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ABSTRACT

CONTEXT: There is growing evidence that agroecology can reconcile the environmental, economic, and social pillars of agricultural sustainability. However, teaching and learning agroecology is challenging, especially since most agricultural graduate programs in Europe are not adapted to teach the diversity of its related practices.
OBJECTIVE: To improve agroecology learning, we built the online simulation game SEGAE. This article illustrates the game's relevance for learning agroecology.
METHODS: The game is based on a modeling framework that gamifies the implementation of agroecological practices in an integrated crop-livestock farm and assesses their impacts on sustainability. To do so, SEGAE is based on an output-oriented approach that represents impacts of practices on various indicators. These impacts are included in a matrix, which is associated with a dynamic graphical interface accessible to players. Two examples of game sessions were developed to illustrate the game's potential.
RESULTS AND CONCLUSIONS: In the first example, players can gain knowledge about agroecological practices by implementing practices that improve soil quality and assessing their impacts on sustainability. Results of this example place the farm's improved overall sustainability into perspective with its reduced food production potential. In the second example, players can improve their skills in transition management and acquire a systems approach by converting the farm to organic farming within five years. Results of this example prompt discussion of the steps needed to obtain organic certification and the coherence between crop and animal production needed to foster sustainability.

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

1. Introduction

There is growing evidence that agroecology represents a pertinent mechanism for fostering agricultural sustainability (FAO, 2019; Gliessman, 2014). Through its holistic approach, agroecology reconciles the environmental, economic and social pillars of sustainability, which are conceptualized here as three distinct but interacting systems (Purvis et al., 2019). Agroecology is a dynamic concept that has been popularized in scientific and political discourse in recent years (Wezel et al., 2020). It embraces a science, a set of practices and a social movement, and can be applied from food production to consumption (Francis et al., 2003; Wezel et al., 2009). Agroecological practices aim to foster ecosystem services in order to sustain production while limiting environmental impacts by decreasing the use of anthropogenic inputs (Altieri and Farrell, 2018). To promote such practices, it is essential to teach agroecological concepts to current and future professionals of the agricultural sector, such as high-school and university students (Jouan et al., 2020).

However, agroecology can be difficult to learn, in particular for students, since it includes a wide variety of practices involved in complex biological processes, while operating within a globalized food system. It is thus necessary to develop interdisciplinary approaches to teaching agroecology that embrace economic and social dimensions (Francis et al., 2019). However, agricultural graduate programs in Europe are usually taught by specialized teachers who focus on a narrow range of disciplines and subjects, which does not train students to develop interdisciplinary approaches (Francis et al., 2008). Moreover, agricultural graduate programs are insufficiently based on systems approaches, which limits the representation of complex relationships between farming practices, agricultural production and sustainability (Francis et al., 2011).

To foster agroecology learning, emergent teaching materials such as serious games have been identified (Duru et al., 2015). These games are designed to ease learning by proposing fun activities (Crookall, 2010). Most serious games related to agriculture are based on boards (Dernat et al., 2019; Loriot and Gowthorpe, 2017; Vaulot et al., 2018). This can limit their accessibility to a large international audience, and also potentially restrain their interactivity, a key element to facilitate learning (Vogel et al., 2006). Other games benefit from more accessible and interactive design but restrict their focus to one part of farming systems, either crop or animal production (Calsamiglia et al., 2020; Dourmad et al., 2013; García-Barrios et al., 2016), since it can be difficult to represent the multiple components of a farming system in which crop and livestock management are highly integrated. In addition, several games focus on social relations among stakeholders involved in management of farming systems, but the inclusion of agroecological practices, as well as their economic impacts, is limited (Braasch et al., 2018; García-Barrios et al., 2008). Other games that rely on agronomic models have the advantage of integrating various practices while producing credible simulations (Martin et al., 2011). Even though they do no reach the complexity of research models (e.g., ORFEE (Mosnier et al., 2017), STICS (Brisson et al., 2003)) or of decision-support tools (Rose et al., 2016), these model-based games are often adapted to a professional audience, which limit their direct use in formal education. Finally, to the best of our knowledge, there is no serious game that highlights agroecology as a mechanism to improve all three pillars of sustainability: environmental, economic and social.

