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Abstract: Agroecology represents a pertinent option to improve the sustainability of agriculture. To promote its application, agroecological concepts should be taught to students and professionals in the agricultural sector. However, most agricultural courses are not adapted to teach these concepts due to little interactivity or interdisciplinarity, and a lack of a systems approach to farm management. Serious games help to fill these gaps by simulating complex models in which players can learn by doing. We thus developed a serious computer game, called SEGAE (SErious Game for AgroEcology learning), which represents a mixed crop–livestock farm and assesses impacts of farming practices on indicators related to environmental, economic, and social sustainability. Its pedagogical interest was evaluated through two types of surveys given to university students who played the game during a one-week workshop: A knowledge survey on agroecology, and a feedback survey based on flow theory. Results showed that students increased their knowledge of agroecology significantly, particularly those who had had little knowledge of crop production. More than 86% of the students enjoyed the game, appreciating its interaction and feedback. Thus, SEGAE is an interesting tool to help students acquire knowledge of agroecology in a fun way by facilitating interdisciplinary and collaborative learning.

Keywords: serious game; agroecology; systems thinking; interdisciplinarity; farming system

1. Introduction

European agriculture is facing many challenges, such as producing food and other ecosystem services in sufficient quantity and quality and providing economic benefits for farmers and food-chain actors, while decreasing negative impacts on the environment [1,2]. Several authors consider agroecology as a pertinent option to reconcile the environmental, economic, and social pillars of agricultural sustainability [3,4]. Agroecology is broadly defined as "the ecology of sustainable food systems" [5]. This article considers a more restrictive definition that focuses on the farm level: "The study of the interactions between plants, animals, humans, and the environment within agricultural systems" [6]. Agroecological practices aim to increase levels of ecosystem services in order to sustain production while decreasing environmental impacts by decreasing anthropogenic inputs [7]. In particular, agroecological practices are based on diversifying the components of the farming system and increasing the interactions among them to close energy and material cycles [8]. Beyond studying agroecological practices and transitions [9], there is an urgent need to build awareness and teach agroecological concepts to future professionals of the agricultural sector (i.e., high-school and university students training to become farmers or extension agents), as well as current professionals [10,11].

However, most agricultural programs in European countries are not completely adapted to teach these concepts, due to a double weakness. First, their courses often fall into a narrow range of specialized disciplines, each of which focuses on its specific subjects. This approach does not train students to address complex agricultural issues, which generally need to be addressed through an interdisciplinary approach to farm management that includes animal and veterinary sciences, agronomy, applied ecology, and soil, environmental, economic, and social sciences [12]. Closely related to the lack of interdisciplinarity, agricultural courses do not develop enough systems approaches: They address most agricultural issues using a narrow range of methods and approaches that do not represent the complex relationships between farming practices, agricultural production, environmental impacts, sociological consequences, and economic results [13]. Indeed, interdisciplinary and systems approaches are now identified as founding principles of educational programs in sustainable agriculture [14,15]. Learning agroecology is not easy, however, since a variety of lock-in mechanisms may appear [16]. In particular, "cognitive lock-in" has been demonstrated in relation to agroecology [17], in which previous knowledge, skills, and personal beliefs may decrease students' motivation to acquire new knowledge.

In addition, current pedagogical methods often lack interactive and experiential dimensions [18,19]. Theories on learning suggest that it is more effective when it is active, experiential, situated and problem-based, and provides immediate feedback [20]. Serious games based on digital tools can exhibit these features, which may explain why they have grown rapidly in recent years [21]. They are "designed experiences" in which players can learn through doing and being, rather than assimilating information from reading and lectures [22]. In addition, by simulating complex models or providing control over parameters that usually cannot be monitored, they can allow players to improve their understanding of systems approaches [23]. Finally, by offering players the ability to envision themselves in the future and see consequences of actions instantly, serious games develop capacities to design the future through "visioning thinking", which can ease assimilation of innovative techniques such as agroecological practices [24].

Nonetheless, few serious games are related to agriculture, and even fewer use interdisciplinary and systems approaches to address agroecological issues. For instance, the game Azteca Chess addresses agroecological practices for shade-coffee production, but focuses on ecological complexity, ignoring farming system management [25]. Certain serious games focus on animal production without considering crop production or socio-economic dimensions [26]. In contrast, other serious games do connect crop and livestock management, but are based on board games, which limits interactivity and visioning thinking [27–29]. Finally, based on our experience, most existing serious games do not seem to be adaptable to a variety of pedagogical objectives (e.g., learning interdisciplinary approach, systems thinking, multicriteria assessment of agroecological practices, or the evaluation of farming system sustainability).

Given the urgent need to develop more sustainable agriculture and increase the attractiveness of active-learning tools, serious computer games on agroecology can be useful learning tools. However, their pedagogical interest should be assessed to ensure their quality and usefulness. They can be evaluated using a variety of theories [30], including flow theory. "Flow" is a state of profound enjoyment and concentration that increases students' ability to learn [31]. To reach this state of mind, clear goals, immediate feedback, and a good balance between challenges and players' skills are essential [32]. This theory has been extended to evaluate serious computer games by considering social interactions and measuring knowledge acquisition more precisely [33,34].

