SEGAE: An online serious game to learn agroecology

(Article begins on next page)

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Highlights

- Agroecology can improve agricultural sustainability but teaching and learning agroecology is challenging

- To improve agroecology learning, we built the online simulation game SEGAE: this article presents its framework and illustrates its potential

- SEGAE can prompt discussion on steps and possible trade-offs when increasing sustainability in an integrated crop-livestock farm

- SEGAE helps to acquire a systems approach and improve skills in agroecological transition management

- SEGAE was designed to strengthen European training in agroecology, and active contributions from users would help to improve this tool

SEGAE, a serious game that relies on a scientific model

SEGAE: a serious game to learn agroecology

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Highlights

- Agroecology can improve agricultural sustainability but teaching and learning agroecology is challenging

35   • To improve agroecology learning, we built the online simulation game SEGAE: this article
36   presents its framework and illustrates its potential
37   • SEGAE can prompt discussion on steps and possible trade-offs when increasing sustainability
38   in an integrated crop-livestock farm
39   • SEGAE helps to acquire a systems approach and improve skills in agroecological transition
40   management
41   • SEGAE was designed to strengthen European training in agroecology, and active contributions
42   from users would help to improve this tool

43   **Abstract**

44   CONTEXT: There is growing evidence that agroecology can reconcile the environmental, economic,
45   and social pillars of agricultural sustainability. However, teaching and learning agroecology is
46   challenging, especially since most agricultural graduate programs in Europe are not adapted to teach the
47   diversity of its related practices.

48   OBJECTIVE: To improve agroecology learning, we built the online simulation game SEGAE. This
49   article presents the framework on which SEGAE is based and illustrates the game's potential to achieve
50   pedagogical objectives.

51   METHODS: The game is based on a modeling framework that gamifies the implementation of
52   agroecological practices in an integrated crop-livestock farm and assesses their impacts on
53   sustainability. To do so, SEGAE is based on an output-oriented approach that represents impacts of
54   practices on various indicators. These impacts are included in a matrix, which is associated with a
55   dynamic graphical interface accessible to players. Two examples of game sessions were developed to
56   illustrate the game's potential.

57   RESULTS AND CONCLUSIONS: In the first example, players can gain knowledge about
58   agroecological practices by implementing practices that improve soil quality and assessing their impacts
59   on sustainability. Results of this example place the farm's improved overall sustainability into
60   perspective with its reduced food production potential. In the second example, players can improve their
61   skills in transition management and acquire a systems approach by converting the farm to organic
62   farming within five years. Results of this example prompt discussion of the steps needed to obtain
63   organic certification and the coherence between crop and animal production needed to foster
64   sustainability.

65   SIGNIFICANCE: SEGAE was designed to strengthen European training in agroecology, and active
66   contributions from users would help to improve this tool, extend it to new farming systems and forge
67   connections within the community of teachers working on agroecology.

1. Introduction

72 There is growing evidence that agroecology represents a pertinent mechanism to foster agricultural

73 sustainability (FAO, 2019; Gliessman, 2014). Through its holistic approach, agroecology reconcile the

74 environmental, economic, and social pillars of sustainability, which are conceptualized here as three

75 distinct but interacting systems (Purvis et al., 2019). Agroecology is a dynamic concept that was

76 popularized in scientific, political discourse in recent years (Wezel et al., 2020). It embraces a science,

77 a set of practices and a social movement, and can be applied from food production to consumption

78 (Francis et al., 2003; Wezel et al., 2009). Agroecological practices aim to foster ecosystem services in

79 order to sustain production while limiting environmental impacts by decreasing the use of anthropogenic

80 inputs (Altieri and Farrell, 2018). To promote such practices, it is essential to teach agroecological

81 concepts to current and future professionals of the agricultural sector, such as high-school and university

82 students (Jouan et al., 2020).

83 However, agroecology can be difficult to learn, in particular for students, since it includes a large

84 diversity of practices involved in complex biological processes, while operating within a globalized food

85 system. It is thus necessary to develop interdisciplinary approaches to teach agroecology, embracing

86 economic and social dimensions (Francis et al., 2019). However, agricultural graduate programs in

87 Europe are usually taught by specialized teachers who focus on a narrow range of disciplines and

88 subjects, which does not train students to develop interdisciplinary approaches (Francis et al., 2008).

89 Moreover, agricultural graduate programs are insufficiently based on systems approaches, which limits

90 the representation of complex relationships between farming practices, agricultural production and

91 sustainability (Francis et al., 2011).

92 To foster agroecology learning, emergent teaching materials such as serious games have been identified

93 (Duru et al., 2015). These games are designed to ease learning by proposing fun activities (Crookall,

94 2010). Most serious games related to agriculture are based on boards (Dernat et al., 2019; Loriot and

95 Gowthorpe, 2017; Vaulot et al., 2018). This can limit their accessibility to a large international audience,

96 and also potentially restrain their interactivity, a key element to facilitate learning (Vogel et al., 2006).

97 Other games benefit from more accessible and interactive design but restrict their focus to one part of

98 farming systems, either crop or animal production (Calsamiglia et al., 2020; Dourmad et al., 2013;

99 García-Barrios et al., 2016), since it can be tricky to represent the multiple components of a farming

100 system in which crop and livestock management are highly integrated. In addition, several games focus

101 on social relations among stakeholders involved in management of farming systems, but the inclusion

102 of various agroecological practices, and their economic impact, is rather limited (Braasch et al., 2018;

103 García-Barrios et al., 2008). Other games that rely on agronomic models have the advantage of

104   integrating various practices while producing credible simulations (Martin et al., 2011). Even though

105   they do no reach the complexity of research models (e.g., ORFEE (Mosnier et al., 2017), STICS (Brisson

106   et al., 2003)) or of decision-support tools (Rose et al., 2016), these model-based games are often adapted

107   to a professional audience, which limit their direct use in formal education. Finally, to the best of our

108   knowledge, there is no serious game that highlights agroecology as a mechanism to improve the three

109   pillars of sustainability: environmental, economic and social.

110   To fill these gaps in agroecology learning, we built the serious game SEGAE (SErious Game for

111   AgroEcology learning; https://rebrand.ly/SEGAE), which is an online simulation game based on an

112   output-oriented modeling approach. This game is the main output of the Erasmus+ SEGAE project, a

113   three-year project that associated six European universities from Belgium, France, Italy and Poland.

114   SEGAE is aimed particularly at university students in fields related to agriculture but can also used with

115   high-school students and extension agents. The aim of this study is to (i) show the relevance of SEGAE

116   for learning agroecology by detailing its modelling framework, and to (ii) illustrate its potential by

117   highlighting the coherence of simulations through examples of game sessions (i.e., a predefined number

118   of game turns to reach specific goals). The examples presented are based on the integrated crop-livestock

119   dairy farm of western France developed in the initial version of SEGAE. Similar farming systems of the

120   other partner countries are still under development and are not illustrated here.

121   **2. Method**

122   **2.1. Conceptual model**

123   ***2.1.1. The integrated crop-livestock farm model***

124   SEGAE's conceptual model represents its theoretical foundation. Designed at the farm scale, the model

125   was developed to address three main educational objectives for players: (i) learn about agroecological

126   practices, (ii) acquire a systems approach by assessing combined impacts of these practices and (iii)

127   improve skills in transition management by reaching given goals with limited time and resources in the

128   game.

