SErious Game for AgroEcology (SEGAE): How much can be delivered with a 4-hour lesson?

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Abstract

CONTEXT: European agriculture faces numerous challenges, and agroecology has emerged as a promising alternative. To facilitate this transition, integrating agroecology into agricultural education is crucial. However, its systemic and interdisciplinary nature makes it difficult to teach and learn. To support teaching, the “SErious Game for AgroEcology” (SEGAE) was developed. SEGAE is a simulated mixed crop–livestock farm model in which players can learn by doing.

OBJECTIVE: This study aims to (1) assess the effectiveness of SEGAE in a 4-hour lesson led by a single teacher, (2) examine the potential added value of classroom-based lessons compared to a fully online setting, and (3) analyze how students from different disciplinary backgrounds acquire agroecological knowledge.

METHOD: A teacher conducted three identical 4-hour lessons using SEGAE, involving undergraduate bioengineering students from four specializations. One lesson was conducted fully online, while the other two were classroom-based. Each lesson included theory, game sessions, and pre- and post-surveys to assess knowledge acquisition. Student scores were converted to percentages and analyzed using descriptive statistics, paired t-tests, and multiple regressions. Feedback on the learning experience was collected through 36 statements related to 'flow' – the level of immersion in a task. A two-factor ANOVA and a Tukey test were performed. A PCA explored the flow-knowledge acquisition relationship.

RESULTS AND CONCLUSIONS: The results show that students significantly increased their knowledge in agroecology. No significant difference between the online and classroom-based lessons on knowledge acquisition could be demonstrated. However, a negative effect was found between the online session and the reported flow levels. A striking result was the increased performance of students upon answering open-ended questions, which required them to articulate knowledge. Moreover, most students enjoyed the game (91%) and believed it enhanced their agroecology knowledge (92%).

SIGNIFICANCE: SEGAE, in a 4-hour lesson with a single teacher, is a relevant tool for teaching agroecology, achieving comparable results in knowledge acquisition and flow to a longer workshop. The impact is particularly evident in open-ended questions. The study provides complementary evidence of a link between the increase in absolute knowledge and two factors of flow: feedback and social interaction.

Keywords: *serious game; agroecology; interdisciplinarity; knowledge; bioengineering*

1. Introduction

European agriculture is currently confronted with many challenging issues and a transition is being urgently called for (IPES-FOOD, 2020). One argument for this required change arises from the well-documented negative impacts such as forest loss, freshwater withdrawals, and emissions of methane and nitrous oxide (Campbell et al., 2017). The biggest challenge is to strike a delicate balance between ensuring an ample food supply to feed a growing population while also staying within the limits set by the Earth's ecological boundaries (Gerten et al., 2020). Associated with the concept of food sovereignty, agroecology is increasingly advocated as a promising alternative (Geelhoed, 2022; Wezel et al., 2014). More particularly, agroecology-based initiatives are designed to meet the triple challenge of proposing a food system that is at the same time more sustainable, efficient, and socially fair (Gliessman, 2014; Godfray et al., 2010).

However, even if the benefits of agroecology have been demonstrated in numerous studies (DeLonge and Basche, 2017; Holt-Giménez and Altieri, 2013; Mousseau, 2015; Petit et al., 2023; Rosset and Altieri, 2017; van der Ploeg et al., 2019; Wezel et al., 2014), various factors need to be addressed for a transition towards agroecology to occur, including scientific and educational barriers (Boulestreau et al., 2023; Sutherland et al., 2012; Vanloqueren and Baret, 2009). While interdisciplinary and systems approaches have been identified as basic foundations of sustainable food systems education programs (Hilimire et al., 2014), teaching and learning such a holistic vision is quite challenging (Fernández González et al., 2021). To foster the agroecology transition, research on efficient pedagogical and didactic practices that can overcome existing educational barriers is thus needed.

As far as bio-engineering programs are concerned, students are still mainly trained to be specialized in a specific field, such as soil science, biotechnology, or economics. Agroecology is a notion that brings together a complex array of components in interaction, such as environmental, social, and economic sciences (Francis et al., 2011). Agroecology needs to be taught differently, to give a more systemic vision of its various components (Francis et al., 2008). Within the food system, complex relationships between farming practices, agricultural yields, environmental impacts, sociological consequences, and economic profitability are at play. Therefore, as David & Bell (2018, p. 615) rightly point out, teaching agroecology "is not just about content, it is also about process".

Additionally, prevalent pedagogical techniques frequently lack interactive and experiential elements (Lieblein et al., 2004; Schroeder-Moreno, 2010). Al Hakim et al. (2022), Boyle et al. (2011) and Kiili (2005) advocated that effective learning involves active, experiential, and problem-solving approaches, supplemented by immediate feedback.

