal–legume intercropping scenarios in given cropping system contexts  
20 and assessing eight ecosystem services provided by intercrops, i.e., intercropped cereal and legume  
21 yields, cereal protein content, nitrogen supply to the following crop, impact on soil structure and weed,  
22 insect and disease control.

### 23 METHODS

24 Interplay aims at being used with groups of farmers and their advisor or students and their agronomy  
25 teacher. The game includes a game board and cards to design intercropping scenarios defined by: (i)  
26 the cropping system and field context; (ii) the farmers' objectives when introducing an intercrop; (iii)  
27 the species to associate and (iv) the crop management. A computer model assesses the ecosystem  
28 services provided by the intercropping scenario designed on the game board. The players compare  
29 these results to their objectives and to sole crop performances and, if necessary, adjust the scenarios.  
30 The players are guided through the design process by a facilitator.

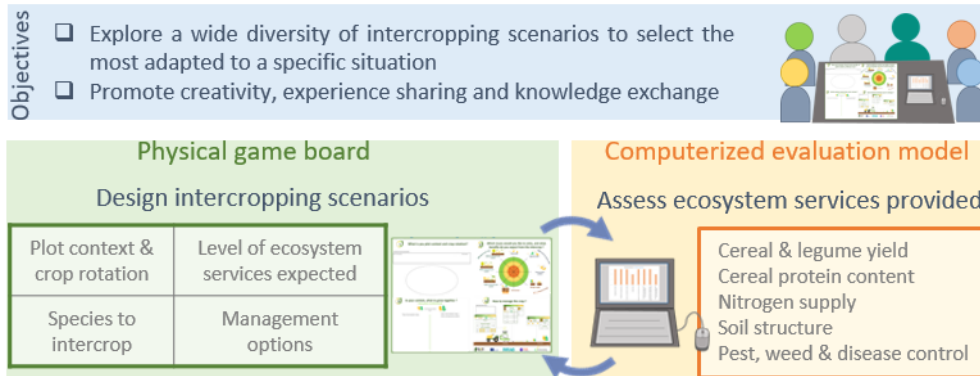
### 31 RESULTS AND CONCLUSIONS

32 In the context of the Covid-19 pandemic, we used the game with 70 French agriculture students divided  
33 into six groups to design intercropping scenarios improving nitrogen supply to the following crop in a  
34 rotation. Students designed scenarios that improved nitrogen supply compared to the initial sole crop,  
35 yet cereal yield decreased more than the farmer desired. Guided by the facilitator, students  
36 reconsidered the cropping system to improve nitrogen supply at the crop rotation level. Interplay is an  
37 interactive tool used to stimulate players' creativity by exploring intercropping scenarios and providing  
38 salient, credible and legitimate assessment of the ecosystem services provided. It also promotes  
39 knowledge sharing on intercropping and allows redesigning the cropping system completely. Students  
40 and teachers who used it declared that it helped enhance their knowledge on intercrops.

41 SIGNIFICANCE

42 Interplay is the first serious game suited to develop the practice of intercropping. It is currently  
43 available for cereal–grain legume intercrops sown simultaneously in a random pattern under French  
44 soil-climate conditions, but could be adapted to other countries and intercrops.

45 **Graphical abstract**



46

47

48 **Highlights**

49

- 50 ● Participatory approaches are needed to support the design and implementation of intercrops.
- 51 ● A serious game was developed to support players' exploration of cereal–grain legume  
52 intercrops.
- 53 ● The game supports the design of intercropping scenarios according to cropping system  
54 contexts.
- 55 ● The game assesses ecosystem services provided by intercrop scenarios, and stimulates the  
56 design of locally adapted intercrops.
- 57 ● The game provides an interactive support to promote creativity, experience sharing and  
58 knowledge exchange.

59

60 **1. Introduction**

61 Intercropping, the simultaneous cultivation of different species in the same field for at least part of  
62 their growing season (Willey, 1979), is a powerful lever toward the development of sustainable  
63 agricultural systems (Jensen et al., 2020; Maitra et al., 2021; Stomph et al., 2020). Cereal–legume  
64 intercropping is of particular interest as it provides a large range of ecosystem services (Maitra et al.,  
65 2021), including weed control (Hauggaard-Nielsen et al., 2001) and soil stability and fertility  
66 improvement (Stomph et al., 2020). It can also improve resource use efficiency (Duchene et al., 2017;  
67 Hauggaard-Nielsen et al., 2003; Jensen et al., 2020) and thereby increases productivity per unit area  
68 compared to a sole crop with similar inputs (Bedoussac et al., 2015; Pelzer et al., 2012; Raseduzzaman  
69 and Jensen, 2017). The higher crop diversity of intercrops also spreads risk and leads to more stable  
70 yields notably against climate hazards compared to sole legume crops (Bedoussac et al., 2015;  
71 Raseduzzaman and Jensen, 2017).

72 Despite these well-established and acknowledged benefits, adoption and dissemination of cereal–  
73 legume intercropping has been slow on European commercial farms (Machado, 2009) and  
74 intercropping is mainly implemented in low-input (e.g. organic) systems. This can be explained by a set  
75 of lock-ins (Magrini et al., 2016; Mamine and Farès, 2020): (i) technical such as unfavorable plant  
76 breeding strategies, knowledge gaps on relevant crop management sequences, lack of equipment  
77 adapted for efficient collecting, sorting and storage of intercrop products; (ii) economic such as cost of  
78 adapted equipment, price of intercrop products; lack of market opportunities, difficulties in  
79 establishing contracts; and (iii) related to public policy, notably no specific subsidies for ecosystem  
80 services provided by intercrops. Overall, there is a lack of knowledge on best intercrop management  
81 practices at all levels of the value chain (i.e. farmers, advisors, processors, researchers, etc.  
82 (Casagrande et al., 2017)).

83 Among these multiple lock-ins affecting the spread of intercropping use in agricultural systems,  
84 knowledge gaps surrounding the technical implementation of intercropping on farms are critical for  
85 farmers. They are facing a range of complex and emergent questions when integrating an intercrop in  
86 their cropping system: when to integrate the intercrop in the crop sequence? Does it require  
87 redesigning the crop rotation? What species and cultivars should be associated? At which density  
88 should each component be sown and with which spatial pattern? How can you best control insects,  
89 weeds and diseases in the mixture? How to plan nitrogen fertilization when nitrogen has an ambivalent  
90 action on the cereal and on the legume growth? Etc. Field trials and technical references on intercrop  
91 management are scarce and often focus on the implementation of one specific practice (e.g. one  
92 species mixture or one management practice, such as nitrogen fertilization). Thus, field trials alone do  
93 not allow farmers to fully explore the many decisions they have to make when introducing an intercrop  
94 into a cropping system, and provide fragmented information that does not offer the necessary global  
95 vision that farmers need.

96 To address complex problems raised by the development of innovations such as intercropping, an  
97 increasing body of the literature (Pigford et al., 2018) suggests implementing participatory approaches  
98 in the framework of innovation ecosystems, defined by Granstrand and Holgersson (2020) as “the  
99 evolving set[s] of actors, activities, and artefacts, and the institutions and relations, including  
100 complementary and substitute relations, that are important for the innovative performance of an actor  
101 or a population of actors”. These frameworks allow the bringing together of different knowledge  
102 sources from scientists to pioneering farmers. By allowing the exploration of multiple solutions without  
103 risks and at limited costs, co-design workshops favor identification of consistent answers to complex  
104 problems and knowledge exchange between different actors (Berthet et al., 2016; Reau et al., 2012;  
105 Voinov et al., 2016). Giving farmers a key role in the design process favors innovations in practice  
106 ensuring that their local conditions and real constraints are adequately considered and leading to the  
107 design of cropping systems specifically adapted to each situation (McGranahan, 2014).

108 Co-design workshops can rely on a variety of approaches: prototyping using drawings (Elzen and Bos,  
109 2019) and sketches, scenario simulation (Bergez et al., 2010), serious gaming (Speelman et al., 2014),  
110 etc. In recent years, serious gaming has gained increasing interest in the agricultural sector. Serious  
111 games are defined as tools that “aim to combine aspects of both serious as, but not limited to,  
112 teaching, learning, communication, or further information with playful springs of the game” (Alvarez  
113 and Djaouti, 2012). They are useful to support the collegiate design and evaluation of agricultural  
114 systems with farmers (e.g. Forage rummy (Martin et al., 2011), Mission Ecophyt'Eau®, SEGAE (Jouan

115 et al., 2021), Dynamix (Ryschawy et al., 2018)). Serious games mobilize boundary objects (Cash et al.,  
116 2003), which create a shared vocabulary to represent current and alternative systems, to materialize  
117 changes to implement, and overall to enhance experience sharing and knowledge elicitation among  
118 players.

119 At present, none of the available serious games focuses on the issues raised by the introduction of an  
120 intercrop in a cropping system. To support the collective design and evaluation of locally adapted  
121 intercrops in given cropping system contexts, we developed a serious game called Interplay (being the  
122 contraction of “intercrop” and “play”). This game, mobilizing multidisciplinary scientific knowledge and  
123 players’ empirical knowledge, aims at allowing players to explore a wide diversity of intercropping  
124 scenarios and the ecosystem services they provide. Interplay consists of iteratively designing cereal–  
125 legume intercropping scenarios in a given cropping system context, and assessing eight ecosystem  
126 services provided by the intercrop, i.e. intercropped cereal and legume yield, cereal protein content,  
127 nitrogen supply to the following crop, impact on soil structure, and weeds, insects and diseases control.  
128 Each scenario is defined as a unique combination of cropping system characteristics, i.e. soil-climate  
129 conditions, crop rotation, landscape effects, intercropped cereal and legume species and cultivars, and  
130 intercrop management practices (sowing and input use). The designed locally adapted intercropping  
131 scenarios and the services provided must be salient, credible and legitimate to all players (Cash et al.,  
132 2003). Interplay engages players as actors in the design and evaluation process. It can be mobilized  
133 with farmers or with students. Players are guided through the design stages by a facilitator, who is  
134 either an advisor when playing with farmers or a teacher when playing with students. The first  
135 complete version of Interplay, finalized in April 2021 after two years of prototyping, is adapted to a  
136 wide diversity of organic and conventional low-input farming situations, for a wide range of cereal–  
137 grain legume intercrops sown simultaneously in a random pattern (thus excluding strip intercropping).

138 In this article, our main objective is to present Interplay. In order to do so, we first present the game  
139 functioning, focusing on how we converted a conceptual model of a cropping system possibly including  
140 intercrops into a series of game elements acting as boundary objects. Then, to help the reader imagine  
141 him/herself participating in the game, we illustrate the description of the game (Section 2) with the  
142 example of agriculture students in Southwestern France designing intercrops for improved nitrogen  
143 supply (Section 3). We finally discuss the game itself, its usage and limitations.