To fill these gaps in agroecology learning, we built the serious game SEGAE (SErious Game for AgroEcology learning; https://rebrand.ly/SEGAE), which is an online simulation game based on an output-oriented modeling approach. This game is the main output of the Erasmus+ SEGAE project, a three-year project that associated six European universities from Belgium, France, Italy and Poland. SEGAE is aimed particularly at university students in fields related to agriculture but can also used with high-school students and extension agents. The objective of this article is to illustrate the relevance of SEGAE for learning agroecology, by (i) detailing the conceptual model and the game itself, and (ii) providing examples of game sessions. The examples presented are based on the integrated crop-livestock dairy farm of western France developed in the initial version of SEGAE. Similar farming systems of the other partner countries are not illustrated here.

2. Method

2.1. Conceptual model

2.1.1. The integrated crop-livestock farm model

SEGAE's conceptual model represents its theoretical foundation. Designed at the farm scale, the model was developed to address three main educational objectives for players: (i) acquire a systems approach by assessing combined impacts of these practices, (ii) improve skills in transition management by reaching given goals with limited time and resources in the game and (iii) learn about agroecological practices.

To address these objectives, the conceptual model represents multiple components of an integrated crop-livestock farm and integrates several categories of practices related to agroecology. It consists of five modules that interact with each other through practices that impact ecosystem services (Fig. 1). Most of these practices are agroecological and were chosen and adapted from two review studies (Dumont et al., 2013; Wezel et al., 2014) (Section 2.2.1). The conceptual model has an annual timescale, and its spatial extent is the farm scale; thus, it does not consider indirect impacts, such as environmental impacts that occur outside of the farm boundaries.

The crop module represents cropping systems of annual crops and forages (including 10 categories of crop-related practices); its main output is crop and forage production. The animal module represents the structure and demographics of the dairy cattle herd, integrates feed requirements, and calculates production of milk, meat and manure. It includes eight categories of animal-related practices. The socio-economic module represents the economic and financial functioning of the farm (e.g., purchases, sales, investment capacity) and estimates the workload of farmers and the farm's contribution to societal expectations. It includes two strategic decisions (i.e., distribution of farm profit and type of agriculture), which are equivalent to practices since they can influence crop and animal modules. The ecosystem module represents ecological components that are not dedicated only to crop and animal production. It includes two categories of practices – agroforestry and green infrastructure – that can influence the other modules. The soil module represents soil functioning (e.g., water, nutrient and carbon cycles, including gaseous emissions, carbon storage and leaching) and considers soil physical properties and soil biodiversity. It includes three categories of practices, which also belong to the crop module.

2.1.2. The output-oriented approach

The main originality of SEGAE's conceptual model lies in the output-oriented approach chosen to represent the impacts of practices (Fig. 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 ap-