Serious games are a way to satisfy the teaching requirements of agroecology because digital tools allow the creation of complex models that allow players to develop their understanding of systems approaches (Wu and Lee, 2015). They are an entertaining tool with an educational purpose. These games offer "designed experiences" in which participants acquire knowledge through action and immersion, rather than passively assimilating information from reading or lectures (Heeter, 2000). Furthermore, by affording players the ability to visualize the consequences of their choices, serious games cultivate the capacity for "visioning thinking," thus facilitating the assimilation and the learning of innovative techniques such as agroecological practices (De Graeuwe et al., 2020). Games are then useful to support farming design and evaluation of agricultural systems (Dernat et al., 2023; Meunier et al., 2022).

Hence, the development of the serious game SEGAE (SErious Game for AgroEcology learning) was undertaken to facilitate the teaching of agroecology, recognizing the necessity to convey both a systemic and interdisciplinary perspective (Jouan et al., 2021a). The game employs a modeling framework to gamify the execution of agroecological practices within an integrated crop-livestock farm, evaluating their effects on sustainability. This is achieved through an output-focused approach that models the consequences of these practices across multiple indicators, presented within a dynamic graphical interface. A previous study demonstrated that SEGAE is an interesting learning tool that enables students to assimilate agroecological knowledge in a fun way, fostering both interdisciplinary and cooperative learning. This previous study analyzed SEGAE in the context of a 5-day international workshop (De Graeuwe et al., 2020). Three activities were organized: (1) a half-day farm visit (2) a 6-hour theoretical lesson given by various teachers on the key aspects of agroecology (i.e, animal production, crop production, agricultural ecology, sociology, and economics) (3) 6-hour of the serious game session.

As far as the present study is concerned, the primary aim is to assess the suitability of using this game in short 4-hour lessons led by a single teacher. Given the complexities involved in redesigning university programs, the study seeks to assess the merits of this concise pedagogical setting, which can more easily be integrated into an existing university course program compared to a 5-day workshop gathering students and professors from different countries.

We hypothesize that serious games, particularly SEGAE, can be an effective educational tool tailored for short lessons, enhancing the agroecological knowledge of university-level students. An associated and complementary hypothesis posits that SEGAE contributes positively to knowledge acquisition by infusing enjoyment into the session. In this paper, we analyze the data relative to three distinct lessons by examining the knowledge acquisition impact and the level of "flow" (i.e. a concept that aims to approach the level of immersion in a task). The level of flow is interesting to assess because it has been demonstrated to increase the ability of students to learn (Csikszentmihalyi, 2014).To measure the extent of flow achieved by each student in the 4-hour lesson, we used the 8 factors of the EgameFlow scale described in Fu et al. (2009). The collected material will also enable us to see whether providing the lesson in a face-to-face setting (i.e. named *classroom-based* lesson in this paper) has an effect. Finally, we will uncover if a link can be made between the absolute change in knowledge performance and the notion of flow.

2. Materials and method

A university teacher gave 3 identical 4-hour lessons using the serious game SEGAE. One lesson was carried out completely *online* in March 2021 due to the Covid-19 pandemic. The other two lessons were *classroom-based* and took place, respectively, in March 2023 (in France) and in May 2023 (in Belgium). The participants are undergraduate students in a bio-engineering program. They are from 4 distinct specializations: Agronomy; Forest; International Development; and Others (i.e. chemistry and environmental science). The overall pedagogical setting includes several activities and is organized as follows (see Figure 1): (1) a theoretical session, (2) a serious game session, and (3) two survey times (referred to as pre- and post-surveys).