The serious game SEGAE (SErious Game for AgroEcology learning) is the main output of the Erasmus+ SEGAE project, a three-year project that associated six European universities from Belgium, France, Italy, and Poland, and was funded with the support of the European Commission and the French Chair of Agroecology. The aim of this study is to present SEGAE and to assess its pedagogical interest for learning agroecology. To do so, a workshop was organized with students from the partner universities. Two types of surveys were performed: (i) A knowledge survey to evaluate students' individual knowledge of agroecology before and after the workshop, and (ii) a feedback survey to evaluate students' perception of the workshop and the game, based in particular on the flow theory. We hypothesized that SEGAE would improve university students' learning about interdisciplinary and systems approaches in sustainable management of mixed crop–livestock farming systems, particularly students who specialize in specific disciplines related to the functioning of farming systems. The main conclusion is that SEGAE is a relevant tool for learning agroecology in a fun way, since students increased their knowledge of agroecology significantly while generally enjoying the game.

2. Materials and Methods

2.1. Development of SEGAE

2.1.1. Overall Description

SEGAE is an online farming simulation game that addresses three main pedagogical objectives. First, players should acquire practical knowledge by learning a variety of agroecological practices and understanding their impacts on the farming system. This practical knowledge is by definition interdisciplinary, since the game includes several scientific disciplines (i.e., plant science, animal and veterinary sciences, soil science, ecology, economic and social sciences). Second, players should acquire a systems approach by assessing the combined impacts of multiple practices on the farming system. Third, they should improve their skills in transition management by testing several options to reach given goals with limited resources. An important feature related to these three objectives is the lack of an automatic balance among choices: Players must verify for themselves the consistency of the agroecological practices they choose (e.g., the cropping system must have sufficient grassland area if the livestock feeding system is based on grass).

SEGAE represents a mixed crop–livestock farm oriented to dairy production (Figure 1). This type of farm was chosen because of its importance in all partner countries and the number of ways in which it can develop agroecology, especially by varying the degree of integration between crops and livestock [8]. For the workshop and this article, the farm corresponded to a typical dairy farm from western France, but SEGAE can represent dairy farms from each partner country, or elsewhere. SEGAE simulates crop and livestock management realistically at an annual time step, but it cannot be used as a decision aid tool for real farms, since it is not detailed enough to provide context-relevant results or represent all important biophysical and socio-economic processes that occur on a farm. SEGAE's specific features are to (i) represent a variety of agroecological practices related to crop and livestock management and (ii) give players the ability to assess impacts of these practices on the three pillars of sustainability: Environmental, economic, and social. SEGAE is available online at no cost at https://rebrand.ly/SEGAE.

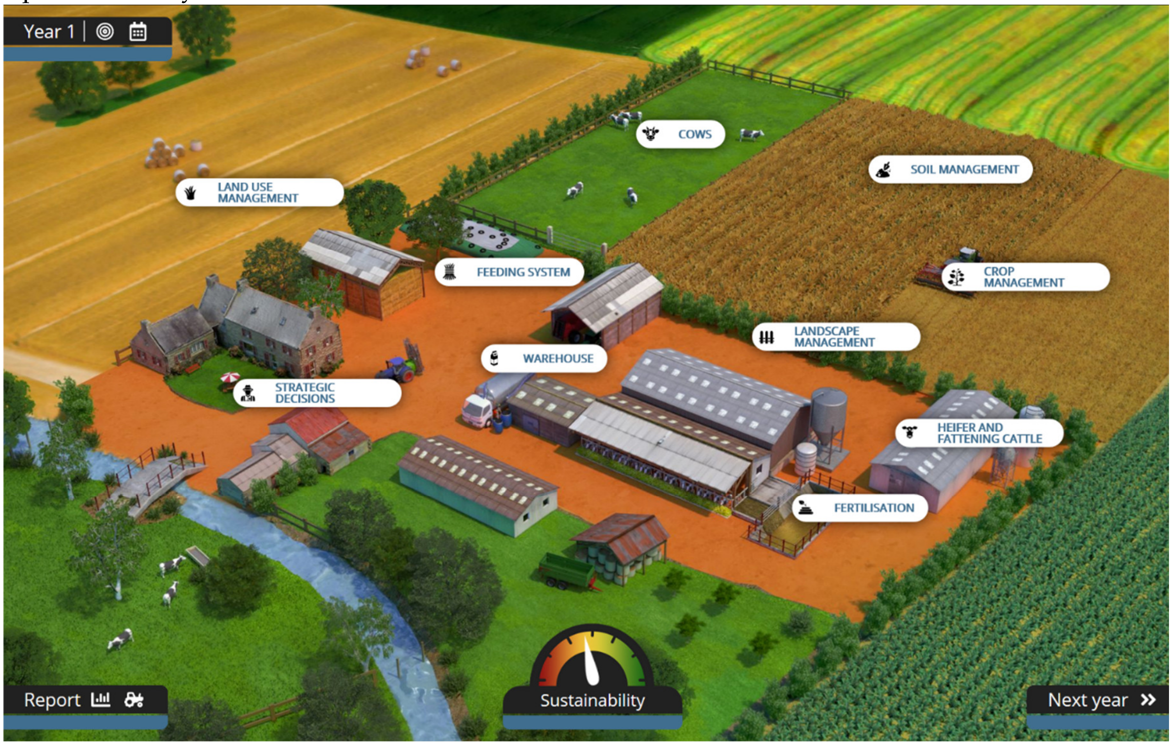

Figure 1. The graphical interface of SEGAE (SErious Game for AgroEcology) shows strategic dimensions and a sustainability score of a mixed crop and dairy farm.