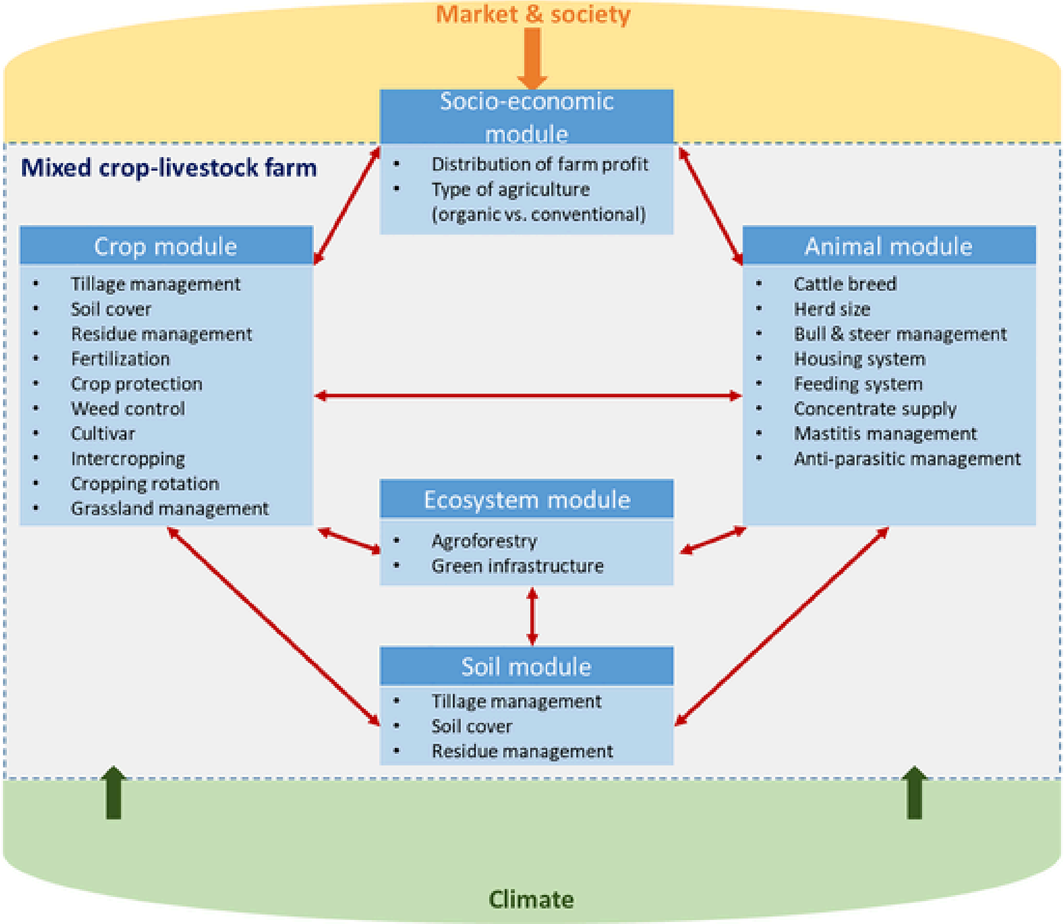

Fig. 1. Conceptual model of the five modules of SEGAE. Each module is associated with various categories of practices and interacts with others through the practices that impact ecosystem services. Practices, and their impacts (red arrows), are considered only at the farm scale (dashed line), except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

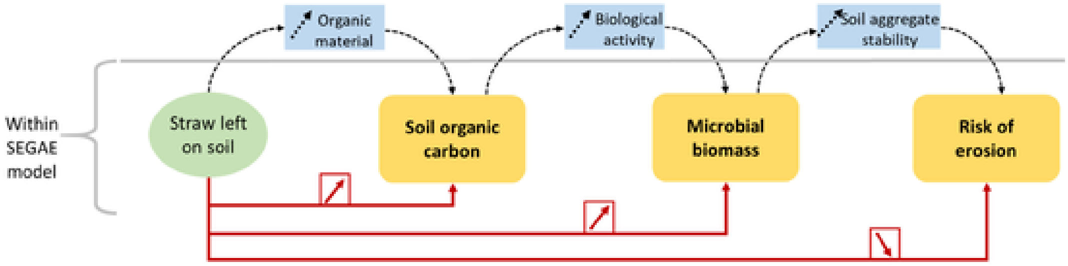

Fig. 2. Example of the output-oriented approach implemented in SEGAE that represents the impact of a practice on various indicators. The illustrated practice (in the green cell) is “Straw left on soil”, which belongs to the category “Residue management”. The framed arrows represent qualitatively the 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.

proach 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).

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), MASC (Sadok et al., 2009) and MASC-OF (Colomb et al., 2013). 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.

The scores for indicators of order n are weighted averages of the scores for indicators of order n + 1. Each indicator is associated with a specific weight that we defined to reflect its relative impact on sustainability. Each indicator score in the hierarchical tree is normalized from

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

	First-order indicators	Second-order indicators	Third-order indicators
Sustainability	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)

0 to 1, and an increase in the score always represents a beneficial change, even for indicators of harm (e.g., "Global warming potential").

2.2. Overview of the game

2.2.1. The matrix

The matrix is a spreadsheet that connects impacts of practices to many indicators. It includes 124 practices in lines and their impacts on 575 primary indicators in columns (Fig. 3). For each category of practices (Fig. 1), a set of practices is available; for example, the category "tillage management" includes "conventional tillage", "reduced tillage" and "no tillage".