## 144 **2. Overview of the game**

### 145 2.1. Conceptual model of a cropping system

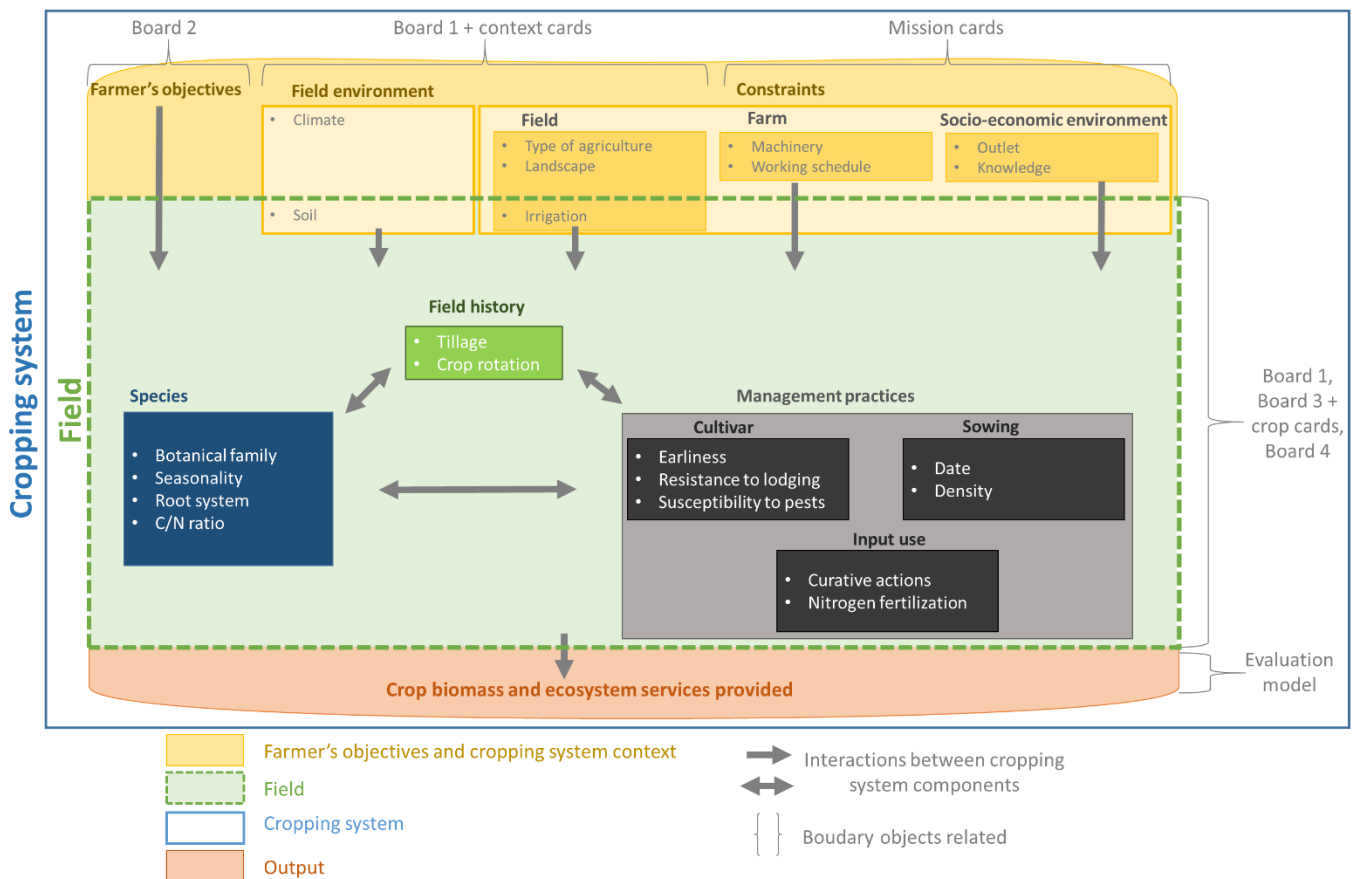
146 The design of locally adapted intercropping scenarios requires considering the cropping system  
147 context. A cropping system is defined as “a set of management procedures applied to a given,  
148 uniformly treated area, which may be a field, part of a field or a group of fields” (Sebillotte, 1990).  
149 These procedures, i.e. crop rotation and management, are defined by players according to their  
150 objectives in a given context. We identified key elements to design a conceptual model of a cropping  
151 system (Fig. 1):

- 152 i. Farmer’s objectives
- 153 ii. Cropping system context, made of :
  - 154 i. field environment (i.e., soil-climate conditions);
  - 155 ii. field constraints (i.e., type of agriculture, impact of the landscape on pest pressure  
156 and irrigation availability);

- 157           iii. farm constraints (e.g. available machinery, working schedule);
- 158           iv. socio-economic environment constraints (e.g. existence of an outlet, knowledge
- 159           availability).
- 160       iii. Field and crop management, including :
- 161           i. field history, i.e., rotation and tillage along the rotation;
- 162           ii. choice of species to grow and their characteristics rationalizing this choice, i.e.
- 163           seasonality, botanical family, root system and C:N ratio;
- 164           iii. crop management practices, including cultivar choice, sowing parameters and
- 165           input use.

166

167 The field history, the choice of the species and the crop management practices are deeply interrelated,  
 168 and all depend on the cropping system context and on the farmer's objectives. The interactions  
 169 between the field, the crop management and the cropping system context determine the crop biomass  
 170 and levels of ecosystem services provided (Fig.1).



171

172 Figure 1: Conceptual model of a cropping system underlying the design of Interplay and related  
 173 boundary objects.

174

## 175 2.2. Development and use of boundary objects

### 176 2.2.1. Game board

177 The game board is a core element of Interplay. It aims at being a transparent implementation of the  
178 conceptual model of a cropping system presented above and at providing a space for shared  
179 understanding and communication among players. We materialized the many elements farmers have  
180 to consider when designing an intercrop on the Interplay game board, i.e. a whiteboard marked with  
181 information (Fig. 2). It is divided into four parts as follows:

- 182 i. Board 1 (part A of the game board presented Fig. 2) represents the field environment (soil-  
183 climate conditions) and its constraints (type of agriculture, irrigation, impact of the  
184 landscape on pest pressure). It also materializes the field history (crop rotation and tillage  
185 strategy along the rotation). (Fig. 1, Fig.2), as described by the scenario farmer, i.e. the  
186 farmer who wants to introduce an intercrop in his/her cropping system, on a field on  
187 his/her farm (whatever its size) ;
- 188 ii. Board 2 (part B of the game board presented Fig. 2) sets the scenario farmer's objectives  
189 (Fig.1, Fig.2), i.e. the level of each ecosystem service (cereal and legume grain yield, cereal  
190 protein content, nitrogen supply to the following crop, impact on soil structure and pest  
191 control) expected from the introduction of an intercrop, as establishing design goals is a  
192 key element to ensure efficient collective workshops (Martin et al., 2013). Three levels of  
193 service are defined (low, intermediate and high), and the scenario farmer is encouraged  
194 by the facilitator to make compromises and prioritize among services. In order to do so,  
195 he/she is asked to allocate poker chips to each ecosystem service to materialize this  
196 prioritization (from zero poker chip if the service is not deemed important at all to five  
197 poker chips if the service is very important), and he/she cannot allocate 5 poker chips to  
198 every service;
- 199 iii. Board 3 (part C of the game board presented Fig. 2) is dedicated to capturing all players'  
200 (including the scenario farmer) suggestions of species to intercrop (two harvested species  
201 or one species and one companion plant). It aims to support knowledge exchange on  
202 species mixtures among players and lead to mutual agreement of a collective choice of the  
203 most consistent ones in the context of the cropping system and objectives defined by the  
204 scenario farmer (Fig. 1; Fig. 2);
- 205 iv. Board 4 (part D of the game board presented Fig. 2) allows definition of the locally adapted  
206 crop management practices regarding cultivars (i.e. earliness, resistance to lodging,  
207 susceptibility to weeds, pests and diseases), sowing (date and density) and input use  
208 (curative actions, date and amount of nitrogen supplied) (Fig. 1; Fig. 2). As for board 3, all  
209 players decide each management option collectively. The game board, along with all other  
210 game elements, are illustrated and described in further detail in the user manual provided  
211 when downloading the game (see 4.3.).

### 212 2.2.2. Crop cards

213 Designing intercrops in the context of a cropping system requires first to choose the species to  
214 intercrop (Fig. 1). We inventoried the species that are mainly grown on French commercial farms and  
215 created 44 crop cards accordingly. These cards are used to represent the crop rotation on board 1 (all  
216 cards) and the species to associate in an intercrop on board 3 (only cereals and grain legumes, e.g.  
217 winter wheat and protein pea; Fig. 2). They are distributed according to two determinant factors, i.e.  
218 the type of crop (annual vs. perennial) and its seasonality (winter, spring or summer) and the botanical

219 family (e.g. poaceae for cereals, fabaceae for legumes) (Fig. 1, Fig. 2). These factors were selected as  
220 they affect both the possibility of growing two particular species together (e.g. one winter crop and  
221 one spring crop cannot be sown and harvested simultaneously) and the choice of species to insert in  
222 the crop rotation to break pest cycle (e.g. by alternating winter and spring crops or species of diverse  
223 botanical families).

224

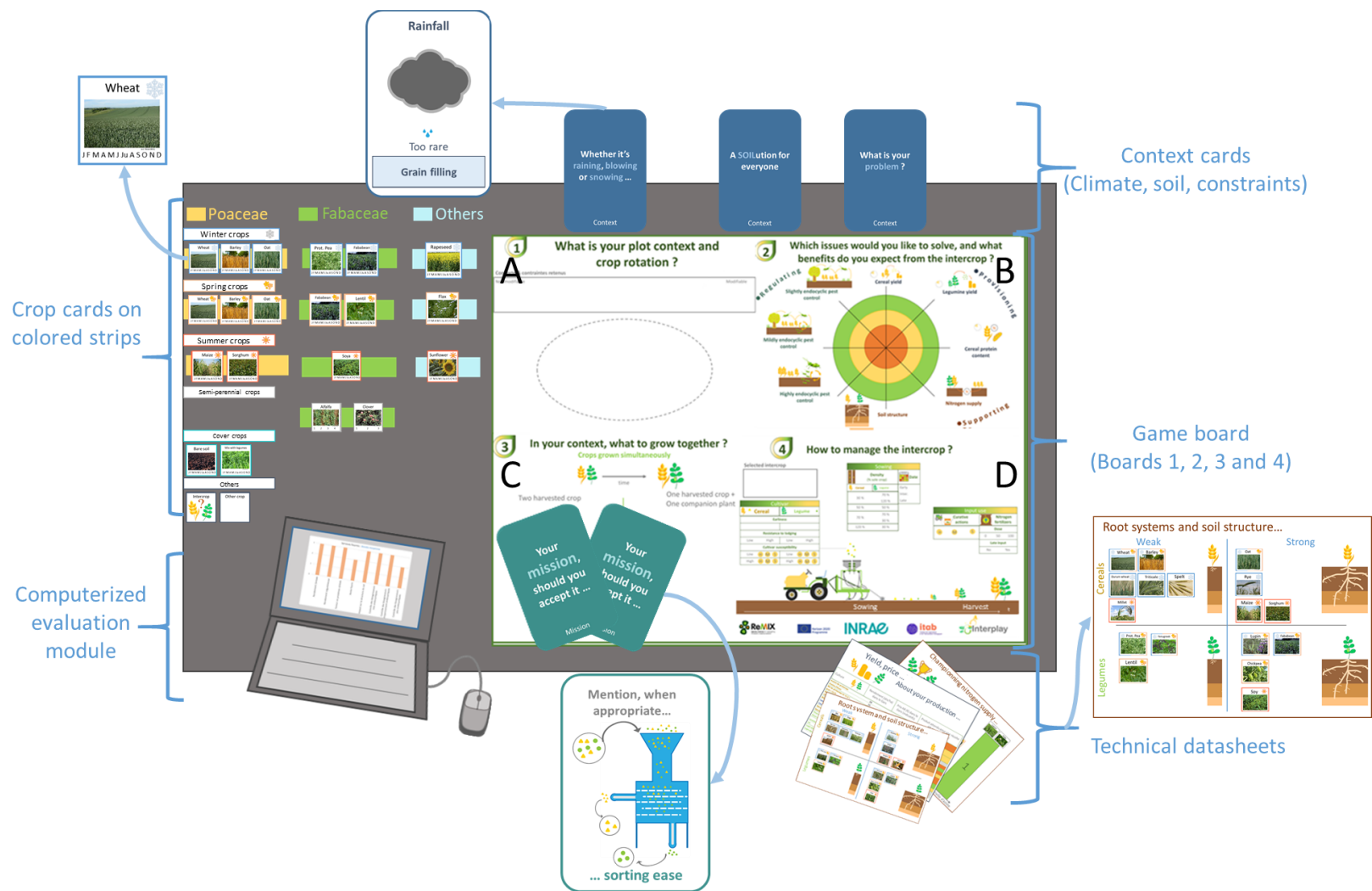
### 225 2.2.3. Context cards

226 Designing intercropping scenarios that are locally adapted to each cropping system implies a precise  
227 description of the context to ensure consistent proposals during the workshop (Lacombe et al., 2018;  
228 Martin et al., 2013). To facilitate this description and make it visual, we created context cards to be  
229 selected and placed on Board 1 (Fig. 1, Fig. 2). Three types of cards are provided reflecting the cropping  
230 system context (Fig. 1):

- 231 • Climate cards describe the main climate risks in the region and the period in the crop cycle  
232 during which they occur (e.g. drought at grain filling, frost risks at early stages);
- 233 • Soil cards represent the main soil characteristics, i.e. texture (e.g. sandy soil), depth (e.g.  
234 shallow soil), hydromorphy (e.g. draining soil), topography (e.g. steep field);
- 235 • Constraint cards inventory the main field constraints: irrigation and machinery availability  
236 (e.g. presence/absence of irrigation, harvesting and sorting equipment nearby), landscape  
237 impact on pest pressure (e.g. simplified landscape favouring pests).