129   To address these objectives, the conceptual model represents multiple components of an integrated crop-

130   livestock farm and integrates several categories of practices related to agroecology. It consists of five

131   modules that interact with each other through practices that impact ecosystem services (Figure 1). Most

132   of these practices are agroecological and were chosen and adapted from two review studies (Dumont et

133   al., 2013; Wezel et al., 2014) (section 2.2.1). The conceptual model has an annual timescale, and its

134   spatial extent is the farm scale; thus, it does not consider indirect impacts, such as environmental impacts

135   that occur outside of the farm boundaries.

136   The crop module represents cropping systems of annual crops and forages (including 10 categories of

137   crop-related practices); its main output is crop and forage production. The animal module represents the

138   structure and demographics of the dairy cattle herd, integrates feed requirements, and calculates

139   production of milk, meat and manure. It includes eight categories of animal-related practices. The socio-

140   economic module represents the economic and financial functioning of the farm (e.g., purchases, sales,

141   investment capacity) and estimates the workload of farmers and the farm's contribution to societal

142   expectations. It includes two strategic decisions (i.e., distribution of farm profit and type of agriculture),

143   which are equivalent to practices since they can influence crop and animal modules. The ecosystem

144   module represents ecological components that are not dedicated only to crop and animal production. It

145   includes two categories of practices – agroforestry and green infrastructure – that can influence the other

146   modules. The soil module represents soil functioning (e.g., water, nutrient and carbon cycles, including

147   gaseous emissions, carbon storage and leaching) and considers soil physical properties and soil

148   biodiversity. It includes three categories of practices, which also belong to the crop module.

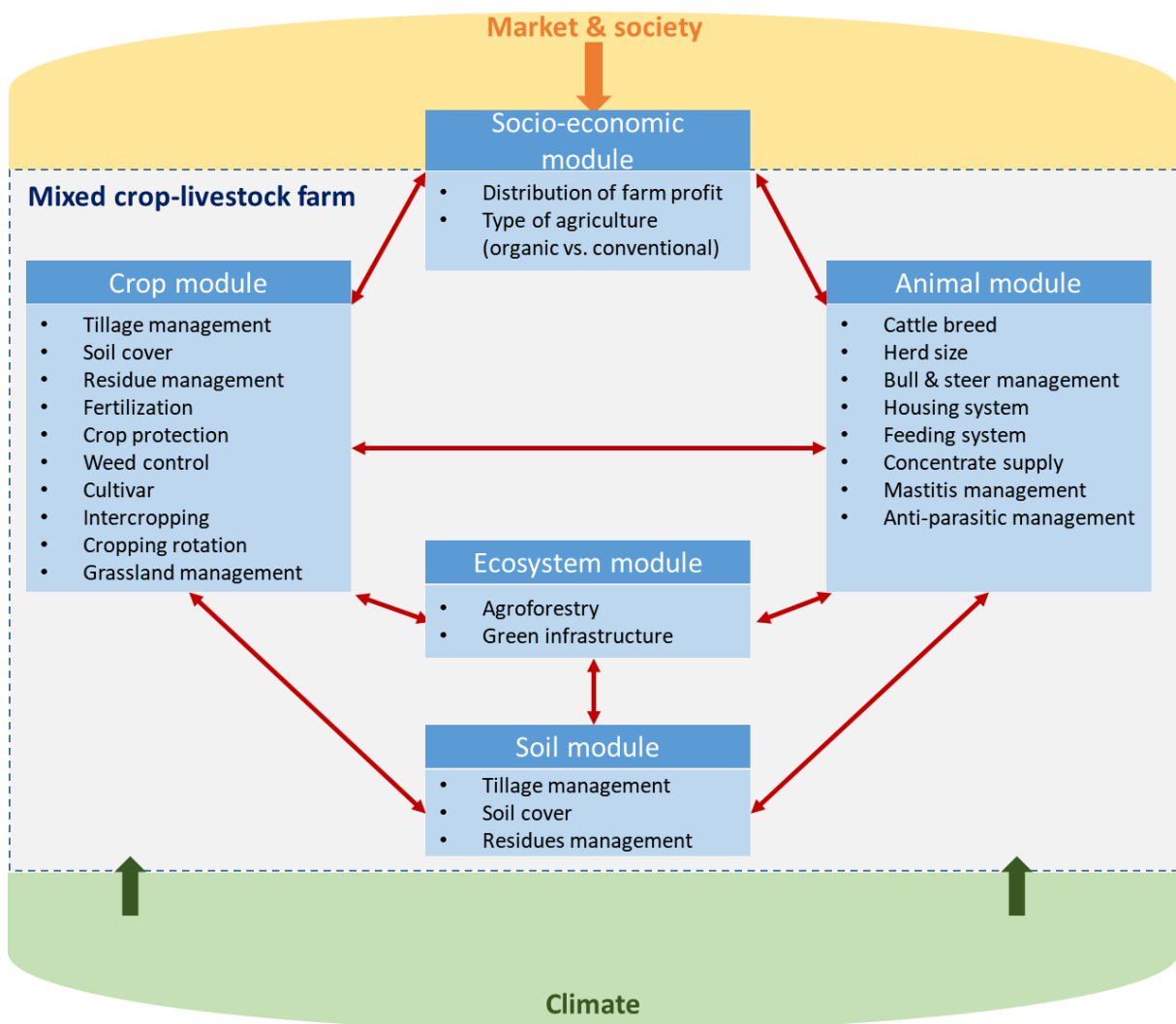**Figure 1.** Conceptual model of the five modules of SEGAE. Each module is associated with various categories of practices and interacts with others through the practices that impact ecosystem services. Practices, and their impacts (red arrows), are considered only at the farm scale (dashed line), except in the socio-economic module, which includes market effects and some societal expectations.

2.1.2. The output-oriented approach to represent impacts of practices

The main originality of SEGAE's conceptual model lies in the output-oriented approach chosen to represent the impacts of practices (Figure 2). Unlike a process-based approach, which mechanistically represents biological processes in a farming system, the output-oriented approach focuses on specific indicators that are impacted by practices. The output-oriented approach can thus be likened to an empirical approach at the farm scale. Thus, SEGAE contains no mechanistic models; instead, impacts of practices were identified by a literature review (section 2.2.1). The main advantage of this framework is to summarize impacts of practices on relevant indicators while avoiding the use of complex calculations that would require large amounts of time and computing capacity (section 2.2.1).
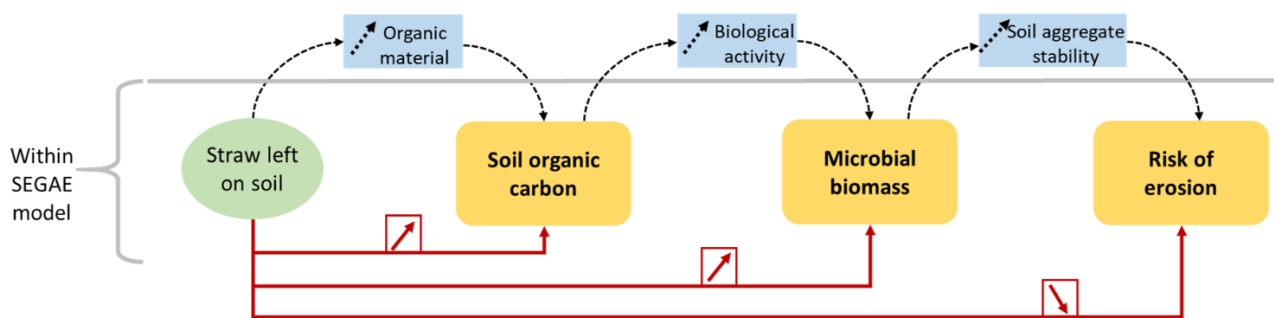