The indicators are related to crops, animals, the environment and socio-economic aspects of the farm. While all 124 practices of the matrix are available in the game, players do not see all 575 indicators. These primary indicators, directly impacted by practices, are used mostly to calculate 365 secondary indicators that are aggregations of the primary ones at farm or herd scales. Some of the 365 secondary indicators are used for internal calculations (e.g., nitrogen flows, economic output), while many of them are displayed to players, either as sustainability indicators in the hierarchical tree of sustainability (e.g., soil biodiversity) or as technical indicators (e.g., amount of feed purchased) to help players understand the farming system.

In the matrix, multiplicative or additive factors are used to calculate the impacts of practices on the 575 indicators. Most practices impact several indicators, which helps players understand the complexity of the system through the interdependence of the three pillars of sustainability. We (i) found these impact factors in original studies described in peer-reviewed articles, (ii) determined them by analyzing several scientific articles or local technical documents, (iii) calculated them using specific tools (e.g., software) or (iv) estimated them based on our expert opinion in the associated fields. Some factors are included in the matrix only to perform certain calculations. The complete matrix, including all practices and indicators, as well as the impact factors and their references, is available in (Jouan et al., Submitted).

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 (Fig. 4). The initial farms represented were parameterized to repre-

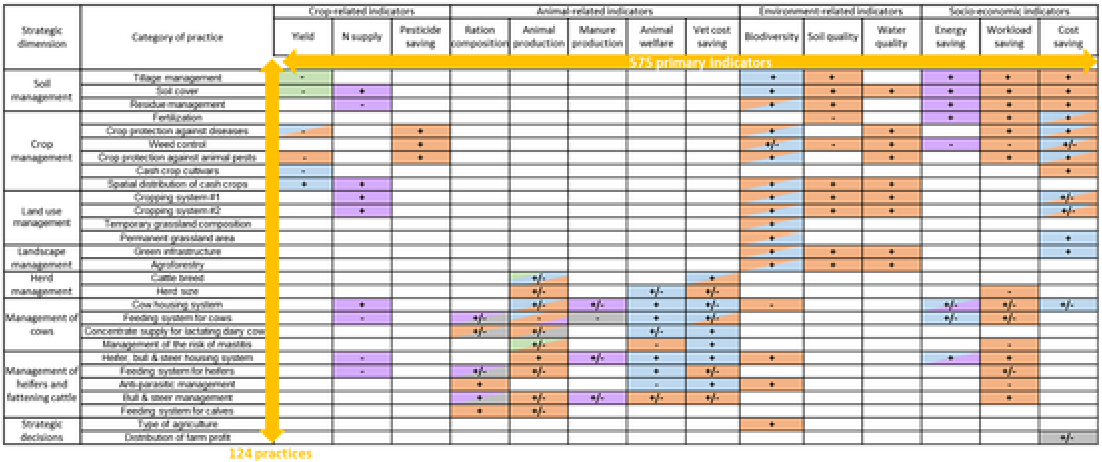

Fig. 3. Illustration of SEGAE's matrix, simplified from Jouan et al. (Submitted), which connects impacts of farm practices to farm indicators. The impact factors are represented qualitatively. +: agroecological practices in the category increase the values of related indicators compared to conventional 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 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.

Fig. 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.

sent 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 was parameterized to represent a typical dairy farm in western France: its initial characteristics for crop production, animal production and economic results (Table 2) are similar to those in official statistics (Draaf Bretagne, 2018). These characteristics are likely to evolve during a game session (i.e., a predefined number of game turns to reach specific goals).

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 (Fig. 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 (Fig. 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'

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})	7546
Number of heifers	45

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 (Fig. 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.

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

2.2.3. *Playing the game*

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

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

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

3. Results of game sessions

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

- SOIL: a one-turn scenario to make players work on a systems approach. The player's objective is to improve soil quality by implementing agroecological practices that improve environmental sustainability without worsening economic or social sustainability. The player must reach the objective within one year.
- ORGANIC: a multi-turn scenario to make players work on transition management. The player's objective is to modify practices to meet European Union specifications for organic farming (European Council, 2007). The farm must be converted within five years. Impacts on the sustainability scores are assessed over several years. Two approaches to conversion are presented: (i) approach A, a basic approach that meets the minimum specifications for organic certification, and (ii) approach B, an improved approach that shows how much improvement is possible when integrating a systems approach into transition management.

In both game sessions, players can also learn practical knowledge about agroecological practices, since they must review the many practices available in the game and choose some of them to achieve their objectives. The risk option was not activated in these sessions.