238





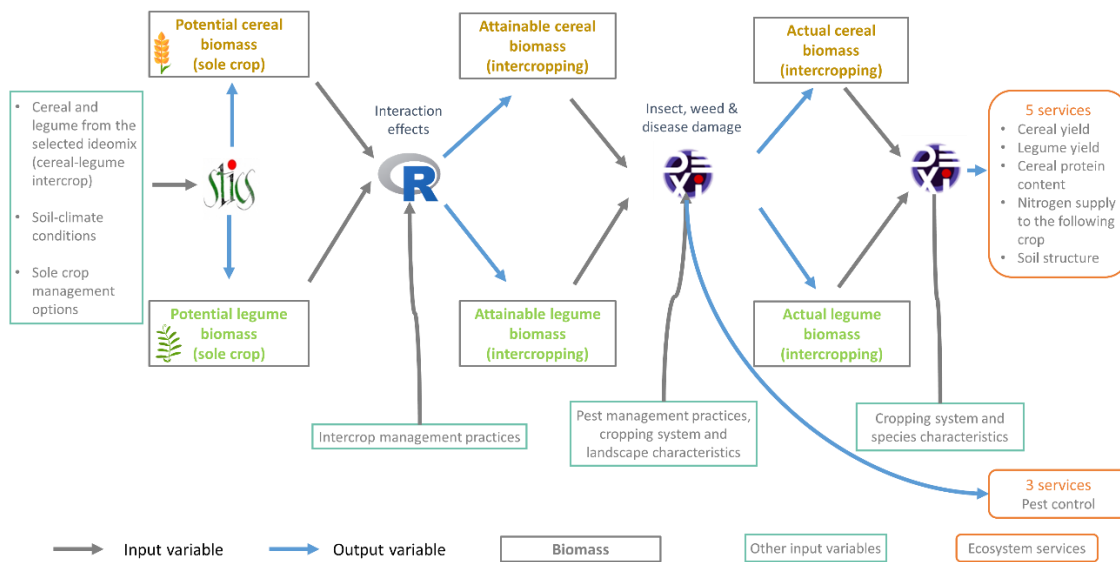
241 Figure 2: Boundary objects included in the Interplay game

242

### 243 2.2.4. Computerized support system – evaluation model

244 To support players’ reflections and estimate the performances of diverse intercrops, we designed an  
 245 evaluation framework based on a hybrid modelling chain that assesses the ecosystem services  
 246 provided by a large diversity of intercropping scenarios (Meunier et al., 2021). The framework  
 247 considers the cropping system context, intercropped species and management practices defined on  
 248 the game board. In this modelling chain, we first use the crop model STICS (Brisson et al., 2003) to  
 249 simulate potential biomass of the sole cereal and legume crops independently in different contexts  
 250 (Fig.3). We then correct potential biomass in sole cropping to attainable biomass in intercropping  
 251 considering competition effects among species, thanks to linear interaction models built in R (R Core  
 252 Team, 2018) based on a field trial database (Gaudio et al., 2021). We finally turn attainable biomass  
 253 into actual biomass considering pest damage thanks to a knowledge-based multi-attribute DEXi model  
 254 (Bohanec, 2008). This model qualitatively assesses pest control (including insect, weed and disease  
 255 control) according to pest levels of endocyclism, defined by Aubertot and Robin (2013) as the level of  
 256 dependence of pests on the cropping system (field endo-inoculum and history, distance of dispersion  
 257 of pests from the field, pest life-cycle completed partly or fully on the field). We use another set of  
 258 multi-attribute DEXi models to assess five additional ecosystem services quantitatively (i.e. cereal and  
 259 legume grain yield, cereal protein content, nitrogen supply to the following crop) and qualitatively (i.e.  
 260 soil structure) from the actual biomass of the intercrop at harvest and/or cropping system features  
 261 (e.g. species root system architecture, C:N ratio, cultivar characteristics (Fig.3)).

262



263

264 Figure 3 : Modelling chain included in the evaluation model of the Interplay game (adapted from  
 265 Meunier et al. (2021)).

266 We used the STICS (v. 9.1) crop model to predict the potential biomass of all the cereal and legume  
 267 species included in the game as sole crops, under diverse soil-climate conditions. As STICS is not  
 268 parameterized for all the cereal and legume species available in the game, we asked experts to create  
 269 groups of species with similar biomass production potential, and defined a model species in each  
 270 group: winter wheat, spring barley, maize, sorghum, winter and spring pea, winter and spring faba

271 bean (Falconnier et al., 2019), lentil and soya bean. When experts suggested that the cultivar strongly  
272 influenced potential biomass of model species, to account for intraspecific variability, we considered  
273 various cultivars with different precocity to simulate the largest range of potential biomass. For each  
274 cultivar, we simulated three sowing dates and scenarios with or without irrigation on the basis of  
275 experts' recommendations. As STICS simulations predicted potential biomass, experts defined optimal  
276 sowing density and doses and dates of nitrogen fertiliser applications for each model species to avoid  
277 nitrogen stress under low-input farming conditions. As we simulated non-limiting nitrogen conditions,  
278 we did not distinguish organic and conventional low-input situations.

279 To predict attainable biomass of the intercropped cereal and legume species based on potential  
280 biomass of their corresponding sole crops, we developed a statistical model using R software v. 3.6.3  
281 (R Core Team, 2018) (Fig.3). We used a database of trials conducted in five European countries from  
282 2001-2017, with several cultivars of four winter species and seven spring species (Gaudio et al., 2021).  
283 The database included pairwise data on the biomass of cereals and legumes under intercropping and  
284 sole-cropping conditions. Complete data were available for 183 experimental units covering four  
285 ideomixes (i.e. expert-defined groups of cereal-legume intercrops with similar behavior: winter cereal  
286 – pea, winter cereal – faba bean, spring cereal – lentil and spring cereal – pea, all details available in  
287 Meunier et al. (2021)). Using this database, we built two linear models to predict the attainable  
288 biomass of each species of the intercrop (one for the cereal and one for the legume). The two models  
289 included the same input variables (cereal and legume characteristics, management practices and  
290 climate variables from sowing to harvest (P = precipitation, ETP = evapotranspiration, GR = global  
291 radiation, T = temperature)), which were selected based on their agronomic effects on the relationship  
292 between sole crop biomass and intercrop biomass:

293 **Associated cereal biomass** = f (Sole cereal biomass + Sole legume biomass +  
294 crop season + cereal potential height + legume potential height +  
295 relative nitrogen fertilization of the cereal + relative sowing density of the cereal +  
296 relative sowing density of the legume +  $\sum(P - ETP) + \sum GR + \sum T_{mean}$ )

297 **Associated legume biomass** = f (Sole cereal biomass + Sole legume biomass +  
298 crop season + cereal potential height + legume potential height +  
299 relative nitrogen fertilization of the legume + relative sowing density of the cereal +  
300 relative sowing density of the legume +  $\sum(P - ETP) + \sum GR + \sum T_{mean}$ )

301 We assessed the statistical performances of the two models using adjusted coefficients of  
302 determination (Adj. R<sup>2</sup>) on the full dataset and RMSE on (i) the full dataset, (ii) a random split of the  
303 dataset (75% of individuals to train the model and 25% to test it) and (iii) a predetermined split of the  
304 dataset (3 of the 4 ideomixes to train the model and the 4<sup>th</sup> to test it). Model predictions for  
305 intercropped cereal and legume biomass were reliable for all ideomixes. Adj. R<sup>2</sup> was 0.6 and 0.7 for the  
306 legume and cereal respectively, relative RMSE ranged from 27-37% for the two models, regardless of  
307 which dataset they had been trained with, which is similar to performances of other crop models (e.g.  
308 relative RMSE of 35% for attainable biomass with STICS; Coucheney et al., 2015). The predictions  
309 remained more accurate on ideomixes included in the database of trials.

310 We relied on experts to build a multi-attribute model in DEXi (Bohanec, 2008) to assess the eight  
311 chosen ecosystem services provided by each scenario designed on the game board. The multi-attribute  
312 model was intended to be simple, i.e. to include a few readily available input variables and to be

313 applicable to all ideomixes. We organized meetings with experts to define relevant input variables to  
314 estimate each ecosystem service and to build the related multi-attribute DEXi trees (i.e. defining by  
315 mutual agreement “if-then” decision rules and aggregation tables). Experts built a first multi-attribute  
316 model to convert attainable biomass into actual biomass considering pest damage in various  
317 conditions, considering susceptibility of the two crops preceding the intercrop to the same pests,  
318 tillage strategy, cultivar susceptibility, impact of the landscape on pests, sowing date and curative  
319 actions as input variables. Intercropped cereal and legume actual biomass was then used to assess the  
320 other ecosystem services : legume yield (assessed from actual cereal and legume biomass and cereal  
321 and legume lodging risks as input variables), cereal yield (actual cereal biomass and lodging risk), cereal  
322 protein content (actual cereal biomass, late nitrogen intake), nitrogen supply to the following crop  
323 (actual cereal and legume biomass (to consider residue left as mulch), cereal and legume C:N ratio),  
324 and soil structure (actual cereal and legume biomass, cereal and legume root system). Experts defined  
325 pest control services as inversely proportional to pest damage. A Monte-Carlo sensitivity analysis of  
326 all DEXi trees included in the modelling chain showed a slight overrepresentation of low classes of  
327 ecosystem services. This implies a conservative and relatively pessimistic assessment of the ecosystem  
328 services provided, which can be consistent with low-inputs systems having lower levels of certain  
329 services (e.g. yield and cereal protein content).

330 To verify the consistency of the levels of ecosystem services assessed by our modelling chain, in  
331 addition to the assessment of the performances of each model of the chain, we organized three  
332 meetings to discuss the results of the modelling chain with experts. We defined 18 scenarios for three  
333 well-known ideomixes (i.e. winter cereal-pea, spring cereal-pea and spring cereal-faba bean) to  
334 maximize the use of experts’ knowledge. For each ideomix, we tested two soil-climate conditions,  
335 levels of nitrogen input, cereal cultivars, sowing densities for the cereal and legume in the intercrop  
336 and levels of pest damage. For each scenario and ecosystem service, each expert assessed the level of  
337 ecosystem service provided by allocating ten poker chips to represent the probability of attaining each  
338 level under the specific scenario. We then summed the number of chips for each level of ecosystem  
339 service and compared the level chosen most frequently to the modelling chain output. The levels of  
340 ecosystem services assessed by the modelling chain were consistent with experts’ predictions for 79%  
341 of the scenarios.

342 The hypotheses, design and performances of the modelling chain are described further in Meunier et  
343 al. (2021). This modelling chain is compiled on a spreadsheet as a ready-to-use tool for the workshop  
344 facilitator, who does not necessarily need to understand in detail of how the modelling chain is built.  
345 The results of the modelling chain are easily accessible to players via an interface (Fig.4) that  
346 summarizes each intercropping scenario input variables, i.e. cropping system context and field history,  
347 species choice and management practices (Fig.1, Fig.4). It then assesses, for an average climate year,  
348 (i) the level of ecosystem services provided by the simulated scenario; and (ii) the level of attainable  
349 and actual biomass. Guided by their facilitator, players can analyse the level of each ecosystem service  
350 provided by examining the input variables used in its calculation and their values. These variables are  
351 presented on datasheets provided to players to support knowledge exchanges amongst them on  
352 processes involved in the establishment of each ecosystem service. Players thus benefit from an  
353 accessible tool that helps compare the designed scenario outputs to the scenario farmer objectives  
354 through easily explainable and transparent graphs summarizing the scenario assessment (Fig. 4). If  
355 deemed necessary, players can adapt their scenario through additional design-evaluation loops to try  
356 to get closer to expected levels of ecosystem services or realize they are not achievable. In addition to

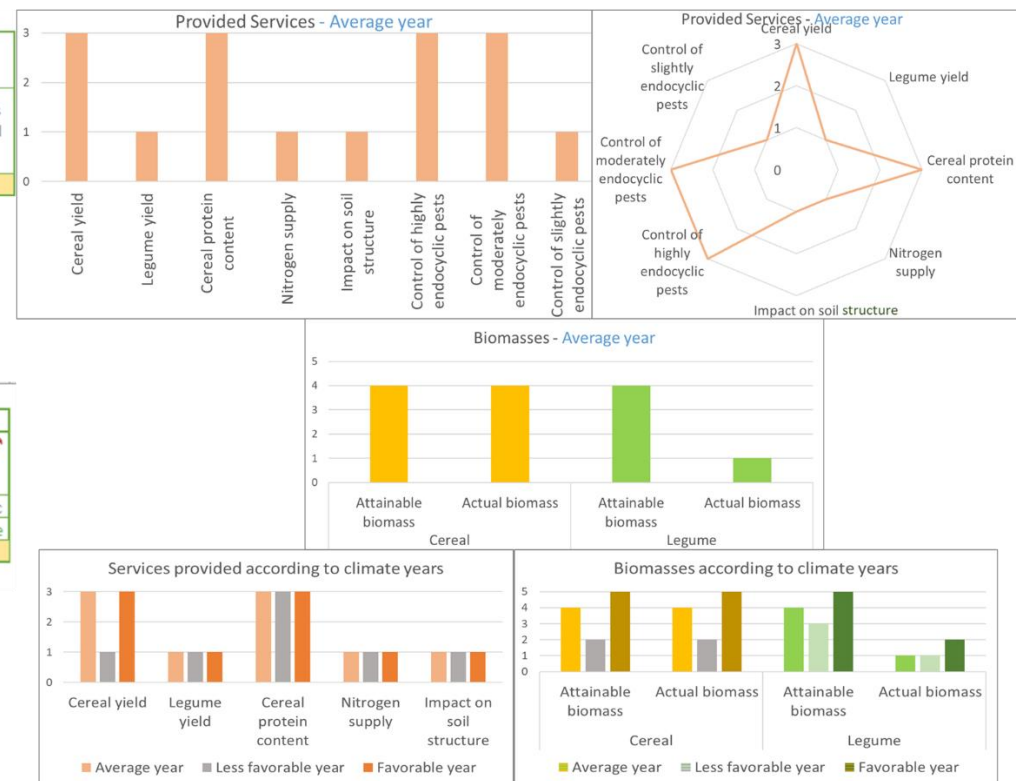
357 the average climate year, levels of ecosystem services, attainable and actual biomass are also assessed  
358 for less-favourable (e.g. frost, drought) and more favourable years for biomass production. Players can  
359 use these additional results to discuss the climate resilience of the designed scenarios.