Figure 2. Example of the output-oriented approach implemented in SEGAE that represents the impact of a practice on various indicators. The illustrated practice (in the green cell) is "Straw left on soil", which belongs to the category "Residues management". The framed arrows represent qualitatively the impact factors; Red arrow: output-oriented approach embedded in SEGAE; Doted black arrows: process approach not embedded in SEGAE; Yellow cell: indicator embedded in SEGAE: Blue cell: process not embedded in SEGAE; Other impacts of "Straw left on soil" assessed in SEGAE (e.g., increase in earthworm abundance) are not represented here.

2.1.3. The sustainability score

Another originality of SEGAE is to emphasize impacts of agroecological practices on the three pillars of sustainability. To do so, a set of sustainability scores was conceptualized based on previous frameworks that assess the sustainability of farming systems, such as the AGRO*ECO method (Girardin et al., 2000) and MASC (Sadok et al., 2009). An overall sustainability score is calculated from a hierarchical tree of sustainability that includes (i) as a first order, three scores that correspond to environmental, economic and social sustainability, respectively; (ii) as a second order, scores for 9 indicators and (iii) as a third order, scores for 13 sub-indicators (Table 1). A detailed description of third-order indicators and second-order economic indicators is available in the Appendix.

Table 1. Indicators included in SEGAE's hierarchical tree of sustainability

First-order indicators	Second-order indicators	Third-order indicators
Environmental sustainability (1/3)	Biodiversity conservation (1/3)	Soil biodiversity (1/2)
		Above-ground biodiversity (1/2)
	Use of abiotic resources (1/3)	Use of energy resources (1/3)
		Global warming potential (2/3)
	Environmental quality (1/3)	Water quality (1/3)
		Air quality (1/3)
		Soil quality (1/3)
Economic sustainability (1/3)	Farm profit (1/3)	
	Farm diversification (1/6)	
	Economic efficiency (1/6)	
	Farmer income (1/3)	
Social sustainability (1/3)	Societal expectations (1/2)	Animal welfare (1/4)
		Contribution to employment (1/4)
		Food production potential (1/2)
	Working conditions (1/2)	Workload (2/5)
		Simplicity of the system (1/5)
		Safety of pesticide user (2/5)

168   The scores for indicators of order n are weighted averages of the scores for indicators of order n+1. Each

169   indicator is associated with a specific weight that we defined to reflect its relative impact on

170   sustainability. Each indicator score in the hierarchical tree is normalized from 0-1, and an increase in

171   the score always represents a beneficial change, even for indicators of harm (e.g., "Global warming

172   potential").

173   **2.2.   Overview of the game**

174   *2.2.1. The matrix*

175   The matrix is a spreadsheet that connects impacts of practices to many indicators. It includes 124

176   practices in lines and their impacts on 575 primary indicators in columns (Figure 3). For each category

177   of practices (Figure 1), a set of practices is available; for example, the category "tillage management"

178   includes "conventional tillage", "reduced tillage" and "no tillage".

179   The indicators are related to crops, animals, the environment and socio-economic aspects of the farm.

180   While all 124 practices of the matrix are available in the game, players do not see all 575 indicators.

181   These primary indicators, directly impacted by practices, are used mostly to calculate 365 secondary

182   indicators that are aggregations of the primary ones at farm or herd scales. Some of the 365 secondary

183   indicators are used for internal calculations (e.g., nitrogen flows, economic output), while many of them

184   are displayed to players, either as sustainability indicators in the hierarchical tree of sustainability (e.g.,

185   soil biodiversity) or as technical indicators (e.g., amount of feed purchased) to help players understand

186   the farming system.

187   In the matrix, multiplicative or additive factors are used to calculate the impacts of practices on the 575

188   indicators. Most practices impact several indicators, which helps players understand the complexity of

189   the system through the interdependence of the three pillars of sustainability. We (i) found these impact

190   factors in original studies described in peer-reviewed articles, (ii) determined them by analyzing several

191   scientific articles or local technical documents, (iii) calculated them using specific tools (e.g., software)

192   or (iv) estimated them based on our expert opinion in the associated fields. Some factors are included in

193   the matrix only to perform certain calculations. The complete matrix, including all practices and

194   indicators, as well as the impact factors and their references, is available in (Jouan et al., in review).

Strategic dimension	Category of practice	Crop-related indicators			Animal-related indicators					Environment-related indicators			Socio-economic indicators		
		Yield	N supply	Pesticide saving	Ration composition	Animal production	Manure production	Animal welfare	Vet cost saving	Biodiversity	Soil quality	Water quality	Energy saving	Workload saving	Cost saving
Soil management	Tillage management	-								+	+		+	+	+
	Soil cover	-	+							+	+	+	+	+	+
	Residue management		-							+	+		+	+	+
Crop management	Fertilization										-		+	+	+
	Crop protection against diseases	-		+						+		+		+	+
	Weed control			+						+/-	-	+	-	-	+/-
	Crop protection against animal pests	-		+						+		+		+	+
	Cash crop cultivars	-													+
	Spatial distribution of cash crops	+	+							+	+	+			
Land use management	Cropping system #1		+							+	+	+			+/-
	Cropping system #2		+							+	+	+			+/-
	Temporary grassland composition									+					
	Permanent grassland area									+					+
Landscape management	Green infrastructure									+	+	+			+
	Agroforestry									+	+	+			
Herd management	Cattle breed					+/-			+						
	Herd size					+/-		+/-	+/-					-	
Management of cows	Cow housing system		+			+/-	+/-	+	+/-	-			+/-	+/-	+/-
	Feeding system for cows		-		+/-	-	-	+	+/-				+/-	+/-	
	Concentrate supply for lactating dairy cow				+/-	+/-		+/-	+						
	Management of the risk of mastitis					+/-		-	+					-	
Management of heifers and fattening cattle	Heifer, bull & steer housing system		-			+	+/-	+	+	+			+	+	
	Feeding system for heifers		-		+/-	+/-		+	+/-						+/-
	Anti-parasitic management				+			-	+	+				-	
	Bull & steer management				+	+/-	+/-	+/-	+/-					+	
	Feeding system for calves				+	+/-									
Strategic decisions	Type of agriculture									+					
	Distribution of farm profit														+/-

575 primary indicators

124 practices

Figure 3. Simplified illustration of SEGAE's matrix (Jouan et al., in review) that connects impacts of farm practices to farm indicators. The impact factors are represented qualitatively. +: agroecological practices in the category increase the values of related indicators compared to conventional practices; -: agroecological practices in the category decrease the values of related indicators; +/ -: agroecological practices in the category increase or decrease the values of related indicators depending on the practice and indicator. Cost saving includes the indicators "various costs", "investment capacity" and "CAP subsidies" (the last equivalent to cost reductions). The values of the impact factors were determined in different ways, as indicated by the color code. Green: found in an original study described in a peer-reviewed article; Blue: determined by analyzing of several scientific articles or local technical documents; Purple: calculated using specific tools (e.g., software); Orange: estimated based on our expert opinion in the associated fields; Gray: used only for internal model calculations.