3.1. *Improve soil quality*

In the SOIL game session, players must introduce agroecological practices to improve soil quality. In the player's shoes, we chose to introduce four agroecological practices from several categories. First, soil management was modified by performing reduced tillage instead of conventional tillage and by leaving straw on the soil instead of removing it. Second, one of the two cropping systems was diversified by selecting the rotation "maize – wheat – maize – barley" to replace the default rotation "maize – wheat". Third, hedgerows were planted as green infrastructure.

Once the player applied these choices, the score of soil quality nearly doubled from 0.34 to 0.67 (out of 1), as shown in the hierarchical tree of sustainability (Fig. 5). This improvement is explained by an increase in the soil's resistance to erosion (due to reducing tillage, leaving straw

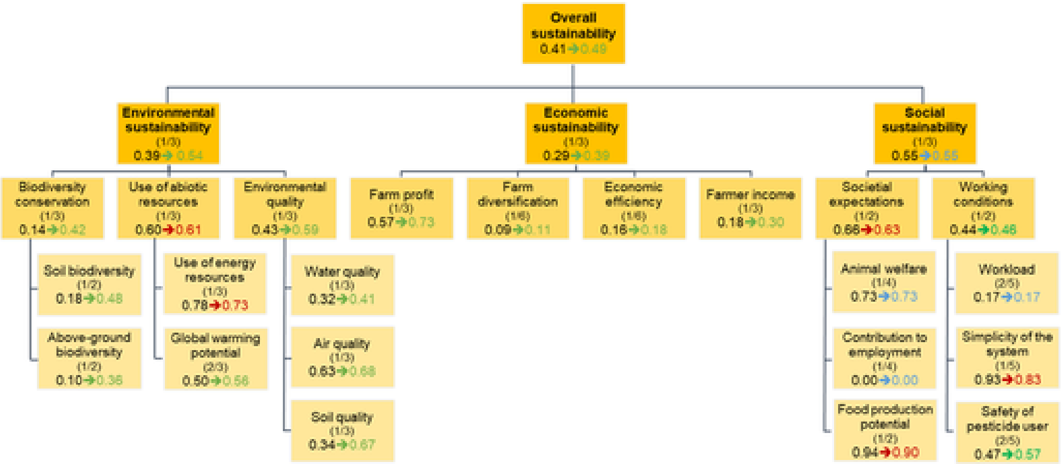

Fig. 5. Detailed scores of the three pillars of sustainability in the farm, before and after implementation of agroecological practices in the SOIL game session. These practices are "reduced tillage", "straw left on soil", rotation maize – wheat – maize – barley" and "hedgerows as green infrastructure". 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.

on the soil and planting hedgerows) and an increase in soil organic carbon content (due to leaving straw on the soil). The two other indicators of environmental quality – water quality and air quality – also improved due to (i) less pesticide use because of crop diversification and (ii) planting hedgerows, which decreased utilized agricultural area by 5%. This combination of agroecological practices also improved the score of biodiversity conservation due to an increase in microbial biomass, soil meso-fauna and earthworm abundance. Nevertheless, the score of pressure on energy resources decreased due to the increase in feed and straw purchases, which worsened the farm's energy efficiency. This increase in feed and straw purchases was due mainly to crop diversification (less forage produced) and leaving straw on the soil. This decreased score of pressure on energy resources offset the increase in the score of global warming potential, which was related to using less fuel and synthetic fertilizers. Because of these changes, environmental sustainability improved from 0.39 to 0.54.

All economic indicators were improved, mainly because the profit from crop production increased. Indeed, the agroecological practices implemented did not decrease crop yields, and the cost of production decreased due to using less pesticides and fertilizers because of crop diversification. Profit also increased because sales of cereals increased and they have a higher price than maize, whose sales decreased. Thus, economic sustainability increased from 0.29 to 0.39.

Regarding social sustainability, the score of societal expectations decreased slightly due to planting hedgerows, which decreased crop production because of less utilized agricultural area. Consequently, it worsened the “Food production potential” indicator. The “Simplicity of the system” indicator was also worsened due to implementing agroecological practices that complicated farm management (except for leaving straw on the soil). Nevertheless, this worsened score was offset by the improved safety of pesticide users due to crop diversification and planting hedgerows. Because of these changes, social sustainability remained stable at 0.55, and overall sustainability improved from 0.41 to 0.49.