360

361

Input										
Context										
<b>Soil-Climat</b>			<b>Constraints</b>		<b>Rotation and cropping system</b>				<b>Landscape</b>	
Region	Site	Soil	Farming type	Irrigated plot	Pre-previous crop susceptibility to the same	Previous crop susceptibility to the same pests	Tillage post pre-previous crop harvest	Tillage post previous crop harvest	Landscape impact on pests (host plants, agroecological infrastructures)	
Centre	site19	314	Conventional	Yes	Host	Host	Yes	No	Favorable to pests	
Species to grow together & Characteristics										
<b>Selected species</b>			<b>C/N</b>		<b>Root system</b>					
Season	Cereal	Legume	Cereal	Legume	Cereal	Legume				
Winter	Wheat_Winter	Protein_pea_Winter	High	Low	Weak	Weak				
Management practices										
Cultivar										
<b>Cultivar earliness</b>			<b>Resistance to lodging</b>			<b>Susceptibility to Pests</b>				
Cereal		Legume	Cereal		Legume	Highly endocyclic		Moderately endocyclic		Slightly endocyclic
Between emergence	Between head	Full cycle	High	Low	Low	High	Low	High	Low	High
Early	Early	Not_applicable								
Sowing					Input use					
Sowing date		Sowing density		Curative action			Nitrogen fertilization			
		Cereal	Legume	Highly endocyclic pests	Moderately endocyclic pests	Slightly endocyclic pests	Dose	Late intake		
Early		C_0.5	L_0.5	Yes	Yes	No	100	Yes		

Output



362

363

364

Figure 4: Overall structure of the inputs and outputs provided by Interplay evaluation model. 0 to 3 scales : 0 = None, 1 = Low, 2 = Intermediate, 3 = High. For 0 to 5 scales : 0 = None, 1 = Very low, 2 = Low, 3 = Intermediate, 4 = High, 5 = Very high.

365

#### 366 2.2.5. Complementary elements

367 The game board, crop cards, context cards and evaluation model are essential supports for an Interplay  
368 session. Additional elements can be added by the facilitator to support players' reflection on the choice  
369 of the most consistent species to intercrop within the frame of the cropping system context and  
370 scenario farmers' objectives (Fig.1). We included five mission cards in the game (Fig. 2), each of them  
371 representing one of the main lock-ins (Fig. 1) that may prevent the introduction of intercropping in a  
372 cropping system at the farm level (compatibility with the working schedule, machinery availability) and  
373 at the socio-economic environment level (knowledge availability, existence of outlets, sorting ease)  
374 (Mamine and Farès, 2020; Meynard et al., 2018; Verret et al., 2017). If the facilitator notes that the  
375 players do not spontaneously mention all the lock-ins inventoried on mission cards during the  
376 discussion on the most locally adapted species combination, he/she distributes mission cards to  
377 players and gives each of them the role of ensuring that the lock-in mentioned on their card is  
378 considered in the final choice (e.g. can wheat and lentil easily be sorted with the machinery available  
379 locally?). We also created up-to-date and easily accessible technical datasheets (Fig. 2) that synthesize  
380 scientific knowledge on uncommon species (e.g. lupine, fenugreek) and understudied ecosystem  
381 services (e.g. impact of the intercrop on soil structure). These datasheets propose, for all the game  
382 species, an estimation of the yield and selling price in the region, a typology of their root system and a  
383 ranking of the potential nitrogen supply of different legume species to the following crop. Technical  
384 datasheets aim at supporting players' exploration of a wide range of intercropping scenarios and  
385 promoting hybridization of this scientific knowledge with players' empirical knowledge during the  
386 workshop.

#### 387 2.2.6. The role of the facilitator

388 Interplay aims at being used with groups of players, guided through the several design stages by a  
389 facilitator. The facilitator, either an advisor (when playing with farmers) or a teacher (when playing  
390 with students), needs to know all the game elements and how to use them through the design stages  
391 to promote knowledge elicitation (Martin et al., 2011). He/she asks probing questions to stimulate the  
392 discussion among players, and requests clarification and agreement to ensure that all decisions are  
393 shared, and considered salient, credible and legitimate by all players (Cash et al., 2003). He/she may  
394 have to provide inputs when players lack knowledge, by either using the technical datasheets provided  
395 or his/her own expertise, especially when using the game with students that are less familiar with  
396 cropping systems than farmers. Thus, it is preferable that the facilitator has sufficient knowledge of  
397 cropping systems and intercropping to stimulate scenario exploration and analysis of levels of  
398 ecosystem services provided. The facilitator needs to be careful to provide inputs only when the  
399 players ask specific technical questions or need information to make a decision, and not to influence  
400 the design process otherwise.

401

#### 402 2.3. Playing the game

403 The first stage of playing the game consists of presenting to the players the context and the initial  
404 situation of the scenario farmer's studied field so as to define the cropping system context (Fig. 1). The  
405 facilitator (when playing with students) or the scenario farmer (when playing with farmers) then  
406 presents the main problems faced in the crop rotation, the sole crop to substitute with an intercrop

407 and the crop management of this current sole crop. These elements are progressively materialized on  
408 the game board to help other players become familiar with the game (Fig.2). The facilitator uses the  
409 evaluation model to assess the level of services provided by the initial sole crop to define the baseline  
410 scenario and discusses the results with the players. The scenario farmer or the facilitator then defines  
411 the desired objectives, i.e. the levels of ecosystem services expected from the intercrop (Fig. 2).

412 Once this presentation stage is over, the game consists of iteratively designing cereal–legume  
413 intercropping scenarios, assessing the levels of ecosystem services they provide in the specific cropping  
414 system context and comparing these levels to the defined objectives and to the performances of the  
415 sole crop. For instance, if the main objective is to increase nitrogen supply to the following crop, the  
416 evaluation process aims at verifying (among other things) that the designed intercrop provides more  
417 nitrogen than the initial sole crop, and that the level provided is consistent with the scenario farmer’s  
418 expectations. Otherwise, additional design and evaluation feedback loops are conducted until this  
419 objective is achieved.

420 To design an intercrop, the facilitator first asks players to think about which species to associate. They  
421 begin by individually proposing two species to associate, so as to avoid censorship or self-censorship,  
422 and positioning crop cards on Board 3 (Fig.2). If necessary, they can utilize the technical datasheets  
423 during this stage. Once all proposals are made, players discuss these, challenge each others ideas and  
424 share their experiences in order to select by consensus the most appropriate intercrop. They can use  
425 the mission cards distributed by the facilitator to ensure that they overcome the main lock-ins at the  
426 farm and socio-economic environment levels. Players then design intercrop management by discussing  
427 each of the choices to be made on Board 4 (Fig.2), and circling the option they collectively select.

428 The facilitator enters all the decisions made by players on the game board in the evaluation model and  
429 launches the simulation. Players discuss the simulation results, i.e. levels of ecosystem services  
430 provided by each intercropping scenario, considering: (i) the match with the defined objectives; (ii) the  
431 analysis of the reasons for a mismatch (e.g. why does the intercrop provide a low level of nitrogen  
432 supply when a high level was expected?); and (iii) the differences between the levels of services  
433 provided by the intercropping scenario and by the reference sole crop or another intercropping  
434 scenario. This analysis should lead to proposals of modifications in the intercropping scenario if the  
435 objectives are not achieved.

436

### 437 **3. Application of Interplay with agriculture students**

#### 438 3.1. Design content

439 We organized six workshops in April 2021 to design intercrops to improve nitrogen supply to the  
440 following crop. These workshops involved French BSc and MSc level agriculture students as main  
441 players and were held online due to the Covid-19 pandemic. Each session lasted between two and  
442 three hours and involved six to twenty students. In total, over 70 students were involved. An agronomy  
443 teacher was also present for 3 out of 6 workshops. At each session, three researchers involved in the  
444 game development or providing punctual help were responsible for the facilitation (C. Meunier), for  
445 using the evaluation model (punctual help of M. Albert) and for observation (M. Casagrande or B.  
446 Rosiès) respectively. At the end of each session, the students and the teacher were asked to fill in a  
447 feedback sheet, on which they had to comment on i) their satisfaction regarding the session,  
448 considering both their expectations and the atmosphere of the workshop ; ii) their perception of



449 whether the workshop has fulfilled its initial objectives, regarding what they had discovered and what  
450 knowledge they had mobilized from previous lessons ; iii) their feeling about the game, regarding its  
451 ease of use and clarity of the guidelines provided; iv) their perceived interest about using serious games  
452 on other issues. Spontaneous oral feedback was also collected once the feedback sheets were filled in,  
453 including aspects not mentioned in the sheets.

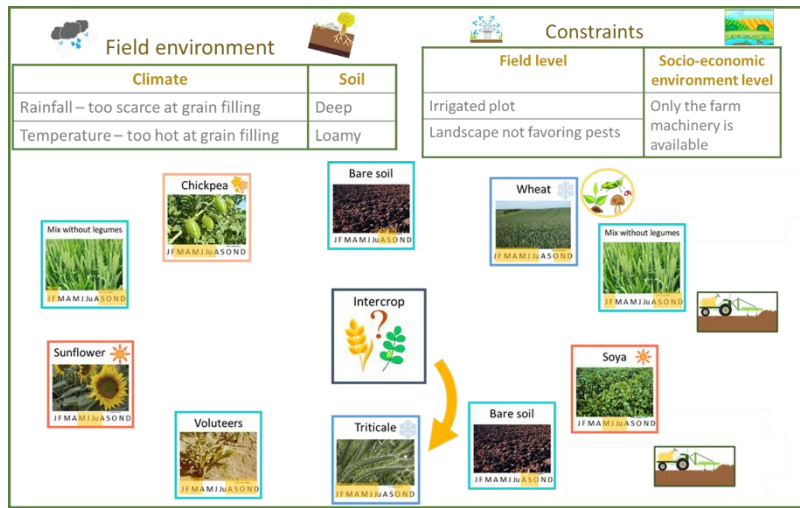
### 454 3.2. Scenario definition

455 Involving students as players implied defining a standard scenario, as, unlike farmers, students do not  
456 have their own farm to serve as a scenario basis. We thus designed a typical cropping system, on  
457 which students worked collectively during each session:

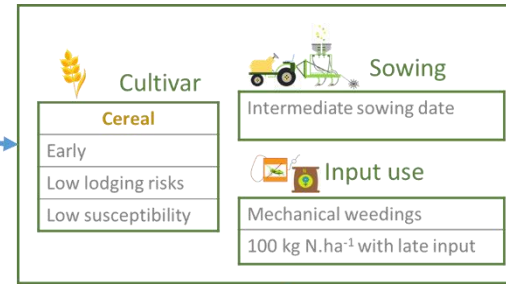
- 458 ● Located in the students' and researchers' work region (i.e. South West of France for 5 out of 6  
459 workshops, North West of France for the last one), yet it can easily be adapted to another  
460 region. Regarding the chosen cropping system context of this farm, the climate was temperate  
461 yet risks of drought during summer were high, soils were deep, loamy and slightly compacted,  
462 the field was irrigated, the landscape was diversified enough to not favor pests and the farmer  
463 already owned all the necessary harvesting and sorting machinery;
- 464 ● A standard crop rotation for an organic farm in the region (winter wheat – soya bean – triticale  
465 – sunflower – chickpea, Fig. 5), that can also be easily adapted for a different region if  
466 necessary, by replacing any crops that cannot be grown;
- 467 ● Typical crop management for the sole cereal crop to be substituted with an intercrop (early  
468 triticale cultivar, resistant to lodging and with a low susceptibility to pests, sown at 300 gr.m<sup>-2</sup>  
469 around the 15<sup>th</sup> of November, with mechanical weeding and organic nitrogen inputs to reach  
470 100 kg available N.ha<sup>-1</sup> including a late application to boost cereal protein content, Fig. 5);
- 471 ● High cereal yield but suffering from a lack of nitrogen through the crop rotation due to grain  
472 legume crops (soybean, chickpea) supplying low levels of nitrogen to the following crops  
473 (Fig.5).