2.1.2. Underlying Model

SEGAE is based on an innovative model created for the game that has three components: (i) A matrix, (ii) a calculation engine, and (iii) a graphical interface that represents the farm. The matrix represents impacts of 124 practices on 591 indicators. Most of the practices are agroecological practices that stemmed from two studies [7,35] and were debated, chosen, and adapted by an interdisciplinary group of experts in the project. They are related to (i) crop management (i.e., rotations, tillage, fertilization, cultivar choice, weeding, pest and disease control), (ii) livestock management (i.e., animal health, feeding systems, manure management), (iii) management of the landscape and biodiversity (planned and natural), and (iv) strategic decisions (i.e., distribution of farm profit, conversion to organic farming, herd size, cattle breed). The indicators reflect technical, economic, environmental, and social aspects of the farm. Each practice influences one or more indicators through multiplicative or additive factors. These factors were determined from a literature review that included (i) meta-analysis (e.g., [36]), (ii) targeted analysis (e.g., [37]), (iii) analysis of more divergent case studies (e.g., [38]), and (iv) quantitative and qualitative expert assessment by experts in the project. Table 1 represents an extract of the matrix: It includes examples of practices for crop, livestock, and landscape management, and links them with examples of indicators reflecting the various aspects of the farm. Players do not see all 591 indicators, since some indicators are aggregated to provide more relevant information (e.g., the time spent on crop management is calculated for each crop each month, but only the total time for all crops each month is shown). Due to the model's complexity, most practices impact several indicators, which helps players understand the many relations among the three pillars of sustainability: Environmental, economic, and social. Finally, scores of the three pillars are aggregated into an overall sustainability score.

Table 1. Extract from SEGAE's matrix of impacts of farm practices on farm indicators. The impacts of practices are represented through multiplicative factors that modify the initial value of the related indicators.

Category	Practice	Indicators			
		Technical	**Environmental**	**Social**	**Economic**
		Winter wheat yield	**Pollinator abundance**	**Animal welfare**	**Machinery cost**
Tillage management	Conventional tillage	1.00	1.00		1.00
	Reduced tillage	1.00	1.01		0.90
	No tillage	0.92	1.03		0.80
Fungicides	Systematic use of chemical molecules	1.00	1.00		1.00
	Sound approach of chemical molecules	1.00	1.01		0.90
	Biocontrol product	0.85	1.02		0.85
	None	0.85	1.03		0.80
Temporary grassland	Grassland-grass		1.00		
	Grassland-grass-legume mixture		1.02		
	Grassland-complex mixture		1.05		
Cropping plan[a]	Maize-wheat	1.00	1.00		1.00
	Rapeseed-wheat-maize-wheat	1.02	1.02		1.00
	Faba bean-wheat-rapeseed-maize	1.03	1.04		1.10
	Grassland (3 years)-maize-wheat	1.02	1.03		0.70
	Grassland-maize-wheat-faba bean-rapeseed	1.03	1.05		0.80
Green infrastructure[a]	None		0.80		
	Wildflower strip		1.30		
	Hedgerows		1.20		
	Grass margins		1.05		
	In-field agroforestry		1.10		
Cow housing	Tie-stalls with straw			1.00	
	Cubicles with straw			1.50	
	Cubicles with slatted floor			1.13	
	Free-stall (deep bedding)			1.65	
	Free-stall (slatted floor)			1.20	
Feeding system[a]	Indoors all year, maize, soybean			1.00	
	Indoors all year, maize + alfalfa, soybean			1.00	
	4 months grazing, soybean			1.31	
	8 months grazing, faba bean			1.63	
	9 months grazing, without supplement			1.70	
Management of the risk of mastitis[b]	Systematic antibiotic treatment			1.00	
	Selective antibiotic treatment			1.00	
	Preventive measures of hygiene			0.98	

Notes: Green infrastructure, green infrastructure, feeding system: Not all practices related to this category are represented; management of the risk of mastitis: Only during the cow's dry period.

The calculation engine, programmed in JavaScript, has equations for crop, livestock, and economic management that calculate impacts of all practices each year of the simulation. It also compiles the indicators' scores to calculate the score of each pillar of sustainability. The code of the calculation engine is open source, which allows future users to add new developments or reuse it in other software. The graphical interface represents the farm's strategic dimensions: Cow management, crop management, feeding system, fertilization, heifer and fattening cattle management, landscape management, land use management, and strategic decisions (Figure 1). By clicking on each strategic dimension, players can choose from a list of related practices. Then, by clicking on the "Next year" button, the game applies the choices, calculates impacts on indicators, and displays a set of steering indicators.