3.2. Manage transition 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 – minimum organic specifications

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 (Fig. 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 – beyond organic specifications

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” (Fig. 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.

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 agroecologi-

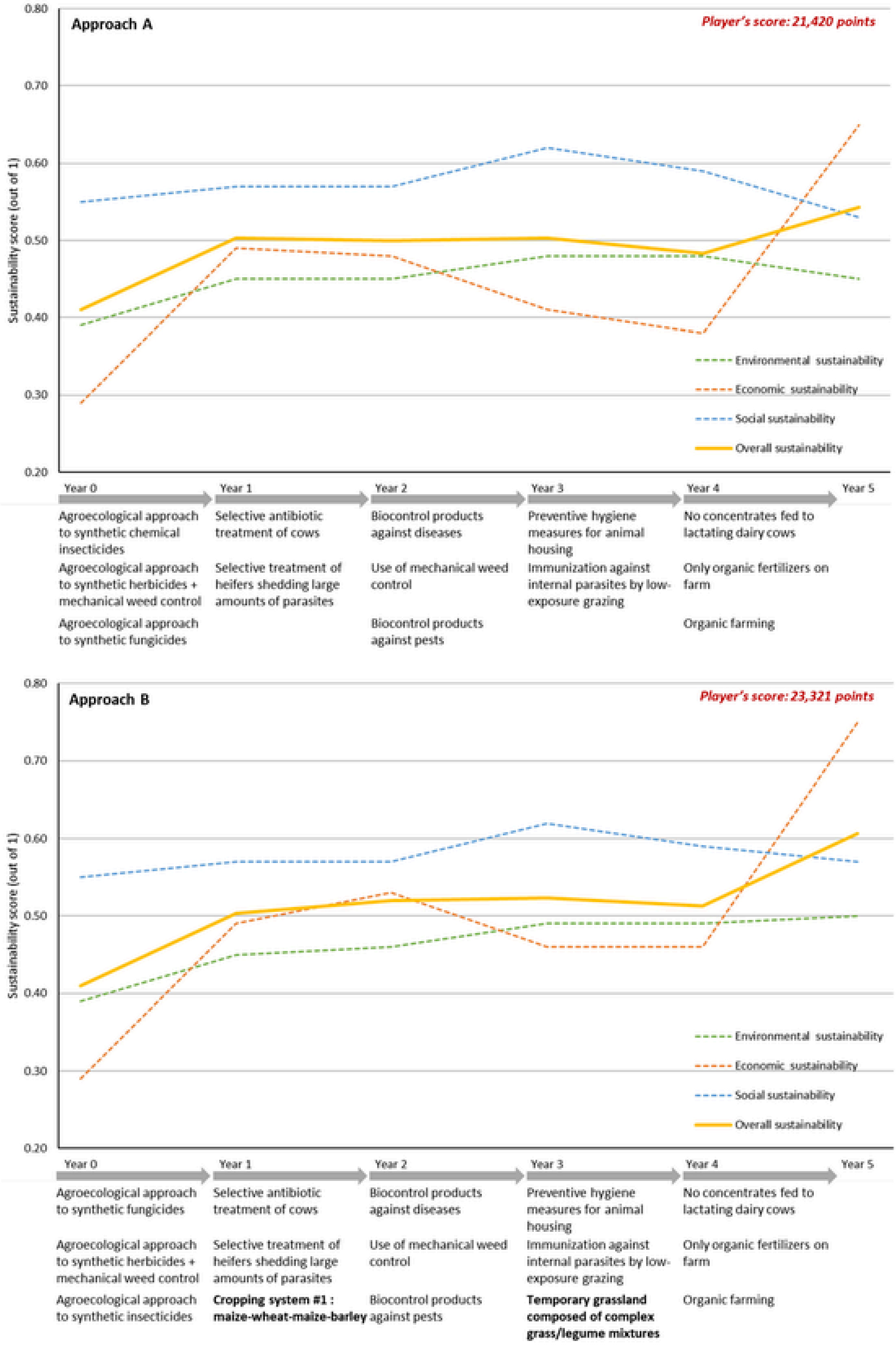

Fig. 6. Evolution of sustainability scores as a function of changes in practices in the two approaches to the ORGANIC game session, in which the player's objective is to convert the farm to organic farming. Changes in bold are those performed in approach B but not approach A.