474 The objectives of the scenario farmer were to improve nitrogen supply without overly decreasing  
475 cereal yield and improving or maintaining soil structure when substituting a sole cereal by an intercro

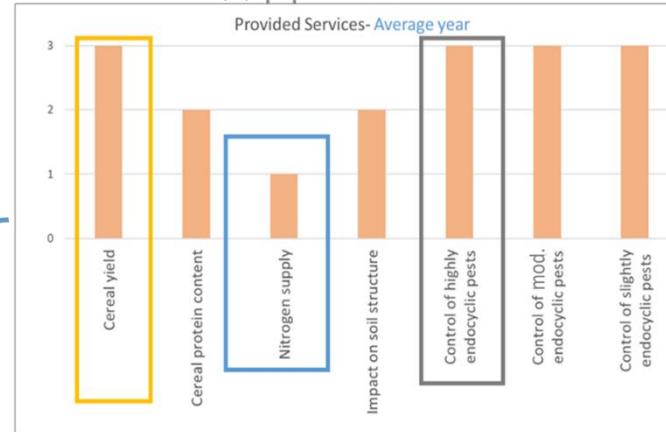
### 1. Cropping system context and crop rotation



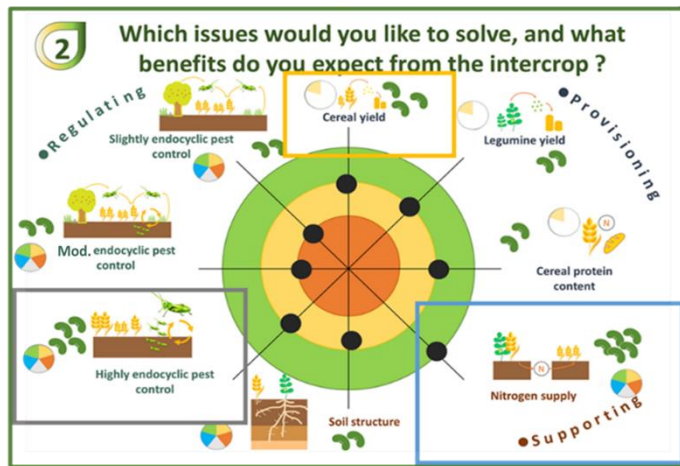
### 2. Sole crop management practices



### 3. Sole crop performances



### 4. Scenario farmer's objectives



476

477 Figure 5: Standard scenario proposed to students to design intercropping scenarios improving nitrogen supply.

478

479 The workshop reported in this article involved 20 students from an agricultural university in their last  
480 BSc year. They already knew each other well and were accompanied by their agronomy teacher. We  
481 chose to report this workshop as it is a good example (among others) of a typical Interplay session,  
482 that exemplifies the description of the game made in Section 2. Reporting on this session may help the  
483 reader visualize how the game works in practice.

### 484 3.3. Designing intercropping scenario

#### 485 3.3.1. Species choice

486 Once the standard scenario was presented by the facilitator (C. Meunier), students' individual  
487 reflection on the choice of the species to intercrop led to fourteen proposals, including seven winter,  
488 three spring and two summer intercrops. The two remaining ideas involved a winter cereal and a spring  
489 legume and these were automatically set aside by the facilitator as they could not be simulated since  
490 these species differ in their sowing date. During the debate to select species mixtures, students and  
491 their teacher first focused on winter crops as the teacher mentioned they could break pest cycles in  
492 the crop rotation that already involved many spring and summer crops (Fig. 5). Even though pest  
493 control was not the main priority for the scenario farmer, the teacher explained that high pest damage  
494 would prevent the attainment of a high level of any other ecosystem service. Students then analyzed  
495 the scenario farmer's main objective (improve nitrogen supply), as recommended by the facilitator.  
496 Among winter legumes, they decided to eliminate lupin because of its low nitrogen supply ability, as  
497 indicated in the technical datasheets provided. Among cereals, the teacher advised his students to set  
498 aside wheat and durum wheat due to their high nitrogen demand compared to other cereals (Fig. 6).  
499 Students then discussed the ease of sorting harvested intercrops as proposed on the mission cards,  
500 and they decided that intercrops involving faba beans were the most promising. Indeed, their teacher  
501 argued that it is hard to sort cereal-pea as the grains have similar size, or cereal-fenugreek as  
502 fenugreek grains are so small they can be lost with contaminants. Finally, students highlighted that the  
503 faba bean's strong root system was consistent with the scenario farmer's second objective (improve  
504 or maintain soil structure). They decided that, given the strong legume root system, they could choose  
505 a cereal with a more superficial root system as they thought it would lower competition by exploring  
506 different soil horizons. They opted for barley, which was, according to them, a good compromise  
507 between high potential yield, low nitrogen demand and a superficial root system. After checking-up  
508 on the other issues mentioned on mission cards (machinery and knowledge availability, existence of  
509 an outlet, compatibility with the working schedule) on the facilitator's demand, students and their  
510 teacher decided that the chosen mixture, i.e. barley-faba bean was suitable (Fig. 6).

#### 511 3.3.2. Integration in the crop rotation

512 Once the species of the intercrop were chosen, the facilitator asked participants to reconsider the  
513 introduction of the intercrop in the crop rotation (winter wheat – soya bean – intercrop – sunflower –  
514 chickpea). Students and their teacher assessed that there were pests, weeds and diseases in common  
515 between winter barley of the intercrop and the winter wheat grown as the pre-previous crop (Fig. 6).  
516 Conversely, they did not identify common pest risks between the previous soybean and faba bean of  
517 the intercrop, especially as their teacher highlighted that, in his knowledge, soybean was not impacted  
518 by anthracnose, the most common disease of faba bean. The group decided to use tillage to destroy  
519 the cover crop following the pre-previous winter wheat. The students agreed to suppress tillage  
520 following soybean as they thought it would lower the risk of contaminating the intercrop by bringing

521 back to the surface wheat residues potentially infected by common pathogens, as mentioned by their  
522 teacher (Fig. 6).

### 523 3.3.3. Intercrop management practices selection

524 As proposed on the game board, students first discussed the necessity to sow barley and faba bean  
525 cultivars with compatible earliness. As the faba bean cultivars available on the market were quite  
526 similar regarding earliness and were compatible with all earliness possibilities for barley, students  
527 chose an early barley cultivar as they thought it would avoid the possibility of too high temperatures  
528 during flowering and grain filling, as frequently observed in this region (Fig. 6). As students lacked  
529 knowledge on specific management practices, their teacher helped them to make some of the  
530 following technical choices. He considered that barley was globally sensitive to lodging, whereas faba  
531 bean was not. He also estimated that barley was globally resistant to all types of pests, mostly basing  
532 his comparison on winter wheat susceptibility. On the contrary, he suggested faba bean was globally  
533 sensitive to all types of pests with, in his experience, anthracnose and bruchids as the main risks.  
534 Students proposed a late sowing date (around 15<sup>th</sup> of December for France) to improve weed control  
535 thanks to the false-seed bed technique and insect and disease control thanks to a risk avoidance  
536 strategy. They felt it would be consistent with the scenario farmer's desire to keep highly endocyclic  
537 pest control (including weed, insect and disease control) at an intermediate level. Students voted for  
538 a balanced mixture, with both cereal and legume sown at 50% of their standard sowing density in sole  
539 crop, as they thought it was a good compromise between the need to increase legume biomass to  
540 supply nitrogen, and the scenario farmer's desire not to overly decrease the cereal yield. Regarding  
541 input use, considering the organic production, they proposed mechanical weeding, which  
542 corresponded, according to the facilitator and consistently with technical datasheets, to curative  
543 actions on slightly and mildly endocyclic pests. They decided not to apply any nitrogen fertilization as  
544 they thought it would maximize the development of rhizobia for nitrogen fixation in nodules on the  
545 legume roots (Fig. 6).

### 546 3.3.4. Analysis of the first intercropping scenario

547 The assessment of the first intercropping scenario (Scenario 1) with the evaluation model showed  
548 promising results regarding pest control, that was as effective as in the sole cropped cereal (i.e. high  
549 control for all types of pests (Fig.7)) and regarding the crop impact on soil structure, which was  
550 intermediate as the scenario farmer desired. Legume yield and cereal protein content were both at an  
551 intermediate level (i.e., yield for faba bean from 1.9 to 2.6 t.ha<sup>-1</sup> and barley protein content from 10 to  
552 12%), which was consistent with the scenario farmers' objectives (Fig.7), although it was not his/her  
553 priority. However, nitrogen supply to the following crop reached an intermediate level (40 to 80 kg  
554 N.ha<sup>-1</sup>; Fig.6) while the objective was a high level (more than 80 kg N.ha<sup>-1</sup>). Similarly, cereal yield was  
555 low (less than 1.9 t.ha<sup>-1</sup>; Fig.7) whereas the target was to maintain it at or above an intermediate level  
556 (1.9 to 2.6 t.ha<sup>-1</sup>). By examining the results provided by the evaluation model and the multi-attribute  
557 trees used to assess ecosystem services, the facilitator explained that the low cereal yield was due to  
558 an intermediate actual biomass (4.5 to 6 t.ha<sup>-1</sup>) for the cereal combined with a high lodging risk. The  
559 facilitator also mentioned that the intermediate nitrogen supply was explained by the cereal and the  
560 legume having quite similar biomass production (intermediate, i.e., 4.5 to 6 t.ha<sup>-1</sup> for the cereal and  
561 high, i.e., 3 to 3.5 t.ha<sup>-1</sup> for the legume). The legume was, in this case, not sufficiently developed as  
562 compared to the cereal to lower the C:N ratio of the intercrop residue and lead to a low level of  
563 nitrogen supply to the following crop.

564

565 3.3.5. Adjustments of the first intercropping scenario to meet objectives

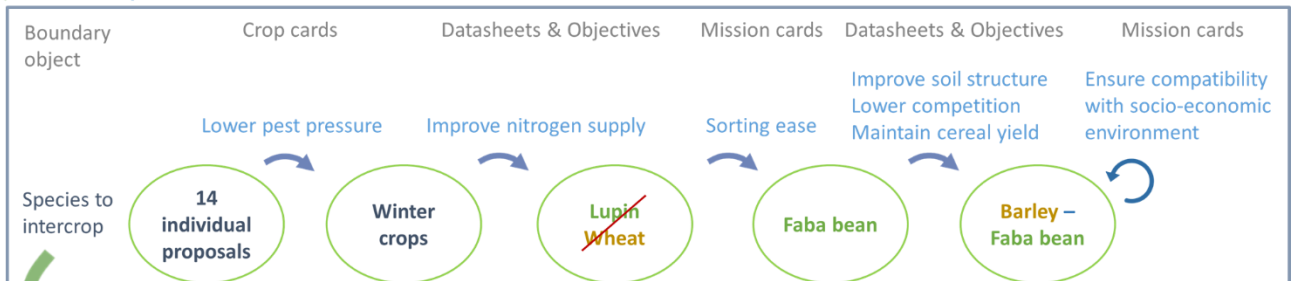
566 Given this first analysis, students concluded that intercropped cereal yield and nitrogen supply were  
567 two opposing services, and proposed the following modifications:

- 568
- 569 • Sow earlier (around the 15<sup>th</sup> of October) as they thought it may help avoid climatic risks and  
570 increase biomass (Scenario 2). Yet, no curative action was applied on slightly endocyclic pests  
571 despite faba bean being judged very sensitive to these pests by the teacher. Therefore, faba  
572 bean actual biomass decreased to a very low level (less than 2 t.ha<sup>-1</sup>) due to pest damage, as  
573 explained by the facilitator. Cereal yield, legume yield and nitrogen supply were consequently  
574 low (i.e. less than 1.9 t.ha<sup>-1</sup>, less than 1.6 t.ha<sup>-1</sup> and less than 40 kg N.ha<sup>-1</sup> respectively), as well  
575 as the impact on soil structure. Consequently, students decided to not retain this option (Fig.  
576 6);
  - 577 • Lower cereal density and higher legume density (respectively 30 and 70% of the sole crop  
578 density) without modifying pest management options (only actions on highly and mildly  
579 endocyclic pests through mechanical weeding) to maximize nitrogen supply, even though  
580 cereal yield would remain low (less than 1.9 t.ha<sup>-1</sup>) (Scenario 3). This improved legume yield to  
581 a high level (more than 2.2 t.ha<sup>-1</sup>), but did not improve nitrogen supply which remained at an  
582 intermediate level (40 to 80 kg N.ha<sup>-1</sup>). Students then favored the legume even more  
583 (respectively 120 and 30% of the sole crop sowing density) still without modifying pest  
584 management options, which allowed a high level of nitrogen supply (over 80 kg N.ha<sup>-1</sup>) and an  
585 intermediate level of impact on soil structure to be achieved as at least desired by the scenario  
586 farmer (Scenario 4). This scenario matched all of the targeted objectives, apart from cereal  
yield that was decreased to a low level (less than 1.9 t.ha<sup>-1</sup>) (Fig. 7).