2.1.3. Pedagogical Activities

Pedagogical activities offered with SEGAE should include (i) presentation of the learning objectives and an overview of the game, (ii) playing the game with a scenario adapted to the context, and (iii) discussion of the results, methodology, and limits of the game with the teacher. Due to SEGAE's high customization capacity, teachers can develop a wide variety of pedagogical scenarios. We imagined four scenarios to reach different pedagogical goals, but others can be proposed:

- "Sandbox": Players explore the game's strategic dimensions and related practices, with the easy goal of simply improving sustainability. This scenario helps players begin to understand impacts of practices and relations between animal and crop production.
- "Systems thinking": Players must improve overall sustainability by changing practices related to either crop or animal production. Usually, the improvement in overall sustainability is lower in this scenario than in the "sandbox". This scenario helps players understand more deeply the close interconnections between crop and animal production.
- "Indicator oriented": Players must improve a specific indicator of the farm (e.g., animal welfare) by developing a step-by-step strategy with other players. This scenario allows players to exchange viewpoints and knowledge, so it can be particularly interesting for a group of students with different backgrounds.
- "Sustainability oriented": Players must improve overall sustainability without decreasing the score of each pillar below a certain threshold. It can be played alone or by small groups of students. This scenario helps players more deeply understand potential trade-offs and synergies among the pillars of sustainability.

2.2. Evaluation of SEGAE

SEGAE workshop was organized during the project with students and teachers from the partner universities. Its objective was to evaluate SEGAE's interest as a learning tool, in particular its ability to (i) help students learn agroecology and (ii) put them into a state of flow. Two other objectives—feedback from students on the design of attractive training sessions and identification of game bugs and weaknesses—will be used to improve SEGAE, but are not described here.

2.2.1. The Workshop

The workshop was held at the Department of Agricultural and Food Sciences, of the University of Bologna (UNIBO) in Italy, during one week (3–7 February 2020). It consisted of three complementary sessions. First, a half-day farm visit was organized to understand the use of agroecological practices in the field. It also allowed students to discuss with farmers their economic strategy for developing agroecology and its positive and negative consequences. Second, six hours of lectures were provided on the main aspects of agroecology (i.e., crop production, animal production, agricultural ecology, economics, and sociology), followed by an additional lecture on sustainability assessment. These lectures highlighted connections between theoretical knowledge and the practices simulated in the game. Third, six hours of game sessions were organized that consisted of a variety of activities, including the four pedagogical scenarios.

The workshop assembled 52 students and 15 teachers from the partner universities. The sample of students was diverse, ranging from first-year Master's students to doctoral students, with most students in the second year of a Master's degree. The disciplines they studied were agroecology, animal science, crop science, economics applied to agriculture, environmental science, mechatronics, and veterinary science (Table 2). Some students were specialized in their field (i.e., those in veterinary science or, from UNIBO, crop science), while the others were generalists who followed an agricultural engineering education that included agriculture-related disciplines.

Table 2. Curriculum and discipline of specialization of the 52 students in the intensive one-week training session.

University	Country	Engineering (multidisciplinary)						Veterinary science	Crop science
		Agroecology	Animal science	Crop science	Economics	Environmental science	Mechatronics		
ESA	France		3	6					
Institut Agro	France	4		2	3				
Oniris	France							8	
ULiège	Belgium	2		4		3			
UAK	Poland		3				4	1	
UNIBO	Italy								9
TOTAL		6	6	12	3	3	4	9	9

Notes: ESA = Graduate school of Agricultures; Institut Agro = National Institute of Education for Agriculture, Food and Environment; Oniris = National Veterinary, Agrifood and Food School of Nantes-Atlantique; ULiège = University of Liège; UAK = University of Agriculture in Krakow, UNIBO = University of Bologna.

2.2.2. Design of Surveys

One of the positive outcomes of Erasmus+ projects for students, regardless of the topic, is that they meet other European students, discover other ways of thinking and, more generally, open their minds. It was collectively decided to keep the students in a single group to enhance peer-to-peer exchanges and social mixing among different origins, cultures, and disciplines.

Two types of surveys were performed during the workshop. First, a knowledge survey was performed to evaluate students' individual knowledge of agroecology, since they came from different academic levels and disciplines. This evaluation was based on summative assessments that used pre- and post-testing, a common approach to test effects of new teaching methods [39]. Students answered the knowledge survey once at the beginning of the week, before any lectures or game sessions (hereafter, "pre-test"), and a second time, with the same questions, at the end of the week, after all lectures and game sessions (hereafter, "post-test"). The knowledge survey was answered by the all the students, except four French students in agroecology since they had helped to develop it. The knowledge survey contained 21 multiple-choice or open-ended questions: 10 specific to crop production, 4 specific to animal production, and 7 general questions (Table S1). For each multiple-choice question, the student earned 1 point if the answer was correct, 0 points for no answer, and –1 point if the answer was incorrect. For each open-ended question, the student earned from –1 to 3 points depending on the number of correct (or incorrect) answers given compared to the number of expected correct answers. To ease interpretation of results, students' scores were converted into a percentage of the maximum score, which was 39 points.