cal 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 modifying practices specific to the soil influenced the entire farming system: environmental and economic sustainability improved, but social sustainability remained constant, mainly due to decreased 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 of 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. 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 this, we performed the ORGANIC game session again (approach A) in the current version of SEGAE while activating the risk option: milk was overproduced at the global level in years 2, 3 and 5, which decreased milk price by 100€.t^{-1}. The sustainability scores were lower than those in the session performed without the risk option: economic sustainability reached 0.36 instead of 0.65, which lead to lower overall sustainability (0.45 instead of 0.54). Teachers can customize these random events are completely, which thus allow for a wide variety of pedagogical scenarios (e.g., adaptation to climate change, increasing price of pesticides due to environmental taxes).

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

4.2. Important pedagogical aspects

SEGAE is available online to all at no cost at https://rebrand.ly/SEGAE. However, SEGAE was not originally designed to be used in an autonomous way: it should ideally form part of a pedagogical activity led by a teacher. As mentioned (Section 2.2.3.), the pedagogical activity should include a discussion of the game's results, methodology and limits with the teacher. A pedagogical guide is available at the SEGAE website to help teachers build such activities. In particular, it is necessary to discuss the sustainability indicators chosen, their calculation methods and their associated weights. Indeed, the sustainability scores are composite scores that enable students to analyze farm sustainability. However, the indicators are aggregated according to their weights, which stem from our expert opinion and influence simulations greatly. A teacher can highlight this issue with a class of students by creating two different sets of weights and then having half of the class play with each set. The teacher can then discuss with all students the differences in sustainability scores due to the differences in weights.

In addition to the sustainability scores, the students can view the main technical results by clicking on the *warehouse* button. Teachers should have students analyze these technical scores, since they will help them understand the sustainability scores. In addition, another score is available: the player's score. This score, calculated from the lowest score of the three pillars of sustainability summed 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 scores introduced in SEGAE – sustainability scores, technical scores and the 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 European farming systems (i.e., French, Belgian, Italian and Polish). The parametrization of these farming systems, based on characteristics of typical farms, influences simulation results greatly. One development path would be to adapt the game to very different contexts, such as tropical farms, on which agroecological practices can be particularly beneficial (Pretty et al., 2006), but doing so would require considerable effort. Since the game was built to be scalable, however, it can be adapted to other temperate farming systems by developing new farms with new practices and indicators. Despite these limitations, to date, SEGAE has been introduced to ca. 200 university and high school teachers and extension agents, who were enthusiastic about the game: some of them have already used it in their courses in the context of the COVID-19 epidemic. To go further, it would be interesting to introduce SEGAE to farmers. Even though they are not the target audience, they could improve the coherence of simulations.

SEGAE was designed to strengthen European training in agroecology, and active contributions from users would help improve the tool, create new scenarios and forge connections within the community of teachers working on agroecology. This community is organizing gradually by developing seminars and international degree programs. This approach complements more local initiatives that include farmers in participatory projects to improve the sustainability of agricultural systems (Lacombe et al., 2018). SEGAE can also complement other digital tools for learning agroecology. In particular, a Massive Open Online Course (MOOC) on agroecology is already available: it offers structured and theoretical content on agroecological practices that would complement SEGAE's contribution (de Tourdonnet, 2020). Similarly, the *Dictionary of Agroecology* (Batifol-Garandel et al., 2020) can help students understand certain terms in the game if the *information* button is not sufficient. Also, for students who want to go further, the data paper associated with this article provides a detailed overview of all impacts of practices as modeled in SEGAE (Jouan et al., Submitted).