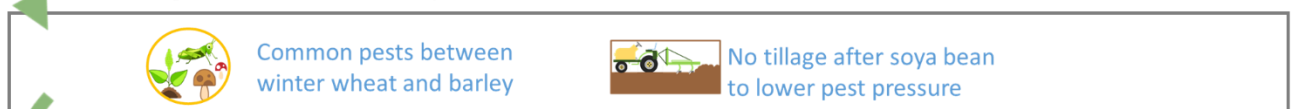
## 0. Performances of the sole crop and objectives

Ecosystem services	Sole crop performances	Objectives
Cereal yield	High	At least intermediate
Nitrogen supply	Low	High
Impact on soil structure	Intermediate	At least intermediate

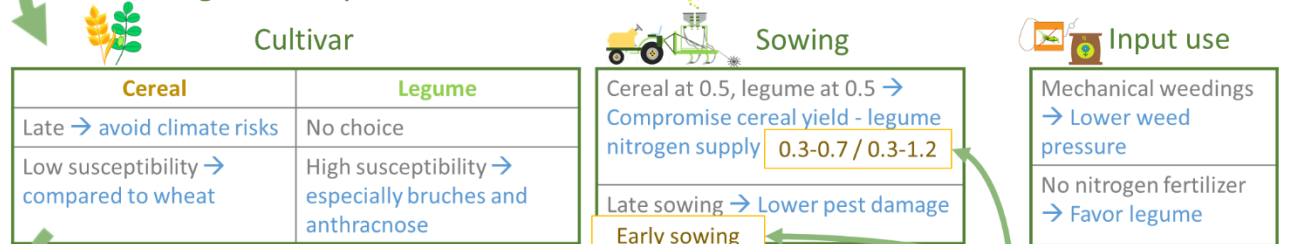
### 1. Species choice



### 2. Integration in the crop rotation



### 3. Management options selection



### 4. Analysis of the first scenario

### 5. Adjustments of the scenario

Ecosystem services	Objectives	Performances of the first scenario		Performances of the last scenario (late sowing, cereal at 0.3-legume at 1.2)	
Cereal yield	At least intermediate	Low	<b>X</b>	Low	<b>X</b>
Nitrogen supply	High	Intermediate	<b>X</b>	High	<b>V</b>
Impact on soil structure	At least intermediate	Intermediate	<b>V</b>	Intermediate	<b>V</b>

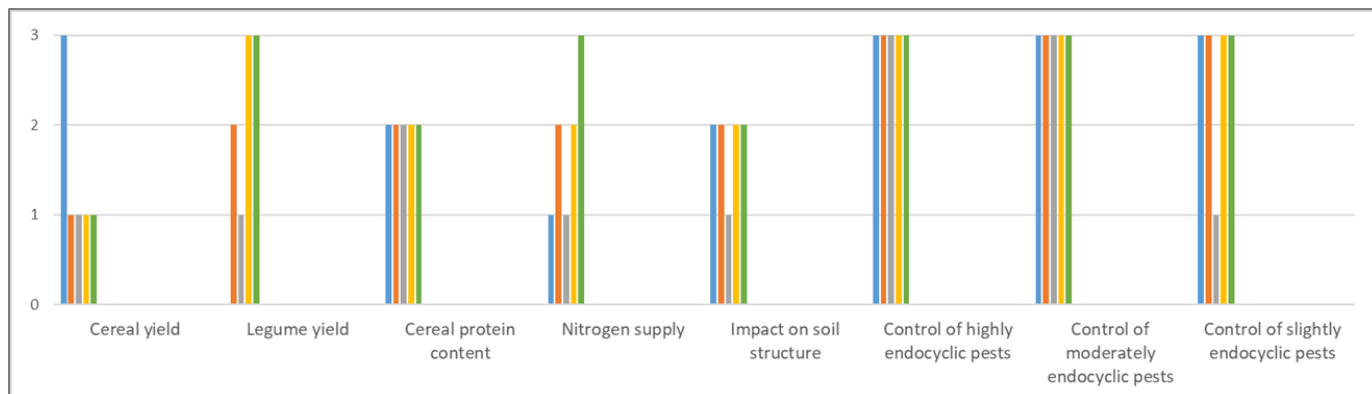
Objective / Reason

Design stages

587

588

Figure 6: Overview of Interplay design process and results obtained during a workshop.



- Scenario 0 : Baseline scenario - Sole triticale
- Scenario 1 : Barley – faba bean, late sowing, cereal at 50%, legume at 50%
- Scenario 2 : Barley – faba bean, early sowing, cereal at 50%, legume at 50%
- Scenario 3 : Barley – faba bean, early sowing, cereal at 30%, legume at 70%
- Scenario 4 : Barley – faba bean, early sowing, cereal at 30%, legume at 120%

589

590 Figure 7: Comparison of the levels of ecosystem services provided by the designed intercropping  
 591 scenarios and the initial sole crop. 0 = None, 1 = Low, 2 = Intermediate, 3 = High.

592 3.3.6. Examination of other options at the crop rotation level to match the scenario farmer’s  
 593 objectives

594 During this workshop, students concluded that introducing the intercrop alone would make it difficult  
 595 to reach all of the scenario farmer’s objectives (Fig. 7), and that they had to prioritize either nitrogen  
 596 supply or cereal yield. The facilitator asked the students to reflect on other options that could be  
 597 mobilized to improve nitrogen supply at the crop rotation level to match the scenario farmer’s  
 598 objectives. They suggested introducing semi-perennial crops with a high potential nitrogen supply in  
 599 the crop rotation (e.g. alfalfa), and/or substituting grain legumes species in the crop rotation by other  
 600 grain legumes species with a higher nitrogen supply potential (e.g. substitute chickpea by spring pea),  
 601 which would require minor adjustments of the cropping system.

602

603 3.4. Benefits of using Interplay with students

604 Students involved in Interplay workshops reported in their feedback sheets that the game helped  
 605 increase their knowledge of ecosystem services provided by intercrops in a more playful and  
 606 interactive way than regular lectures. They also declared that the game helped them mobilize  
 607 theoretical knowledge and apply it in a concrete situation making it easier to memorize. Students  
 608 emphasized the importance of mission cards and technical datasheets (including the one presenting  
 609 the variables considered for the assessment of each ecosystem service). They also highlighted the  
 610 importance of the support from the facilitator and from their teacher, to enrich the debate as they  
 611 sometimes lacked specific knowledge. Information provided covered: (i) general agronomic knowledge  
 612 about cropping systems (e.g. species characteristics, impact of management practices on provided  
 613 ecosystem services, timing of introduction of a crop or intercrop in the crop rotation to control pests);  
 614 (ii) specific information about intercropping (which species can be combined and how to manage the  
 615 intercrop); and (iii) examination of the consistency of the choices made for the cropping system  
 616 regarding farm characteristics (e.g. working schedule, machinery) and socio-economic environment  
 617 (e.g. outlet, sorting ease). The pleasant workshop atmosphere helped students feel at ease and

618 supported their exploration of atypical proposals (e.g. oat–lupin or barley–fenugreek). Teachers  
619 involved in the workshops appreciated the interactive nature of the game and acknowledged its  
620 educational purpose, as they felt it helped students assimilate knowledge more easily thanks to the  
621 trial-and-error approach. They mentioned that students generally enjoy this type of interactive  
622 approach, which motivated their wish to include games like Interplay in their education program.

623 So far, the current version of the game has not been used with farmers due to the COVID19 pandemic.  
624 As for the use with students, Interplay would allow a large range of intercropping scenarios to be  
625 explored and may lead to concrete cropping system scenarios which could be implemented on the  
626 farm of the scenario farmer. It could support knowledge exchange among farmers with various  
627 backgrounds regarding intercropping and raise their awareness about ecosystem services provided by  
628 intercrops. We may assume the advisor would have less technical inputs to provide when playing with  
629 farmers compared to a teacher playing with students, especially if farmers with experience of  
630 intercropping are present.

631

## 632 **4. Discussion**

### 633 4.1. Interplay: a salient, legitimate and credible serious game

634 Interplay aims to allow players to explore a wide diversity of intercropping scenarios to increase their  
635 knowledge of intercrops, and thus relies on the three pillars suggested by Cash et al. (2003) to develop  
636 effective knowledge systems for sustainability.

637 First, Interplay is salient (i.e. relevant for practice) as it offers players a systems approach re-positioning  
638 intercropping in a cropping systems perspective that no other tool provides so far (Barot et al., 2017;  
639 Bedoussac and et al., 2014; Duchene et al., 2017). By supporting simulated experimentation on the  
640 impact of the introduction of an intercrop in a given cropping system, it allows players to develop  
641 anticipatory learning (Tschakert and Dietrich, 2010) on the most locally adapted species and  
642 management practices. Interplay has been tested with students, but also with scientists, advisors and  
643 farmers in France and in Scotland, during its development. Following the developments of previous  
644 serious games (e.g. Martin et al., 2011), players' feedback collected during each testing session and  
645 observers' comments has been integrated in the game through iterative improvements to match  
646 players' needs and expectations (e.g. introduction of information on crop selling prices in the region),  
647 and thus improve the game saliency. Interplay is calibrated for a wide diversity of intercropped species  
648 (all cereal-grain legume species sown simultaneously in a random pattern in France) and management  
649 practices, on diverse soil-climate conditions covering most arable areas in France, and thus allows each  
650 player to run simulations in a context that is close to their own.

651 Interplay is also legitimate, first of all because it transparently builds on an explicit conceptual model  
652 materialized on the game board which demystifies the design process (Fig. 1). This model is easily  
653 accessible and understandable by players as it remains simple. All the processes involved in the  
654 assessment of ecosystem services provided by intercrops can easily be explained by the facilitator,  
655 which favors players' familiarization with the underlying concepts (Liu et al., 2008; Voinov and  
656 Bousquet, 2010). The simulation model is also accessible to the facilitator and players through the  
657 interactive interface and easy-to-read graphs. It is made transparent thanks to the technical data  
658 sheets explaining the very limited number (from two to four) of input variables required to assess the  
659 level of each ecosystem service. This original and parsimonious approach, already implemented in the



660 development of previous serious games (e.g. Forage rummy (Martin et al., 2011), Rangeland Rummy  
661 (Farrié et al., 2015)) differs from most model-based farming system design approaches. Indeed, the  
662 latter are much more detailed, data and time-demanding, usually applicable in very specific contexts,  
663 and providing results that are neither intelligible, salient or legitimate to most players' (Martin et al.,  
664 2011; McCown et al., 2009). Transparency of simulation models such as the one integrated in Interplay  
665 combined with the facilitator's explanation can stimulate players' discovery of the processes involved  
666 in the establishment of ecosystem services.

667 To maximize the credibility of Interplay, we synthesized up-to-date scientific knowledge on  
668 intercropping and combined it with expert knowledge. We relied on the STICS crop model, a well-  
669 established model for assessing sole crop biomass production (Coucheney et al., 2015). We used the  
670 largest European database on intercropping (Gaudio et al., 2021) available to date to build statistical  
671 interaction models and reached performances that are consistent with our objectives to support co-  
672 design (Meunier et al., 2021). We mobilized some of the best experts on crop modelling, intercropping,  
673 cropping systems and ecosystem services provided by intercrops, all along the development and  
674 evaluation of our modelling chain (Meunier et al., 2021). We also followed the good practices enacted  
675 by Sinclair and Seligman (2000) for crop modelling during the development of this modelling chain by  
676 clearly defining: (i) a scientific objective, i.e. assessing a bundle of ecosystem services provided by a  
677 wide diversity of intercropping scenarios; (ii) a domain of relevance, i.e. for now, cereal–grain legumes  
678 intercrops in simultaneous sowing under French soil-climate conditions ; and (iii) a mechanistic  
679 framework, i.e. the combination of process-based, statistical and knowledge-based models, which is  
680 also an innovation in crop modelling. When shown to experts, over eighteen scenarios, 79% of the  
681 modelling chain predictions were accurate. This is also consistent with the fact that during our testing  
682 campaign, no student nor teacher declared being surprised by any of the results provided on the  
683 intercropping scenarios tested.