The second type of survey, the feedback survey, was performed to evaluate students' perception of the game and the workshop. In particular, it allowed us to characterize the states of flow that they experienced during the game, using the eight factors of EgameFlow of Fu et al. [34]:

- Concentration: The game must provide activities that encourage players' concentration while minimizing stress from learning overload.
- Clear goal: Tasks should be clearly defined at the beginning of game sessions.
- Feedback: Regular feedback should be given to allow players to determine the gap between their current stage of knowledge and the target stage.
- Challenge: The game should offer challenges that fit players' skill levels.
- Autonomy: Players should enjoy taking initiatives in game sessions and asserting total control over their choices.
- Immersion: The game should lead players into a state of immersion, which is characterized in particular by an altered sense of time.
- Social interaction: Tasks in the game should favor social interactions between players.
- Knowledge acquisition: The game should increase players' knowledge.

Students answered the feedback survey once at the end of the workshop, after all lectures and game sessions. Results of the feedback survey were not collected for two students due to technical issues. The feedback survey contained four open-ended questions about the workshop and a Likert-type inventory of 45 statements: 2–5 statements to assess each of the eight flow factors (e.g., "the overall game goals were presented clearly" assesses the factor "clear goal") and additional statements to assess the game more generally (Table S2). Students evaluated statements on a four-point scale (1 = strongly disagree, 2 = disagree, 3 = agree, and 4 = strongly agree). The feedback survey also contained background questions to describe students (e.g., age, nationality, level of studies) and their experience in agroecology and gaming (Table S3).

2.2.3. Analysis of Survey Results

Analysis of survey results consisted mainly of analyzing students' scores. For the knowledge survey, scores were summed to calculate students' pre-test and post-test scores. Mean scores were calculated for the group of all students, by curriculum and discipline, and by theme of the questions. Statistical analysis was then performed using R software v.3.6.1 (Foundation for Statistical Computing, Vienna, Austria). [40]. First, descriptive statistics (e.g., mean, median, standard deviation) of scores and student descriptors (e.g., age, agroecology background) were calculated. Next, equivalence tests with paired data were used to calculate the change in scores between the pre-test and post-test. Finally, Pearson correlation coefficients and one-way analysis of variance were calculated to assess the significance of observed differences.

For the feedback survey, each flow factor was assessed by averaging the scores of its questions. Thus, each student was associated with eight mean scores, one for each flow factor. These eight scores were then averaged to obtain an overall assessment of the flow factors. Mean scores were calculated for the group of all students and by discipline. Then, to confirm the results, principal component analysis (PCA) of the mean values of the eight flow factors for each student (i.e., 50 × 8 matrix) was performed. It helped us understand students' perception and explanatory variables more precisely, which could explain the perception of flow.

3. Results

3.1. Results of Knowledge Acquisition

On the knowledge survey pre-test, students had a mean score of 43% of answers correct. The scores differed significantly among the disciplines: Students in crop science had the highest scores (51%), while those in mechatronics had the lowest (14%). On the post-test, students' mean score was significantly ($p < 0.001$) higher: 51% of answers correct. Overall, 33 of 48 students increased their scores, 6 had the same scores, and 9 decreased their scores slightly (Figure 2). In addition, scores of pre- and post-tests were strongly positively correlated ($r = 0.69$; $p < 0.001$); thus, students who had the highest pre-test scores also had the highest post-test scores.

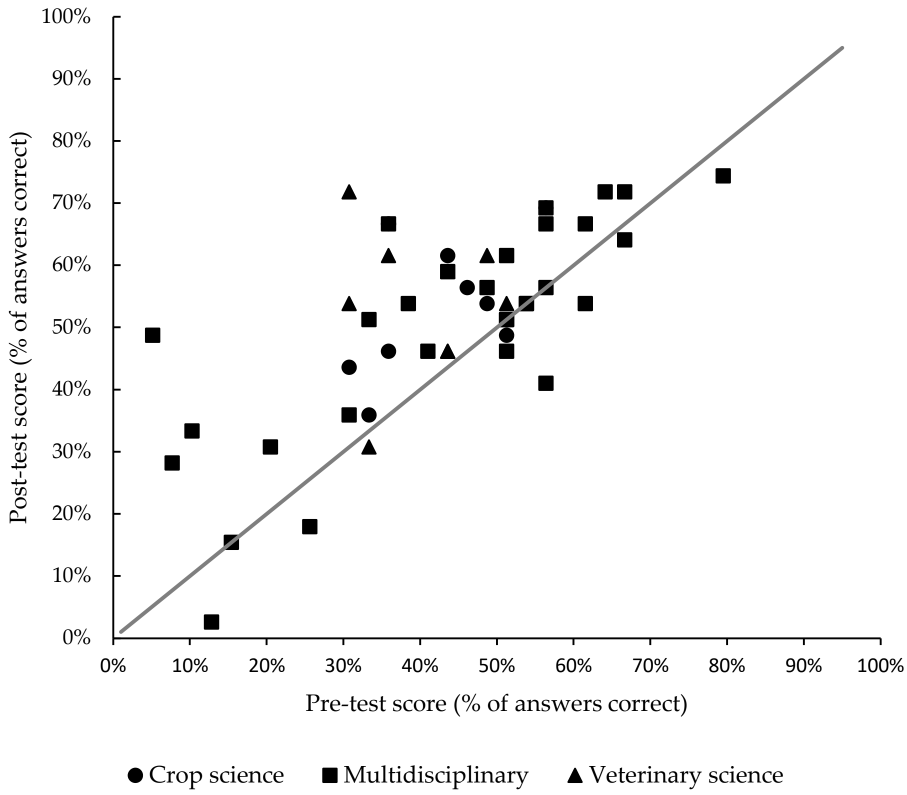

Figure 2. Comparison of students' mean scores on the pre-test and post-test knowledge surveys, by their curriculum: Crop science (UNIBO), multidisciplinary (all engineering students), and veterinary science (Oniris and UAK).