2.2.2. The graphical interface

The graphical interface represents the various elements of an integrated crop-livestock farm enriched with several game tabs and buttons (Figure 4). The initial farms represented were parameterized to represent a typical integrated crop-livestock dairy farm of each partner country that participated in the development of the game (i.e., Belgium, France, Italy, and Poland). The French farm (Table 2) was parameterized to represent a typical dairy farm in western France: its initial characteristics, which are presented in table 2, are very close to official statistics in term of crop production, animal production and economic results (Draaf Bretagne, 2018).

Table 2. Main characteristics of the French integrated crop-livestock farm represented in SEGAE

Total area (ha)	**85**
• Wheat (ha)	**17**
• Forage maize (ha)	**31**
• Temporary grassland (ha)	**28**
• Permanent grassland (ha)	**9**
Number of dairy cows	**60**
• Milk yield (L.cow^{-1})	**7,546**
Number of heifers	**45**

The farm page of the graphical interface displays the residential and operating buildings (e.g., shed, stable), fields, cows and agricultural machines to increase the realism (Figure 4). Nine white buttons represent strategic dimensions within which practices are grouped into coherent sets to optimize the playability. In particular, the *feeding system* button groups crop and animal practices available in other buttons to help players think about the coherence between cropping and animal production. By clicking on any of these nine buttons, players can change practices on the farm. Each practice has an *information* button that details the practice, its potential impacts and how it can be managed in the game (e.g., the housing system of cows can be changed only once during a game session). A tenth white button called *warehouse* allows players to analyze the main technical results of the farm: crop and livestock production and sales, purchased inputs, workload and economic results.

Several black monitoring tabs (Figure 4) help players track their status in the game (e.g., year, practices available) and assess its choices. In particular, the *Report* tab describes the sustainability scores in detail over time. To supplement this tab, a central gauge and three secondary gauges, one for each pillar of sustainability, gives an overview of the sustainability scores. The strategic dimension buttons can also display the evolution of many related technical indicators. In addition, to reinforce the game aspect and provide a stimulating effect, players obtain a game score that can be compared to those of other players. Players' scores start at zero and increase each year by the lowest of the three sustainability scores (i.e., economic, environmental or social).

Finally, the graphical interface can change depending on the practices chosen (Figure 4b): implementing agroforestry and hedgerows adds trees and hedges, improving erosion control makes the river turn blue, leaving straw on soil makes bales of straw disappear, installing a slatted floor for cow housing changes the manure pit into a slurry tank, and converting the farm to organic production makes the tractor with a pesticide sprayer disappear.

Figure 4. The graphical interface available for (a) the baseline situation and (b) implementation of three agroecological practices: in-field agroforestry, hedgerows and no tillage. Agroforestry and hedgerows cause trees and hedges to appear. When several erosion-control practices are implemented, the color of the river turns from brown to blue.

229 The engine that calculates indicator values each year was programmed in JavaScript. The graphical
230 interface and its changes were programmed by Succubus Interactive, a French company specialized in
231 developing digital serious games (http://www.succubus.fr).

2.2.3. Playing the game

233 Players play the game via the graphical interface. By clicking on each strategic dimension (white
234 button), players can access the related practices and change them. In the single-player mode (see details
235 below), up to five practices from the nine dimensions can be changed per year, in order to ease the
236 understanding of impacts. Then, by clicking on the *Next year* tab, the game applies the choices:
237 indicators are calculated, and their scores and the sustainability gauges are updated.

238 Two game modes are available. In the single-player mode, the player is autonomous and chooses one of
239 the predefined farms, and the game session lasts up to 10 game turns (i.e., 10 years in the game). The
240 player wins if the farm reaches a good economic, environmental and social sustainability, i.e., a score
241 above 0.6 for each sustainability, within 10 game turns. The player loses if these goals are not reached
242 within 10 game turns, or if the farm profit is negative for more than 3 game turns. A risk option is
243 available to make predefined hazards (e.g., drought, milk or input price fluctuations) occur with a 10%
244 probability each year. At the end of the game, the player's final score is recorded in the scoreboard
245 published on the game's website. In the classroom mode, the player joins a game created by a teacher,
246 who can define (i) the main parameters of the farm, (ii) specific goals to be reached and (iii)
247 characteristics of hazards (probability of occurrence and impacts). At the end of the game, data tracking
248 allows the teacher to analyze the strategies of multiple players and discuss these strategies with them.

249 Both game modes are designed to be used within pedagogical activities that should include (i)
250 presentation of the learning objectives and an overview of the game, (ii) one or more game sessions with
251 one or several scenarios adapted to the pedagogical objective and the level of students and (iii)
252 discussion of the results, methodology and limits of the game with the teacher. Several scenarios are
253 proposed by Jouan et al. (2020).

2.3.   Examples of game sessions

255 To illustrate the game's potential for learning agroecology and the coherence of simulations, two
256 examples of game sessions are presented:

257 - SOIL: a one-step scenario to make players work on a systems approach. The player's objective
258   is to improve soil quality by implementing agroecological practices that improve environmental
259   sustainability without worsening economic or social sustainability. The player must reach the
260   objective within one year.

261 - ORGANIC: a multi-step scenario to make players work on transition management. The player's
262   objective is to modify practices to meet European Union specifications for organic farming
263   (European Council, 2007). The farm must be converted within five years. Impacts on the
264   sustainability scores are assessed over several years. Two approaches to conversion are

265   presented: (i) the approach A is a basic one that meets the minimum specifications for organic

266   certification and (ii) the approach B is an improved one that shows what improvement is possible

267   when integrating a systems approach into transition management.

268 In both game sessions, players can also learn practical knowledge about agroecological practices, since

269 they must review the many practices available in the game and choose some of them to achieve their

270 objectives. Hazards were not activated in these sessions.

3. Results of game sessions

3.1.   Session to improve soil quality

273 In the SOIL game session, players must introduce agroecological practices to improve soil quality. In

274 the player's shoes, we chose to introduce four agroecological practices from several categories. First,

275 soil management was modified by performing reduced tillage instead of conventional tillage and by

276 leaving straw on the soil instead of removing it. Second, one of the two cropping systems was diversified

277 by selecting the rotation "maize – wheat – maize – barley" to replace the default rotation "maize –

278 wheat". Third, hedgerows were planted as green infrastructure.