684 4.2. Interplay: a serious game to bridge the technical gaps towards practicing intercropping  
685 Interplay eases players' understanding of intercrop complexity by decomposing it into the many  
686 decisions to be made when introducing an intercrop in a cropping system. The game board offers a  
687 systemic view and a concrete representation of most of the questions raised by intercropping,  
688 considering both practical questions at the field level (Casagrande et al., 2017) and lock-ins at the farm  
689 and value-chain level (Magrini et al., 2016; Mamine and Farès, 2020). The game also allows exploring  
690 a large diversity of intercropping scenarios, and thereby is a basis to sensitize players to intercrops. It  
691 provides scientific knowledge on the ecosystem services they provide through the evaluation model,  
692 which allows the comparison of the performance of several intercropping scenarios in the cropping  
693 system context. Players can thus identify the most appropriate and locally adapted species and  
694 management practices in regard to their objectives thanks to a trial-and-error approach (Jouan et al.,  
695 2021; Martin et al., 2011). For instance, in the workshop presented above, students progressively  
696 realized that to improve nitrogen supply, they should grow intercrops including a legume with high  
697 nitrogen content and sown with a favorable density compared to the cereal. During Interplay gaming  
698 sessions, players also declared that they learnt about the processes influencing each ecosystem service  
699 and the leverages to improve them, as they could easily identify the impact of each of their choices.  
700 Such information, as well as species characteristics presented on datasheets (root system, nitrogen  
701 supply, yield and selling price) could easily be reused in other situations, such as a global reflection on  
702 the crop rotation. For example, during the workshop described above, players reused information on  
703 the potential nitrogen supply of legumes to propose substituting chickpea by a spring pea in the crop

704 rotation or introducing a semi-perennial fodder legume. Interplay also favors knowledge exchange and  
705 promotes creativity, as it creates a place and time where players, i.e. farmers or students interested in  
706 intercropping, can meet, debate and share knowledge and experience in a pleasant atmosphere, as  
707 already observed with other games (Martin et al., 2011; Farrié et al., 2015). Interplay can be seen as a  
708 collaborative game. Players collectively win when they manage to design an intercropping scenario  
709 that matches the scenario farmer objectives or have him/her realize these objectives are not  
710 achievable. The interactivity of the evaluation model that allows quick assessment of ecosystem  
711 services provided and comparison with the objectives encourages players to explore many scenarios.  
712 The physical game board used to build playful representations and the roles distributed to players with  
713 mission cards also contribute to bring some fun in Interplay sessions. Interplay promotes creativity  
714 through the exploration of uncommon intercropping scenarios. It includes technical datasheets  
715 providing the characteristics of some less well-known species (e.g. lupin, fenugreek) that may raise  
716 players' curiosity. During our testing campaign, students asked us several times to simulate the services  
717 provided by an intercropping scenario including one of these species because they wanted to discover  
718 and discuss their advantages together with the teacher and the facilitator even though they did not fit  
719 the objectives set in the workshop. Such tests can easily be performed as the evaluation model allows  
720 a quick assessment of ecosystem services provided by intercropping scenarios, and with low-risks  
721 compared to implementation in the field. The evaluation model can also simulate very novel scenarios,  
722 which are on the edge of its validity domain. In the above-described workshop, students designed a  
723 barley–faba bean intercrop with faba bean sown at 120% of the sole crop density. Such a scenario has  
724 an educational purpose and aims at extending the reflection by wondering to what extent it is  
725 necessary to increase the difference between legume biomass and cereal biomass to reach a high level  
726 of nitrogen supply.

727

#### 728 4.3. Reflections on usage of the game

729 Interplay is freely available when following the link: <https://forms.gle/K8SDGuaxYg2CPkcp9>. The files  
730 provided include all the game elements, in French and in English, as well as a hundred-page user  
731 manual including many photos and pictures to progressively guide the future facilitator in the discovery  
732 and use of the game with a group. The manual also mentions adaptations needed for use with  
733 students, for which all the materials (extra slides, evaluation model) are provided.

734 The game is not aimed at being used by individuals. Indeed, it has been designed to be used in a  
735 collective workshop led by an advisor or a teacher being the facilitator, in the framework of a half-day  
736 event. The selection of players must be made carefully to ensure a good atmosphere, which is crucial  
737 in such workshops to obtain the expected results (Reau et al., 2019). Players must be open-minded  
738 and non judgmental, and the group should not be too large. We recommend mobilizing between four  
739 and eight players per session to optimize interactions. All players must share similar constraints  
740 (region, type of farming) to increase the consistency of proposed scenarios. Exchanges are expected  
741 to be more fruitful if some of the players (e.g. farmer, advisor or teacher) already have relevant  
742 knowledge and experience of intercropping which they can relate to other players who are new to  
743 intercropping implementation. The facilitation is easier if players already know and have affinities with  
744 each other, but an ice-breaker at the beginning of the workshop (e.g. egg challenge to stimulate  
745 collaboration and collective intelligence) can easily help them relax otherwise (Reau et al., 2019). The  
746 role of the facilitator is also determinant as it conditions the quality of the exchanges, and thereby the

747 workshop outcomes. Specifically, his/her knowledge of cropping systems and intercrops needs to be  
748 salient, credible and legitimate as it is disseminated to players. During the above described workshop,  
749 this role was held by a researcher involved in the game development (C. Meunier), yet it rather aims  
750 at being transferred to an advisor or to a teacher, trained to use the game by reading the user manual.  
751 It is then up to the game downloader to ensure that he/she has sufficient knowledge about cropping  
752 systems and intercrops to facilitate an Interplay meeting, or to mobilize someone who has this  
753 knowledge if necessary.

754 Interplay allows the exploration of a wide diversity of intercropping scenarios, and focuses on the  
755 species to associate and management practices to implement. Such a focus does not necessarily  
756 encourage a whole system redesign at first glance, while it might be needed in some cases (Hill, 1985),  
757 as shown by the workshop described above. These questions can be dealt with in the facilitation  
758 process by proposing a global reflection at the cropping system level at the end of the workshop, as  
759 we did. Interplay could also be integrated as a part of a holistic redesign strategy, which would,  
760 however, be more time consuming. Interplay evaluation model assesses the ecosystem services  
761 provided by the intercrop, as our aim was to compare intercropping scenarios to one another. Due to  
762 our wish to develop a transparent model, we could not consider all the interactions occurring  
763 throughout the crop rotation, and only focused on the impact of the two crops preceding the intercrop  
764 on pest pressure. This may have led to delayed effects being neglected (Jernigan et al., 2020). As we  
765 aimed at proposing a game that promotes the exploration of unusual intercropping scenarios, we  
766 included species and management practices on which little knowledge is available to date. We filled  
767 the existing gaps in literature with experts' knowledge, though uncertainties remain high on very novel  
768 intercropping scenarios (e.g. sorghum–soya bean) for which the robustness of simulations is  
769 questionable. The facilitator should keep this in mind during a workshop, and present cautiously the  
770 simulations results in these cases, as mentioned in the user manual provided with the game. Further  
771 research on modelling and intercrops may help increase the performances of our modelling chain with  
772 additional field trial data to build statistical models estimating attainable biomass and increased expert  
773 knowledge to update ecosystem service DEXi trees.

774 For now, Interplay is calibrated for cereal–grain legumes intercrops sown simultaneously, under  
775 French soil-climate conditions, yet adapting it to other temperate climate situations would be feasible  
776 at low cost. Adapting the game to other countries would “only” imply running ad hoc STICS simulations,  
777 which does not require advanced modelling skills. By mobilizing the necessary knowledge and experts,  
778 other services provided by the intercrop could also be assessed with new multi-attribute DEXi trees, if  
779 consistent with the objectives of the design process (e.g. straw biomass or feed value for intercrops  
780 for animal feeding). Integrating intercrops including fodder legumes and/or relay cropping is also  
781 feasible but would require a more consequent adaptation and calibration efforts, as it would imply  
782 adapting linear interaction models and most probably multi-attribute DEXi trees.

783 In this paper, we wanted to present the Interplay game, its elements and an example of typical use  
784 situation. As we did not aim at assessing students' learning, we did not analyze in-depth the knowledge  
785 exchanged along with the successive scenario designs during the session, and we did not question the  
786 factors favoring this learning, especially those related to the teacher (presence, knowledge,  
787 interventions), the proposed scenario (improving nitrogen supply in an organic farm in the South West  
788 of France), the facilitation (including the fact that the session was held online), nor the interactions

789 between players. These elements are to be further considered in a proper assessment of Interplay as  
790 an educational tool.

## 791 **5. Conclusions**

792 When considering the practice of intercropping, farmers are facing a range of complex and practical  
793 questions. Interplay is the first serious game developed to address these questions. It allows the design  
794 of intercropping scenarios in a given cropping system context and assessment of the levels of  
795 ecosystem services they provide. Tested with student groups, it stimulated exploration of atypical  
796 proposals, knowledge exchange and, according to students and their teachers, discovering intercrops  
797 and their integration at the cropping system, farm and socio-economic environment levels. Interplay  
798 is currently available for cereals–grain legumes sown and harvested together but further  
799 developments may extend its scope to include relay cropping and fodder legumes. Also, it is currently  
800 calibrated for French conditions but can be adapted to other contexts with minimal calibration.  
801 Interplay is available for researchers, teachers and advisors interested in addressing the practice of  
802 intercropping from a systems perspective.

## 803 **Acknowledgements**

804 The authors acknowledge funding from the European Union’s Horizon 2020 Program for Research and  
805 Innovation under grant agreement no. 727217 (ReMIX: Redesigning European cropping systems based  
806 on species MIXtures).

807

## 808 **References**

- 809 Alvarez, J., Djaouti, D., 2012. An introduction to serious games 1–324.
- 810 Aubertot, J.N., Robin, M.H., 2013. Injury Profile SIMulator, a Qualitative Aggregative Modelling  
811 Framework to Predict Crop Injury Profile as a Function of Cropping Practices, and the Abiotic  
812 and Biotic Environment. I. Conceptual Bases. PLoS One 8.  
813 <https://doi.org/10.1371/journal.pone.0073202>
- 814 Barot, S., Allard, V., Cantarel, A., Enjalbert, J., Gauffreteau, A., Goldringer, I., Lata, J.C., Le Roux, X.,  
815 Niboyet, A., Porcher, E., 2017. Designing mixtures of varieties for multifunctional agriculture  
816 with the help of ecology. A review. Agron. Sustain. Dev. 37. <https://doi.org/10.1007/s13593-017-0418-x>  
817
- 818 Bedoussac, L., et al., 2014. Eco-functional Intensification by Cereal-Grain Legume Intercropping in  
819 Organic Farming., in: Bellon, S., Penvern, S. (Eds.), Organic Farming Systems for Increased Yields,  
820 Reduced Weeds and Improved Grain Protein Concentration. Springer, Dordrecht.
- 821 Bedoussac, L., Journet, E.P., Hauggaard-Nielsen, H., Naudin, C., Corre-Hellou, G., Jensen, E.S., Prieur,  
822 L., Justes, E., 2015. Ecological principles underlying the increase of productivity achieved by  
823 cereal-grain legume intercrops in organic farming. A review. Agron. Sustain. Dev. 35, 911–935.  
824 <https://doi.org/10.1007/s13593-014-0277-7>
- 825 Bergez, J.E., Colbach, N., Crespo, O., Garcia, F., Jeuffroy, M.H., Justes, E., Loyce, C., Munier-Jolain, N.,  
826 Sadok, W., 2010. Designing crop management systems by simulation. Eur. J. Agron. 32, 3–9.  
827 <https://doi.org/10.1016/j.eja.2009.06.001>
- 828 Berthet, E., Barnaud, C., Girard, N., Labatut, J., Martin, G., 2016. How to foster agroecological

- 829 innovations? A comparison of participatory design methods. *J. Environ. Plan. Manag.* 59, 280–  
830 301. <https://doi.org/10.1080/09640568.2015.1009627>
- 831 Bohanec, M., 2008. DEXI : Program for Multi-Attribute Decision Making User ' s Manual. Evaluation.
- 832 Brisson, N., Gary, C., Justes, E., Roche, R., Mary, B., Ripoche, D., Zimmer, D., Sierra, J., Bertuzzi, P.,  
833 Burger, P., Bussiere, F., Cabidoche, Y.M., Cellier, P., Debaeke, P., Gaudillere, J.P., Henault, C.,  
834 Maraux, F., Seguin, B., Sinoquet, H., 2003. An overview of the crop model STICS. *Eur. J. Agron.*  
835 18, 309–332.
- 836 Casagrande, M., Alletto, L., Naudin, C., Lenoir, A., Siah, A., Celette, F., 2017. Enhancing planned and  
837 associated biodiversity in French farming systems. *Agron. Sustain. Dev.* 37.  
838 <https://doi.org/10.1007/s13593-017-0463-5>
- 839 Cash, D.W., Clark, W.C., Alcock, F., Dickson, N.M., Eckley, N., Guston, D.H., Jäger, J., Mitchell, R.B.,  
840 2003. Knowledge systems for sustainable development. *Proc. Natl. Acad. Sci. U. S. A.* 100, 8086–  
841 8091. <https://doi.org/10.1073/pnas.1231332100>
- 842 Coucheney, E., Buis, S., Launay, M., Constantin, J., Mary, B., García de Cortázar-Atauri, I., Ripoche, D.,  
843 Beaudoin, N., Ruget, F., Andrianarisoa, K.S., Le Bas, C., Justes, E., Léonard, J., 2015. Accuracy,  
844 robustness and behavior of the STICS soil-crop model for plant, water and nitrogen outputs:  
845 Evaluation over a wide range of agro-environmental conditions in France. *Environ. Model.*  
846 *Softw.* 64, 177–190. <https://doi.org/10.1016/j.envsoft.2014.11.024>
- 847 Duchene, O., Vian, J.F., Celette, F., 2017. Intercropping with legume for agroecological cropping  
848 systems: Complementarity and facilitation processes and the importance of soil  
849 microorganisms. A review. *Agric. Ecosyst. Environ.* 240, 148–161.  
850 <https://doi.org/10.1016/j.agee.2017.02.019>
- 851 Elzen, B., Bos, B., 2019. The RIO approach: Design and anchoring of sustainable animal husbandry  
852 systems. *Technol. Forecast. Soc. Change* 145, 141–152.  
853 <https://doi.org/10.1016/j.techfore.2016.05.023>
- 854 Falconnier, G.N., Journet, E.P., Bedoussac, L., Vermue, A., Chlébowski, F., Beaudoin, N., Justes, E.,  
855 2019. Calibration and evaluation of the STICS soil-crop model for faba bean to explain variability  
856 in yield and N<sub>2</sub> fixation. *Eur. J. Agron.* 104, 63–77. <https://doi.org/10.1016/j.eja.2019.01.001>
- 857 Farrié, B., Jouven, M., Launay, F., Moreau, J.C., Moulin, C.H., Piquet, M., Taverne, M., Tchakérian, E.,  
858 Thénard, V., Martin, G., 2015. Rangeland Rummy - A board game to support adaptive  
859 management of rangeland-based livestock systems. *J. Environ. Manage.* 147, 236–245.  
860 <https://doi.org/10.1016/j.jenvman.2014.08.018>
- 861 Gaudio, N., Violle, C., Gendreau, X., Fort, F., Mahmoud, R., Pelzer, E., Médiène, S., Hauggaard-Nielsen,  
862 H., Bedoussac, L., Bonnet, C., Corre-Hellou, G., Couëdel, A., Hinsinger, P., Steen Jensen, E.,  
863 Journet, E.P., Justes, E., Kammoun, B., Litrico, I., Moutier, N., Naudin, C., Casadebaig, P., 2021.  
864 Interspecific interactions regulate plant reproductive allometry in cereal–legume intercropping  
865 systems. *J. Appl. Ecol.* 1–16. <https://doi.org/10.1111/1365-2664.13979>
- 866 Granstrand, O., Holgersson, M., 2020. Innovation ecosystems: A conceptual review and a new  
867 definition. *Technovation* 90–91. <https://doi.org/10.1016/j.technovation.2019.102098>
- 868 Hauggaard-Nielsen, H., Ambus, P., Jensen, E.S., 2003. The comparison of nitrogen use and leaching in  
869 sole cropped versus intercropped pea and barley. *Nutr. Cycl. Agroecosystems* 65, 289–300.  
870 <https://doi.org/10.1023/A:1022612528161>