All student groups increased their scores significantly, but there was no significant difference in the mean increase among groups (Figure 3; $p = 0.10$). Although not significant, students in specialized curricula (i.e., veterinary science and crop science) increased their scores more than those in other curricula (by a mean of 14 and 11 percentage points, respectively), which allowed them to catch up with the engineering students and obtain a mean score higher than the overall mean (Table A1, Appendix A).

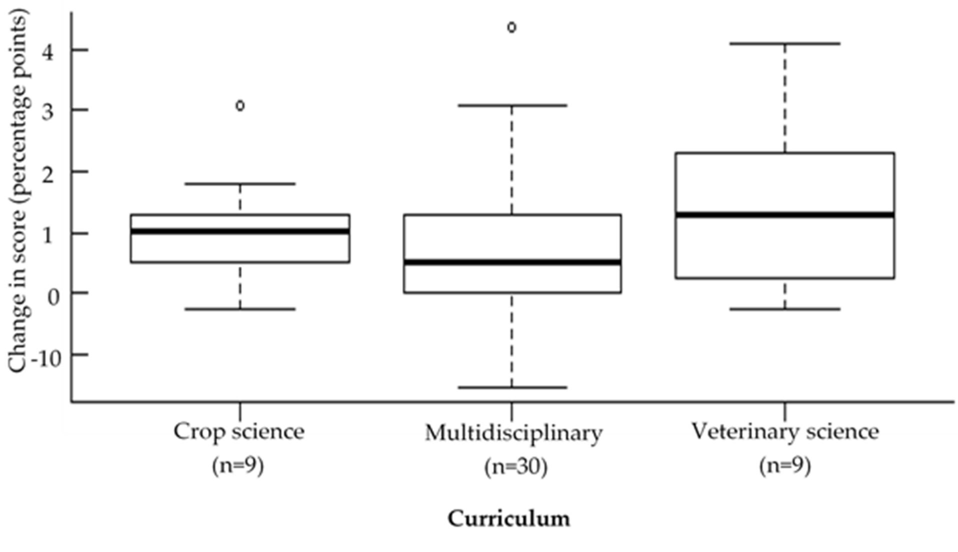

Figure 3. Boxplots of the change in students' scores on the knowledge survey between the pre-test and post-test, by their curriculum: Crop science (UNIBO), multidisciplinary (all engineering students), and veterinary science (Oniris and UAK). Whiskers show 1.5 times the interquartile range.

Students in agroecology and crop science (in engineering or specialized in crop science) had the highest scores. Although mechatronics students increased their mean score by nearly 50% (6 percentage points), it remained the lowest (i.e., 21% of answers correct). By theme of the questions, the mean score increased the most overall for animal-production questions (i.e., by 12 percentage points).

3.2. Perception of SEGAE and its Evaluation Through Flow Factors

On the feedback survey, 86% of students "agreed" or "strongly agreed" with the statements "I enjoyed playing this game" and "I will advise students from my university to play this simulation game". Thus, students appreciated SEGAE overall. More precisely, students assessed the flow factors positively, with an overall mean score of 2.96 points (i.e., ≈ "agree") out of 4. The factors "knowledge acquisition", "interaction", and "feedback" were rated particularly highly (Figure 4). Two groups of students differed in their assessment of flow factors. Students in economics gave higher scores for most of the factors, especially knowledge acquisition (3.70 points out of 4). In contrast, students in environmental science were more critical, highlighting a lack of concentration during the game and low clarity of its goal (means of 2.17 and 2.33 points, respectively).

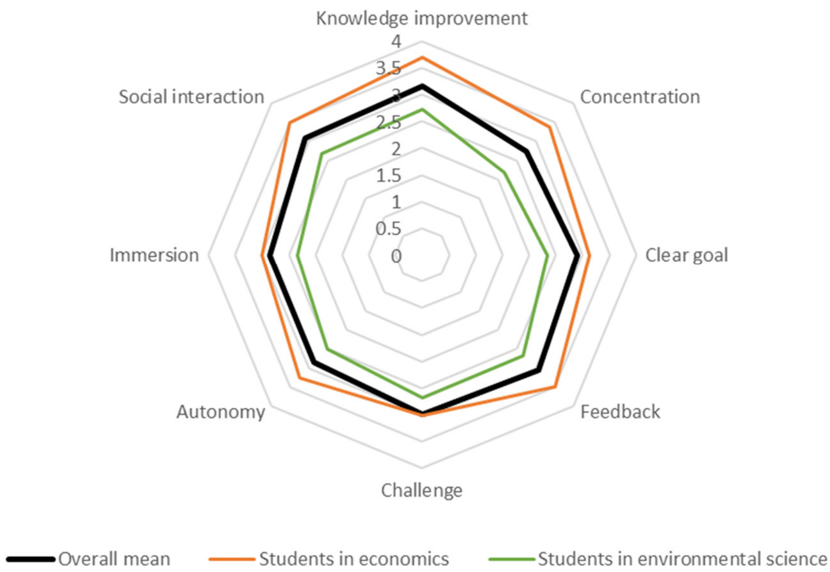

Figure 4. Mean scores of the eight flow factors by students on the feedback survey, including those of the two groups of students that gave the highest and lowest scores (in economics and environmental science, respectively).