279 Once the player applied these choices, the score of soil quality nearly doubled from 0.34 to 0.67 (out of

280 1), as shown in the hierarchical tree of sustainability (Figure 5). This improvement is explained by an

281 increase in the soil's resistance to erosion (due to reducing tillage, leaving straw on the soil and planting

282 hedgerows) and an increase in soil organic carbon content (due to leaving straw on the soil). The two

283 other indicators of environmental quality – water quality and air quality – also improved due to (i) less

284 pesticide use because of crop diversification and (ii) planting hedgerows, which decreased utilized

285 agricultural area by 5%. This combination of agroecological practices also improved the score of

286 biodiversity conservation due to an increase in microbial biomass, soil meso-fauna and earthworm

287 abundance. Nevertheless, the score of pressure on energy resources decreased due to the increase in feed

288 and straw purchases, which worsened the farm's energy efficiency. This increase in feed and straw

289 purchases was due mainly to crop diversification (less forage produced) and leaving straw on the soil.

290 This decreased score of pressure on energy resources offset the increase in the score of global warming

291 potential, which was related to using less fuel and synthetic fertilizers. Because of these changes,

292 environmental sustainability improved from 0.39 to 0.54.

293 All economic indicators were improved, mainly because the profit from crop production increased.

294 Indeed, the agroecological practices implemented did not decrease crop yields, and the cost of

295 production decreased due to using less pesticides and fertilizers because of crop diversification. Profit

296 also increased because sales of cereals increased and they have a higher price than maize, whose sales

297 decreased. Thus, economic sustainability increased from 0.29 to 0.39.

298 Regarding social sustainability, the score of societal expectations decreased slightly due to planting

299 hedgerows, which decreased crop production because of less utilized agricultural area. Consequently, it

300 worsened the "Food production potential" indicator. The "Simplicity of the system" indicator was also
301 worsened due to implementing agroecological practices that complicated farm management (except for
302 leaving straw on the soil). Nevertheless, this worsened score was offset by the improved safety of
303 pesticide users due to crop diversification and planting hedgerows. Because of these changes, social
304 sustainability remained stable at 0.55, and overall sustainability improved from 0.41 to 0.49.
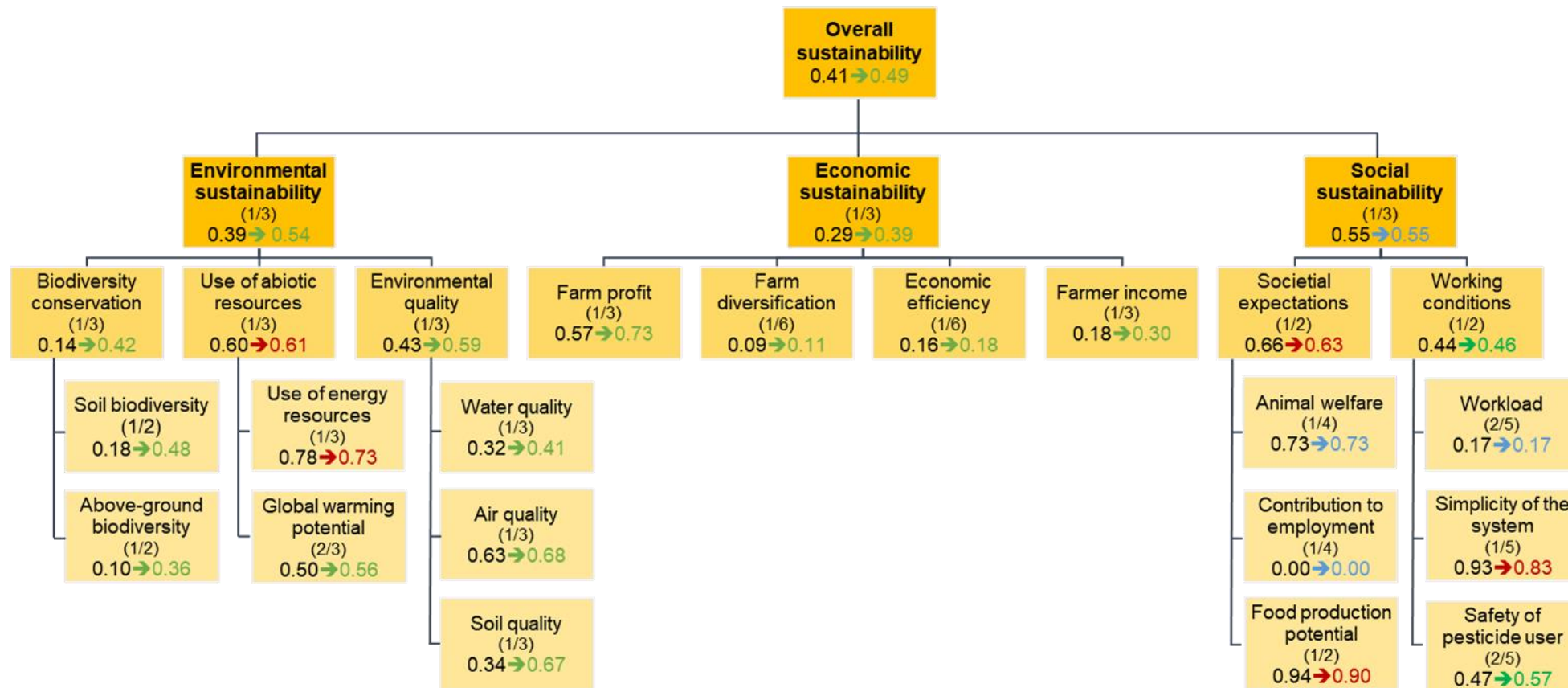
Figure 5. Detailed scores of the three pillars of sustainability in the farm, before and after implementation of agroecological practices in the SOIL game session. These practices are "reduced tillage", "straw left on soil", rotation maize – wheat – maize – barley" and "hedgerows as green infrastructure". Scores for indicators of order n are weighted averages of the scores for indicators of order n+1. The weight of each indicator is shown in parentheses.

305

3.2. Session to manage transitions to organic farming

In the ORGANIC game session, players must convert the farm to meet organic certification specifications within five years. These specifications, adapted to the game, are detailed in the *information* button corresponding to the strategic decision "Type of agriculture: Organic farming". Once all the practices necessary for conversion have been implemented in a game session, players can choose to trigger the conversion to organic certification.