- 871 Hauggaard-Nielsen, H., Ambus, P., Jensen, E.S., 2001. Interspecific competition, N use and  
872 interference with weeds in pea-barley intercropping. *F. Crop. Res.* 70, 101–109.  
873 [https://doi.org/10.1016/S0378-4290\(01\)00126-5](https://doi.org/10.1016/S0378-4290(01)00126-5)
- 874 Hill, S., 1985. Redesigning the food system for sustainability. *Alternatives* 12, 32–36.
- 875 Jensen, E.S., Carlsson, G., Hauggaard-Nielsen, H., 2020. Intercropping of grain legumes and cereals  
876 improves the use of soil N resources and reduces the requirement for synthetic fertilizer N: A  
877 global-scale analysis. *Agron. Sustain. Dev.* 40, 5. <https://doi.org/10.1007/s13593-020-0607-x>
- 878 Jernigan, A.B., Wickings, K., Mohler, C.L., Caldwell, B.A., Pelzer, C.J., Wayman, S., Ryan, M.R., 2020.  
879 Legacy effects of contrasting organic grain cropping systems on soil health indicators, soil  
880 invertebrates, weeds, and crop yield. *Agric. Syst.* 177, 102719.  
881 <https://doi.org/10.1016/j.agsy.2019.102719>
- 882 Jouan, J., Carof, M., Baccar, R., Bareille, N., Bastian, S., Brogna, D., Burgio, G., Couvreur, S., Cupiał, M.,  
883 Dufrière, M., Dumont, B., Gontier, P., Jacquot, A.-L., Kański, J., Magagnoli, S., Makulska, J.,  
884 Pérès, G., Ridier, A., Salou, T., Sgolastra, F., Szelaż-Sikora, A., Tabor, S., Tombarkiewicz, B.,  
885 Węglarz, A., Godinot, O., 2021. SEGAE: An online serious game to learn agroecology. *Agric. Syst.*  
886 191, 103145. <https://doi.org/10.1016/j.agsy.2021.103145>
- 887 Lacombe, C., Couix, N., Hazard, L., 2018. Designing agroecological farming systems with farmers: A  
888 review. *Agric. Syst.* 165, 208–220. <https://doi.org/10.1016/j.agsy.2018.06.014>
- 889 Liu, Y., Gupta, H., Springer, E., Wagener, T., 2008. Linking science with environmental decision  
890 making: Experiences from an integrated modeling approach to supporting sustainable water  
891 resources management. *Environ. Model. Softw.* 23, 846–858.  
892 <https://doi.org/10.1016/j.envsoft.2007.10.007>
- 893 Machado, S., 2009. Does intercropping have a role in modern agriculture? *J. Soil Water Conserv.*  
894 <https://doi.org/10.2489/jswc.64.2.55A>
- 895 Magrini, M.B., Anton, M., Cholez, C., Corre-Hellou, G., Duc, G., Jeuffroy, M.H., Meynard, J.M., Pelzer,  
896 E., Voisin, A.S., Walrand, S., 2016. Why are grain-legumes rarely present in cropping systems  
897 despite their environmental and nutritional benefits? Analyzing lock-in in the French agrifood  
898 system. *Ecol. Econ.* 126, 152–162. <https://doi.org/10.1016/j.ecolecon.2016.03.024>
- 899 Maitra, S., Hossain, A., Brestic, M., Skalicky, M., Ondrisik, P., Gitari, H., Brahmachari, K., Shankar, T.,  
900 Bhadra, P., Palai, J.B., Jena, J., Bhattacharya, U., Duvvada, S.K., Lalichetti, S., Sairam, M., 2021.  
901 Intercropping—A Low Input Agricultural Strategy for Food and Environmental Security.  
902 *Agronomy* 11, 343. <https://doi.org/10.3390/agronomy11020343>
- 903 Mamine, F., Farès, M., 2020. Barriers and levers to developing wheat-pea intercropping in Europe: A  
904 review. *Sustain.* 12. <https://doi.org/10.3390/SU12176962>
- 905 Martin, G., Felten, B., Duru, M., 2011. Forage rummy: A game to support the participatory design of  
906 adapted livestock systems. *Environ. Model. Softw.* 26, 1442–1453.  
907 <https://doi.org/10.1016/j.envsoft.2011.08.013>
- 908 Martin, G., Martin-Clouaire, R., Duru, M., 2013. Farming system design to feed the changing world. A  
909 review. *Agron. Sustain. Dev.* 33, 131–149. <https://doi.org/10.1007/s13593-011-0075-4>
- 910 McCown, R.L., Carberry, P.S., Hochman, Z., Dalgliesh, N.P., Foale, M.A., 2009. Re-inventing model-  
911 based decision support with Australian dryland farmers. 1. Changing intervention concepts  
912 during 17 years of action research. *Crop Pasture Sci.* 60, 1017–1030.

- 913 <https://doi.org/10.1071/CP08455>
- 914 McGranahan, D.A., 2014. Ecologies of scale: Multifunctionality connects conservation and agriculture  
915 across fields, farms, and landscapes, *Land*. <https://doi.org/10.3390/land3030739>
- 916 Meunier, C., Alletto, L., Bedoussac, L., Bergez, J.-E., Casadebaig, P., Constantin, J., Gaudio, N.,  
917 Mahmoud, R., Aubertot, J.-N., Celette, F., Guinet, M., Jeuffroy, M.-H., Robin, M.-H., Médiène, S.,  
918 Fontaine, L., Nicolardot, B., Pelzer, E., Souchère, V., Voisin, A.S., Rosies, B., Casagrande, M.,  
919 Martin, G., 2021. A modelling chain combining soft and hard models to assess a bundle of  
920 ecosystem services provided by a diversity of cereal-legume intercrops. *Eur. J. Agron.*  
921 EURAGR1070, accepted with minor revisions.
- 922 Meynard, J.-M., Charrier, F., Fares, M., Le Bail, M., Magrini, M.-B., Charlier, A., Messéan, A., 2018.  
923 Socio-technical lock-in hinders crop diversification in France. *Agron. Sustain. Dev.* 38, 54.  
924 <https://doi.org/10.1007/s13593-018-0535-1>
- 925 Pelzer, E., Bazot, M., Makowski, D., Corre-Hellou, G., Naudin, C., Al Rifai, M., Baranger, E., Bedoussac,  
926 L., Biarnès, V., Boucheny, P., Carrouée, B., Dorvillez, D., Foissy, D., Gaillard, B., Guichard, L.,  
927 Mansard, M.-C., Omon, B., Prieur, L., Yvergniaux, M., Justes, E., Jeuffroy, M.-H., 2012. Pea–  
928 wheat intercrops in low-input conditions combine high economic performances and low  
929 environmental impacts. *Eur. J. Agron.* 40, 39–53. <https://doi.org/10.1016/j.eja.2012.01.010>
- 930 Pigford, A.A.E., Hickey, G.M., Klerkx, L., 2018. Beyond agricultural innovation systems? Exploring an  
931 agricultural innovation ecosystems approach for niche design and development in sustainability  
932 transitions. *Agric. Syst.* 164, 116–121. <https://doi.org/10.1016/j.agsy.2018.04.007>
- 933 R Core Team, 2018. R: A language and environment for statistical computing.
- 934 Raseduzzaman, M., Jensen, E.S., 2017. Does intercropping enhance yield stability in arable crop  
935 production? A meta-analysis. *Eur. J. Agron.* 91, 25–33.  
936 <https://doi.org/10.1016/j.eja.2017.09.009>
- 937 Reau, R., Cerf, M., Cros, C., Ferrane, C., Reau, R., GELOEN, M., Lefevre, V., Pasquier, C., Petit, M.-S.,  
938 Schaub, A., 2019. Atelier de conception de systèmes de culture, Guide de conception 1–33.
- 939 Reau, R., Monnot, L.A., Schaub, A., Pambou, I., Bockstaller, C., Cariolle, M., Chabert, A., Dumans, P.,  
940 2012. Les ateliers de conception de systèmes de culture pour construire, évaluer et identifier  
941 des prototypes prometteurs. *Innov. Agron.* 20, 5–33.
- 942 Ryschawy, J., Charmeau, A., Martin, G., Moraine, M., Pelletier, A., 2018. Dynamix, un « jeu sérieux »  
943 pour concevoir des scénarios d’achat-vente entre céréaliers et éleveurs : une application en  
944 Ariège. *Fourrages* 325, 207–212.
- 945 Sebillotte, M., 1990. Systeme de culture, un concept operatoire pour les agronomes, in: L. Combe et  
946 D. Picard Coord., *Les Systemes de Culture*. Inra, Versailles. pp. 165–196.
- 947 Sinclair, T.R., Seligman, N., 2000. Criteria for publishing papers on crop modeling. *F. Crop. Res.* 68,  
948 165–172. [https://doi.org/10.1016/S0378-4290\(00\)00105-2](https://doi.org/10.1016/S0378-4290(00)00105-2)
- 949 Speelman, E.N., García-Barríos, L.E., Groot, J.C.J., Tittonell, P., 2014. Gaming for smallholder  
950 participation in the design of more sustainable agricultural landscapes. *Agric. Syst.* 126, 62–75.  
951 <https://doi.org/10.1016/j.agsy.2013.09.002>
- 952 Stomph, T.J., Dordas, C., Baranger, A., de Rijk, J., Dong, B., Evers, J., Gu, C., Li, L., Simon, J., Jensen,  
953 E.S., Wang, Q., Wang, Y., Wang, Z., Xu, H., Zhang, C., Zhang, L., Zhang, W.P., Bedoussac, L., van

- 954 der Werf, W., 2020. Designing intercrops for high yield, yield stability and efficient use of  
955 resources: Are there principles?, 1st ed, *Advances in Agronomy*. Elsevier Inc.  
956 <https://doi.org/10.1016/bs.agron.2019.10.002>
- 957 Tschakert, P., Dietrich, K.A., 2010. Anticipatory learning for climate change adaptation and resilience.  
958 *Ecol. Soc.* 15, 11. <https://doi.org/10.5751/ES-03335-150211>
- 959 Verret, V., Gardarin, A., Pelzer, E., Médiène, S., Makowski, D., Valantin-Morison, M., 2017. Can  
960 legume companion plants control weeds without decreasing crop yield? A meta-analysis. *F.*  
961 *Crop. Res.* 204, 158–168. <https://doi.org/10.1016/j.fcr.2017.01.010>
- 962 Voinov, A., Bousquet, F., 2010. Modelling with stakeholders. *Environ. Model. Softw.* 25, 1268–1281.  
963 <https://doi.org/10.1016/j.envsoft.2010.03.007>
- 964 Voinov, A., Kolagani, N., McCall, M.K., Glynn, P.D., Kragt, M.E., Ostermann, F.O., Pierce, S.A., Ramu,  
965 P., 2016. Modelling with stakeholders - Next generation. *Environ. Model. Softw.* 77, 196–220.  
966 <https://doi.org/10.1016/j.envsoft.2015.11.016>
- 967 Willey, R.W., 1979. Intercropping—its importance and research needs. *F. Crop Abstr.* 32, 1–10.  
968