The first dimension of the PCA (inertia of 51%) was correlated significantly with the eight flow factors ($p < 0.001$), all of which had $r > 0.5$. Students gave similar scores for most of the flow factors (i.e., most high or most low). Since the second dimension of the PCA had an inertia of only 10%, it was excluded from further analysis.

Four qualitative variables were strongly and significantly correlated with the mean flow score. The first, "discipline" ($r = 0.51$; $p < 0.05$), showed that economics and veterinary science students reached higher flow states than environmental science students. The second, agreement with the statement "I will advise students from my university to play this simulation game" ($r = 0.51$; $p < 0.05$), showed that students who reached higher flow states were more willing to recommend the game. Finally, the two statements "I learned about an integrated vision of agriculture" ($r = 0.73$; $p < 0.001$) and "I learned about agroecology as an interactive set of agricultural practices" ($r = 0.57$; $p < 0.001$) were significantly correlated with the PCA dimension. Since these statements were included to assess interdisciplinarity, the correlation showed that students who experienced higher flow states also perceived that they had acquired knowledge of agroecology, in particular its interdisciplinary aspects.

The scores on the knowledge survey and of flow factors were not significantly correlated. Thus, some students (e.g., those in economics) may have enjoyed and been involved in the serious game even if they did not increase their scores on the knowledge survey greatly.

4. Discussion

Results showed that students increased their knowledge of agroecology significantly, with a mean increase of nine percentage points in their scores on the knowledge survey. This confirms the relevance of serious games as learning tools to teach complex concepts [41]. Nonetheless, students' mean score remained low (51% of answers correct). This result may be explained by students having given many vague answers to the open-ended questions, which were not considered correct. The survey may also have been too difficult, since teachers and four second-year Master's students in agroecology designed it so that it would not be too simple for agroecology students. In addition, the high diversity of the students was not optimal for developing activities that could help all of them increase their knowledge in a variety of disciplines.

Students in veterinary science made the most progress, which shows that SEGAE is particularly useful for specialized students who lack a systems approach or knowledge of crop or animal production. Thus, it confirms the hypothesis that SEGAE helps specialized students acquire interdisciplinary knowledge in agroecology. The modest increase in performance of other students (i.e., in mechatronics), however, also shows limits of this learning tool. In this case, some students in mechatronics may have had difficulty getting involved in the game (their mean score for the flow factor "immersion" was 2.40 out of 4 points). They may also have suffered from a lack of knowledge of biology or problems understanding English. Thus, particular attention should be paid to students' prerequisites and academic curricula to reach the pedagogical goals. In addition, to decrease language barriers, we plan to translate SEGAE into several languages.

The knowledge survey had two drawbacks that could limit the scope of these results. First, the sizes of student groups varied greatly, from large (e.g., French students, crop science students) to small (e.g., mechatronics students). Second, there was no control group [42]. Although the lectures were designed to explain only SEGAE's mechanisms and not to provide new knowledge, the lack of a control raises questions about whether the game helped students learn more than they would have with the lectures alone. To strengthen the validity of our conclusions, it would be necessary to compare the results of students who experienced only lectures to those who experienced both the lectures and the game.

Regarding student perceptions, 86% of students enjoyed playing SEGAE, which shows high appreciation of the game. They also assessed the eight flow factors positively overall, but some students identified difficulties with concentration, the clarity of goals, or the need for autonomy. These results highlight a slight difficulty in becoming immersed in the game, which may be due to insufficient guidelines on how to play it. Nonetheless, these results are encouraging, since the game was not completely finished by the time of the workshop. Since then, some "gamification" features have been added to SEGAE, including some requests from the workshop, which should improve students' engagement with this learning tool.

SEGAE is an interesting tool to help students learn agroecology in a fun way. By allowing players to apply agroecological practices directly on a virtual farm and then analyze their impacts, this game represents "learning by doing in silico". It is particularly relevant because it helps overcome the knowledge–action gap, which is identified as a critical skill for learning agroecology [43]. Another interesting feature of SEGAE is that it highlights animal production, especially its reconnection to the land, as a core element of agroecology, which is rarely done in agroecological thinking [4]. However, the sets of practices in the game related to animal production, biodiversity management, and socio-economic decisions are less developed than that related to crop production. Thus, SEGAE could be improved by adding practices related to these aspects. In addition, some students would have appreciated having access to more theoretical information in the game to help them understand impacts of practices before applying them. We decided to limit theoretical information in the game to improve SEGAE's playability, simplify its graphical interface, and encourage "learning by doing". However, this design can make it difficult for undergraduate students to play the game and improve their understanding of relations between practices and impacts. Using SEGAE with undergraduate students requires pedagogical activities that allow the students to play the game step-by-step, including more directive scenarios than those described here.