3.2.1. Approach A

For approach A, we chose to implement agroecological practices gradually to meet the minimum specifications of organic certification within five years. In the first year, practices for crop protection were changed from conventional practices to practices based on an agroecological approach (Figure 6; Approach A). These changes increased the scores of all three pillars of sustainability, mainly due to substantial improvements in biodiversity conservation, environmental quality and profit. Indeed, the cost of crop protection was nearly halved, while the yields remained constant. Overall sustainability reached 0.50. In the second year, treatments of cows and heifers became selective, which led to minor changes in indicator scores and constant overall sustainability. In the third year, crop production practices were changed further by using only biocontrol products against pests and diseases and mechanical weed control against weeds. These changes decreased crop yields, which led to an increase in feed purchases and thus a decrease in the score of abiotic resource use. However, this worsened score was offset by the improvement in biodiversity conservation made possible by decreasing pesticide use. Thus, environmental sustainability improved slightly, from 0.45 to 0.48. Social sustainability also improved, mainly due to an increase in the scores of workload and safety of pesticide users. However, economic sustainability decreased from 0.48 to 0.41, due to the decrease in crop yields that decreased farm profit. Overall sustainability remained constant. In the fourth year, management of animal health was changed further by using only preventive measures and immunizing cattle against parasites. As a result, economic sustainability continued to decrease, reaching 0.38, because animal production became less profitable, with a slight decrease in milk and meat yields, along with higher feed requirements. The score of animal welfare worsened due to the decrease in veterinary treatment. The scores of workload and simplicity of the system also worsened, which decreased social sustainability. Thus, overall sustainability began to decrease, reaching 0.48. Finally, in the fifth year, fertilization practices were changed by using only organic fertilizers, feed concentrates for dairy cows were reduced and organic certification was triggered. Due to the certification, economic sustainability increased (+0.27 points): the value of production was improved by higher prices, which offset the loss of profitability due to the decrease in crop yields caused by the new fertilization practices. However, this decrease worsened the "Food production potential" indicator, which decreased social sustainability. Environmental sustainability also decreased due the worsening of the score of abiotic resource use with an increase in feed purchases. Indeed, forage self-sufficiency, which was 100% at the beginning of the session, reached

only 78%, while protein self-sufficiency reached only 57%. However, overall sustainability improved from 0.41 to 0.54.

3.2.2. Approach B

For approach B, we also chose to implement agroecological practices gradually over five years but also to exceed the specifications of organic certification to improve overall sustainability. In the first year, implementing the same practices as in approach A yielded the same changes in sustainability scores. In the second year, we implemented an additional practice compared to those implemented in the second year of approach A: we diversified one cropping system from the default rotation "maize – wheat" to "maize – wheat – maize – barley" (Figure 6; Approach B). By doing so, environmental sustainability increased more than in approach A due to better biodiversity conservation and environmental quality. Economic sustainability also improved more because crop sales increased. Thus, overall sustainability was 0.02 points higher in approach B than in approach A. In the third year, the same practices as in approach A were implemented, which yielded the same changes. In the fourth year, we implemented an additional practice compared to those in approach A: temporary grassland was composed of complex grass/legume mixtures instead of only grass. Due to the higher protein content of the grass/legume grassland, feed purchases decreased, which led to higher economic sustainability (+ 0.08 points) than in approach A. In the fifth year, the same practices as in approach A were implemented. However, the decrease in grassland yield observed in approach A was no longer observed since temporary grasslands with legumes needed less fertilization. Thus, on-farm feed production decreased less, and feed purchases increased less. Indeed, compared to the beginning of the session, forage self-sufficiency decreased by only 6 percentage points, and protein self-sufficiency even increased by 16 percentage points. Consequently, the score of abiotic resource use increased instead of decreasing, and economic sustainability increased more than in approach A, reaching 0.75. In approach B, overall sustainability reached 0.61, which was 0.07 points more than in approach A.
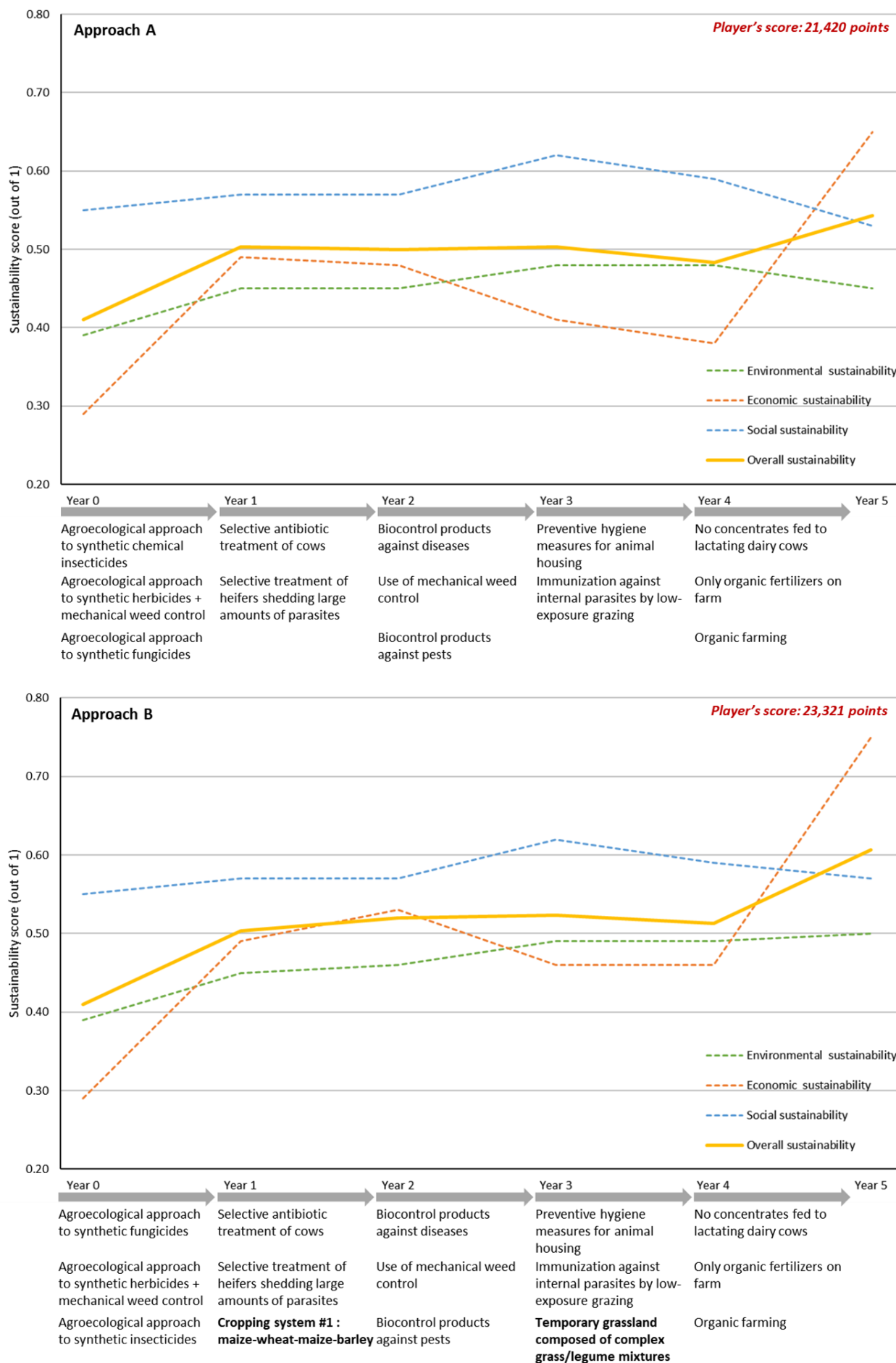
Figure 6. Evolution of sustainability scores as a function of changes in practices in the two approaches to the ORGANIC game session, in which the player's objective is to convert the farm to organic farming. Changes in bold are those performed in approach B but not approach A.

4. Discussion

4.1. SEGAE: an innovative tool for learning agroecology

SEGAE is a promising tool to learn agroecology. It is based on a modeling framework that gamifies the implementation of agroecological practices on a farm and stylizes their impacts on sustainability. This game addresses three main educational objectives for players.