In addition, by connecting multiple dimensions of farm sustainability, as well as some societal expectations, SEGAE provides a fresh look at agroecological practices. These farming practices, which are usually considered as unprofitable and under-optimized, are depicted in the game in an interdisciplinary and integrated way that highlights their utility and ease their understanding by students. Finally, overall sustainability is estimated using a smaller set of indicators that have different weights. The indicators chosen and the balance among them stem from our expert opinion, which is an important issue that deserves to be studied further. In particular, the challenges to social sustainability that agroecological practices may cause, such as an increase in workload and decrease in food production potential, should be studied deeply. Closely related to sustainability, the concept of farm resilience should also be emphasized in European agricultural programs. SEGAE could contribute to this goal by using the classroom mode, which can simulate persistent stress such as climate change. By studying a system's ability to prepare for threats, absorb impacts and adapt to them, current and future professionals could become better prepared to face the many challenges that face the agricultural sector.

5. Conclusion

To improve agroecology learning, we built the online simulation game SEGAE (https://rebrand.ly/SEGAE). This article illustrates the relevance of SEGAE for learning agroecology, by (i) detailing the conceptual model and the game itself and (ii) providing examples of game sessions. SEGAE is based on an output-oriented approach that represents impacts of practices on multiple indicators. These impacts are included in a matrix that is connected to a graphical interface that stylizes them. The results of the first game session, which aimed to improve soil quality, allow players to put the improvement of overall sustainability into perspective with a decrease in food production potential. The results of the second game session, which aimed to convert the farm to organic farming, allow players to discuss the steps needed to obtain organic certification and the coherence between crop and animal production needed to foster sustainability. SEGAE is currently adapted to four farming systems in Europe, but since it was designed to be scalable, active contributions from users would allow it to be improved and adapted to other European contexts.

Declaration of Competing Interest

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

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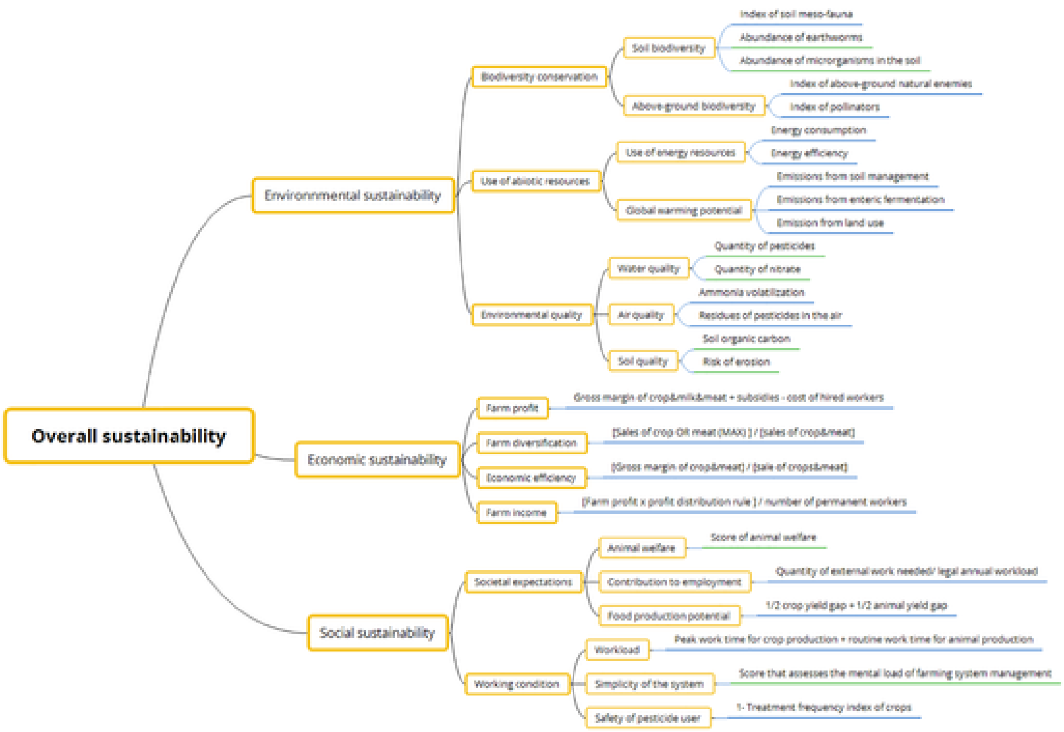
Appendix A

Detailed description of the indicators included in the hierarchical tree of sustainability (in yellow)., with qualitative (in green) and quantitative (in blue) sub-indicators. “Yield gap” equals the maximum yield attainable in the game minus the yield reached during the game session.



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