The initial goal of the SEGAE project was to build a serious game that would also be suitable for high-school students and extension agents. Using SEGAE with high-school students would require more preparation of game scenarios and perhaps simplification of the practices available and sustainability indicators, while being careful not to lose the game's interdisciplinary or systems approaches. In contrast, extension agents may be frustrated by SEGAE's low flexibility, in particular the fact that players cannot create crop rotations or feeding rations but must choose them from a short list. Since SEGAE is available online at no cost, individuals can play it independently, but exchanges between students and teachers appear to be crucial to learn effectively and highlight the game's limits.

The wide range of practices available in the game, which highlights interactions among the three pillars of sustainability, shows that SEGAE favors an interdisciplinary approach. The game and its related pedagogical activities could be improved to move closer to a transdisciplinary approach. In particular, more non-academic participants, such as farmers and extension agents, should be included in lectures to enhance participatory approaches and thus transdisciplinarity [44]. Similarly, many students asked for more farm visits, but this could be difficult due to the universities' economic and logistical constraints. As suggested by [45], however, additional case studies can be developed in the future; adapting the French farm currently in SEGAE to represent farms in each partner country is an initial step that is underway.

Like SEGAE, other digital tools can be developed to learn agroecology. In particular, Massive Open Online Courses (MOOC) represent an interesting way to provide educational content similar to that of lectures to as many people as possible. A MOOC on agroecology is already available and complements SEGAE, since it offers more structured and theoretical content on agroecological practices [46]. Another interesting free online tool is the Dictionary of Agroecology [47], which contains simple definitions of terms related to agroecology, which are often poorly understood. It values knowledge in a participative way, allowing collaboration among researchers, students, and actors in the field, who illustrate the definitions with their experiences. Finally, many associations and extension services offer face-to-face training on agroecology for both novices and farmers. These initiatives, whether digital or not, contribute greatly to the agroecological transition of European agriculture and should become more closely interconnected to increase their effectiveness.

5. Conclusions

European agriculture is facing many challenges, and agroecology is considered as a pertinent option to reconcile the various pillars of agricultural sustainability. However, most agricultural courses are not adapted to teach agroecological concepts. The objective of this study was to present SEGAE and to assess the pedagogical interest of this serious game for learning agroecology. Results showed that students increased their knowledge of agroecology significantly, with a mean increase of nine percentage points in their scores on the knowledge survey. Students in veterinary science made the most progress, which confirmed the hypothesis that SEGAE helps specialized students acquire interdisciplinary knowledge. However, the modest increase in performance of other students highlighted the need to check students' prerequisites and academic curricula to reach the pedagogical goals. Regarding student perceptions, 86% of students enjoyed playing SEGAE, which shows high appreciation of the game. They particularly appreciated the available feedback and the possibility of interacting, but some students identified difficulties with concentration. Overall, it can be concluded that SEGAE is a relevant tool for learning agroecology in a fun way. Since this serious game is available online at no cost, it can be used in addition to other trainings on agroecology, whether digital or not, and thus contribute greatly to the agroecological transition of European agriculture.

Supplementary Materials: The following are available online at www.mdpi.com/2071-1050/12/11/4351/s1, Table S1: Knowledge survey, Table S2: Feedback survey; Table S3: Database.

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Appendix A

Table A1. Mean (and standard error) of students' scores (percentage of answers correct) on the knowledge survey during the pre-test and post-test, and the increase between the tests (percentage points).

Grouping of data (and number of students)	Pre-test	Post-test	Increase
All students	42.7 (2.4)	51.4 (2.3)	8.7 ***
By curriculum			
• Veterinary science (9)	40.2 (2.6)	53.9 (3.9)	13.7 *
• Crop science (9)	42.5 (3.0)	53.6 (3.7)	11.1 **
• Multidisciplinary (30)	43.6 (3.6)	50.0 (3.3)	6.4 **
By discipline of specialization			
• Veterinary science (9)	40.2 (2.6)	53.9 (3.9)	13.7 *
• Agroecology (2)	46.2 (2.6)	57.7 (1.3)	11.5 ns
• Animal science (6)	35.9 (10.1)	45.7 (7.9)	9.8 ns
• Environmental science (3)	36.8 (3.1)	45.3 (5.2)	8.6 ns
• Crop science (21)	50.9 (2.8)	57.8 (2.3)	6.8**
• Mechatronics (4)	14.1 (4.0)	20.5 (6.8)	6.4 ns
• Economics (3)	48.7 (6.5)	53.9 (7.4)	5.1 ns
By theme of the questions			
• Crop production	44.2 (3.0)	50.4 (2.3)	6.1 **
• Animal production	52.9 (3.3)	65.1 (3.1)	12.2 ***
• General	35.7 (2.8)	45.1 (3.2)	9.4 **

Notes: The "crop science" discipline includes engineering students in crop science and students specialized in crop science; *** $p < 0.001$; ** $p < 0.01$; * $p < 0.05$; ns, not significant ($p > 0.05$).

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