First of all, the objective of acquiring a systems approach was illustrated through the SOIL game session, in which players aim to improve soil quality by choosing agroecological practices from the farms' strategic dimensions and to assess their impacts on the three pillars of sustainability. Session results showed that environmental and economic sustainability were improved, but that social sustainability remained constant, mainly due to a decrease in food production potential. This is an important issue for the large-scale development of agroecology and thus can lead to interesting discussions with students. Indeed, beyond learning about agroecological practices and their impacts, SEGAE was built to foster discussion and debate in ways that complement other studies of agroecology and its impacts on sustainability (e.g., Poux and Aubert (2019)).

Then, the objective of improving skills in transition management was illustrated through the ORGANIC game session, in which players aimed to convert the farm to organic farming within five years. To illustrate the importance of transition management, this game session was repeated with two approaches. Results from approach A showed that conversion to organic farming improves the three pillars of sustainability, even though certain indicators were worsened, and some impacts were not included in the game's boundaries (e.g., environmental impacts due to input production and transport). These results are consistent with recent reviews (Reganold and Wachter, 2016; Seufert and Ramankutty, 2017). The improvement in economic sustainability was enabled by obtaining an organic price premium after conversion. Here, we assumed that conversion subsidies, associated with the higher prices during conversion, were equivalent to organic prices, which the farmer can legally benefit from 2 years after beginning the conversion. However, the example game sessions did not consider an important factor that can compromise the viability of organic farming greatly: price and production risks (Berentsen et al., 2012). Nonetheless, this factor can be considered in the game by activating the risk option. By doing so, predefined hazards can occur, which makes it possible to test the farm's resilience while challenging students. To illustrate it, we implemented again the ORGANIC game session (approach A) in the current version of SEGAE by activating the risk option: a global milk overproduction happened in year 2, 3 and 5, which made milk price decrease by $100€.t^{-1}$. The sustainability scores were lower than in the version presented in this article: the economic sustainability reached 0.36 instead of 0.65, which lead to a lower overall sustainability (0.45 instead of 0.54). These random events are totally customizable by the teacher, and can thus allow a wide diversity of pedagogical scenarios (e.g., adaptation to climate change, increasing price of pesticides due to environmental taxes).

402   In addition, even though the farm's sustainability scores improved in the approach A, forage and protein
403   self-sufficiency decreased. This decrease differs from practices observed on farms that develop a
404   strategy based on grazing and feed self-sufficiency to increase their resilience during conversion
405   (Bouttes et al., 2019; Perrin et al., 2020). However, results can be improved by introducing legumes to
406   temporary grassland, as in approach B, in which protein self-sufficiency increased, as did the three
407   pillars of sustainability. Thus, SEGAE provides opportunities for players to develop learning through
408   trial-and-error (Couvreur et al., 2018) by testing several combinations of practices and looking for clues
409   in technical indicators to improve sustainability scores. This is especially true since the order in which
410   practices are chosen matters: for example, if mineral fertilization is removed in the first year of
411   conversion, overall sustainability plunges to 0.30, which threatens the farm's viability.
412   A last objective, to learn about agroecological practices, was assessed in a previous article that details
413   SEGAE's potential to help learn in an entertaining way (Jouan et al., 2020). To do so, an evaluation of
414   university students who played the game was performed during a one-week workshop, by implementing,
415   beyond others, a knowledge survey. In this article, we showed that students significantly increased their
416   knowledge of agroecology with a mean increase of nine percentage points in their scores. In addition,
417   more than 86% of the students enjoyed the game, appreciating its interaction and feedback. We thus
418   concluded that SEGAE was an interesting tool to help students acquire knowledge of agroecology in a
419   fun way.

420   ## 4.2.   Important pedagogical aspects

421   SEGAE is available online to all at no cost at https://rebrand.ly/SEGAE. However, SEGAE was not
422   originally designed to be used in an autonomous way: this tool should preferably be part of a pedagogical
423   activity led by a teacher. As already mentioned in section 2.2.3., the pedagogical activity should include
424   a discussion on the results, the methodology, and the limits of the game with the teacher. A pedagogical
425   guide is available on SEGAE website to help teacher build such activities. In particular, it is necessary
426   important to discuss the choice of various indicators of sustainability indicators chosen, their calculation
427   methods and their associated scores weights. Indeed, the sustainability scores are composite scores that
428   enable students to analyze the sustainability of the farm. However, the indicators are aggregated based
429   on various weights, which stem from our own expertise and have substantial impacts on the simulation.
430   To highlight this issue with students, one solution for the teacher is to come up with two different sets
431   of weights and subdivide the class to make half the students play with each of the set of weights. The
432   teacher can then discuss the differences in sustainability scores due to the differences in weights with
433   the all students.
434   In addition to the sustainability scores, the students have access to the main technical results in the
435   "warehouse" button. It is essential for the teacher to make students analyze these scores since they help
436   them to understanding the sustainability scores. Besides, another score is available: the player's score.
437   This score, calculated from the lowest score of the three pillars of sustainability cumulated over the

years, helps students to question the sustainability scores since it highlights the necessary balance between these three pillars. Overall, the three types of score introduced in SEGAE – sustainability scores, technical scores and player's score – should be used together to optimize the pedagogical outputs of the game.

4.3.   Strengths, limits and perspectives

SEGAE has three main advantages. First, the diversity of indicators covers the three pillars of sustainability, which enables players to understand potential antagonistic impacts of agroecological practices. Second, the interactivity of the graphical interface enables players to display a summary of these indicators in the hierarchical tree of sustainability and to envision some impacts of the practices implemented. It also incites players to investigate impacts of practices further through a wide range of information available in the *Report* tab. By doing so, players can improve their knowledge about various disciplines in an active way. Third, the adaptability of several game elements enables users, especially teachers, to transpose the game to their context and improve it. In particular, the code of the calculation engine that connects the matrix to the graphical interface is open source, which allows future users to improve the game or reuse it in other software.

Since the model was developed for educational purposes, representation of impacts was simplified using an output-oriented approach. This choice may cause impacts that are related to complex and indirect processes to be ignored. In particular, the impacts of practices appear instantly and the game does not capture interactions that could appear when several practices are implemented. The small set of rations and rotations in the game also makes it difficult to match them to each other exactly, which can lead to configurations that would probably not exist in reality. In addition, the game focuses only on the farming system itself: indirect impacts of practices that do not occur directly on the farm are not considered (e.g., CO_2 emissions from production of inputs, impacts on the nearby water ecosystems from reducing the use of antibiotics in animal production). One improvement would thus be to include data from life cycle assessment in the evaluation of agroecological practices (van der Werf et al., 2020). Finally, the current version of SEGAE includes four farming systems still under development (i.e., French, Belgian, Italian and Polish). The parametrization of these farming systems is based on typical farms, and does impacts greatly the results of the simulation. A development path would be to adapt the game to very different contexts, such as tropical farms where agroecological practices can be particularly beneficial (Pretty et al., 2006), but it would require considerable effort. However, since the game was built to be scalable, it can be adapted to other temperate farming systems by developing new farms with new practices and indicators. Despite these limitations, SEGAE was already introduced to c.a. 90 university teachers and extension agents who were enthusiastic about the game: some of them already used it in their courses in the context of covid-19 epidemic. To go further, it would be interesting to present this game to farmers. Even if they are not the target audience, they could also improve the coherence of simulations.

473 SEGAE was designed to strengthen European training in agroecology, and active contributions from
474 users would help improve the tool, create new scenarios and forge connections within the community
475 of teachers working on agroecology. This community is organizing gradually by developing seminars
476 and international degree programs. This approach complements more local initiatives that include
477 farmers in participatory projects to improve the sustainability of agricultural systems (Lacombe et al.,
478 2018). In addition, by connecting multiple dimensions of farm sustainability, as well as some societal
479 expectations, SEGAE provides a fresh look at agroecological practices. These farming practices, which
480 are usually considered as unprofitable and under-optimized, are depicted in the game in an
481 interdisciplinary and integrated way that highlights their utility and ease their understanding by students.
482 Finally, overall sustainability is estimated using a smaller set of indicators that have different weights.
483 The indicators chosen and the balance among them stem from our expert opinion, which is an important
484 issue that deserves to be studied further. In particular, the challenges to social sustainability that
485 agroecological practices may cause, such as an increase in workload and decrease in food production
486 potential, should be studied deeply. Closely related to sustainability, the concept of farm resilience
487 should also be emphasized in European agricultural programs. SEGAE could contribute to this goal by
488 using the classroom mode, which can simulate persistent stress such as climate change. By studying a
489 system's ability to prepare for threats, absorb impacts and adapt to them, current and future professionals
490 could become better prepared to face the many challenges that face the agricultural sector.

491 **5. Conclusion**

492 To improve agroecology learning, we built the online simulation game SEGAE
493 (https://rebrand.ly/SEGAE). This article presented the model framework on which it is based and
494 illustrated the game's potential. SEGAE is based on an output-oriented approach that represents impacts
495 of practices on multiple indicators. These impacts are included in a matrix that is connected to a
496 graphical interface that stylizes them. The article presented and discussed two examples of game
497 sessions and their results. The results of the first example, which aimed to improve soil quality, allow
498 players to put the improvement of overall sustainability into perspective with a decrease in food
499 production potential. The results of the second example, which aimed to convert the farm to organic
500 farming, allow players to discuss the steps needed to obtain organic certification and the coherence
501 between crop and animal production needed to foster sustainability. SEGAE is currently adapted to four
502 farming systems in Europe, but since it was designed to be scalable, active contributions from users
503 would allow it to be improved and adapted to other European contexts.

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620 **Appendix**

621 Detailed description of the indicators included in the hierarchical tree of sustainability (in yellow). In green, qualitative sub-indicators; in blue, quantitative sub-

622 indicators. Yield gap is the difference between the maximum yield attainable in the game and the yield reached during the game session.

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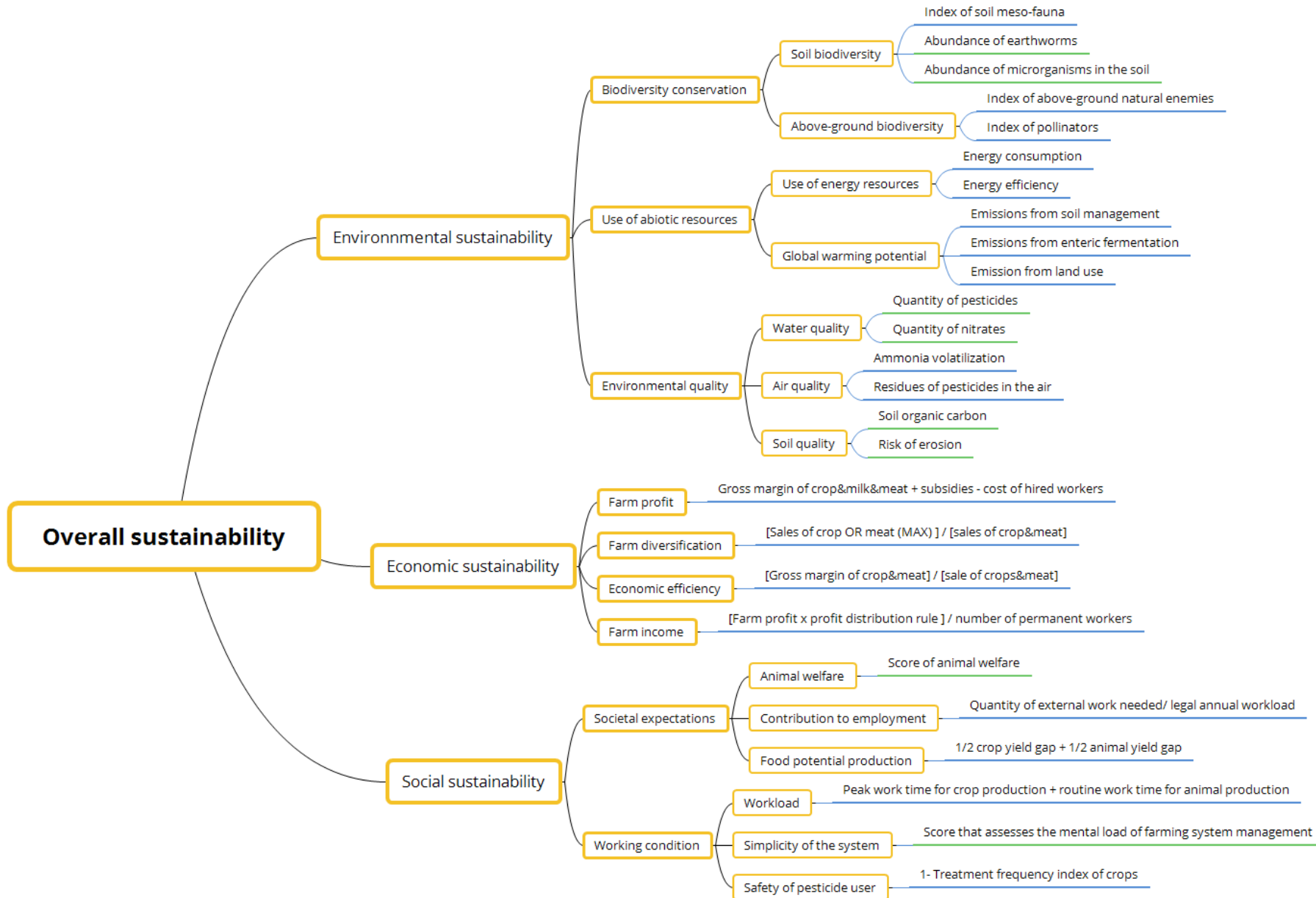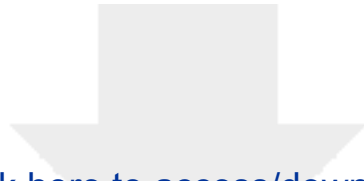
Click here to access/download

Data in Brief

DataInBrief_SEGAE_AS.zip

Declaration of interests

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

☐The authors declare the following financial interests/personal relationships which may be considered as potential competing interests:

Julia Jouan, 1st author