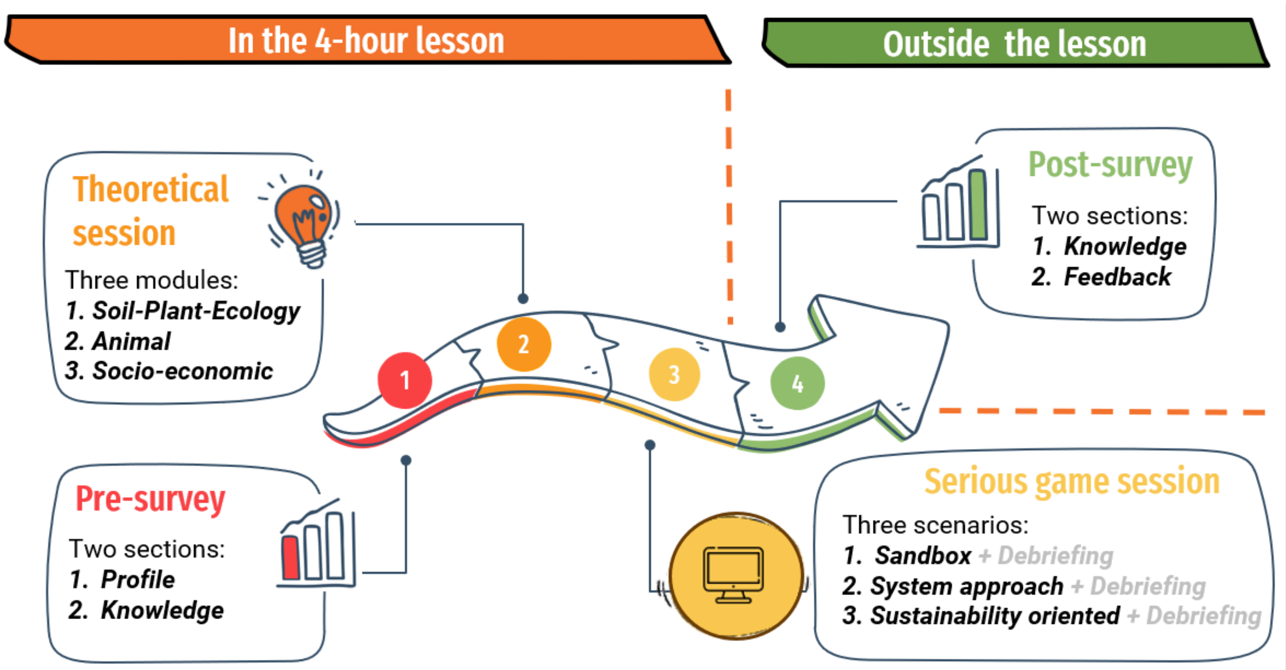

Figure 1. Timeline of a lesson (created on a template of Slidego)

2.1 Theoretical session

Once the pre-survey was filled out by each student and submitted (see section 2.3 below), a 2-hour theoretical lesson was given to introduce agroecological notions and concepts. The teacher used the PowerPoint presentations of the SEGAE game as the basis for creating three distinct teaching modules: (1) "Soil-Plant-Ecology", (2) "Animal", and (3) "Socio-economic". These presentations can be found under the "Tutorials" tab on the SEGAE website (see www.segae.org, within the folder titled "SEGAE teacher training"). This introduction aims to present basic knowledge of agroecology and its effects, introduce a systems approach to assess a combination of practices on the production system and explore different options to solve a given problem with limited resources.

2.2 Serious game session

Following the theoretical session, an additional two-hour lesson was provided to the students. This period was specifically dedicated to familiarizing students with the practical aspects of the serious game. Several farms, corresponding to different levels of game difficulty, are available within SEGAE. Participating students in all 3 lessons played to the intermediate level: the French farm. During the online session, the entire student cohort was divided into several smaller groups, each consisting of 20 to 30 students, as a consequence of a compromise between efficiency in managing virtually multiple groups and the limited capacity of creating and managing multiple parallel teaching rooms. These groups were formed by randomly mixing individuals from different areas of specialization. In the classroom-based session, students could choose their group, which varied from 3 to 6 persons. The teacher advised students to form groups with students from different specializations and backgrounds. Throughout this serious game session, the students played three different scenarios (for a more detailed description, the interested reader can turn to the 'Teacher guide' from SEGAE).

- The "***Sandbox***" scenario:
  This scenario allows students to discover the serious game. Students could only change one practice per year to maximize their impact on the sustainability score of their virtual farm.
- The "***System approach***" scenario:
  Students could change two practices per year and are required to increase the forage self-sufficiency of the farm which allows them to understand how a farm operates a system. Indeed, increasing self-sufficiency depends on the global demand which is, for example, a function of the livestock size, given feed ratio, and selling date of young bulls.
- The "***Sustainability oriented***" scenario:
  Students could change from 1 to 5 practices per year during a simulation of 10 years. They have to reach the highest level of sustainability with a minimum of 0.6 in each of the three dimensions, namely: *social*, *economic* and *environment*. They are also requested to convert the farm to organic farming.

After this group exercise, at the end of each scenario, students returned to a plenary setting and a brief debriefing moment took place with the teacher. This session of about 5 to 15 minutes was intended for discussing the outcomes and limitations of the serious game.

2.3 Times of surveys

Before starting the theoretical session and during the lesson, students were asked to fill in individually a pre-survey which was divided into two sections. The first contains a few questions about the profile of respondents (*see* Appendix 1). This set of questions allows us to get some control variables which could be helpful to distinguish students. The second one contains 15 multiple-choice and 6 open-ended questions about agroecology knowledge (*see* Appendix 1). Filling out this survey took less than 15 minutes.

To be able to measure the acquisition of knowledge through the lesson/game modality, the same questions as in the second section of the pre-survey were asked in the post-survey. Moreover, a feedback section was added to assess whether the SEGAE game was effective as a learning tool and the extent to which it was appreciated. It included 4 open-ended questions and 36 statements (*see* Appendix 1). Students ranked each statement on a 4 Likert scale ('strongly disagree', 'disagree', 'agree', and 'strongly agree').

Within this feedback section of the post-survey, 30 statements concern the notion of 'flow' (i.e. grasping the extent of immersion in a given task). Each flow factor was assessed with 2-5 statements. More precisely, borrowing from Fu et al. (2009), the eight factors of EgameFlow were used to characterize the state of flow that students experienced:

- Concentration: The game should incorporate activities that promote player focus while avoiding overwhelming them with excessive learning demands.
- Clear goal: Game tasks must have well-defined objectives from the start of each game scenario.

- Feedback: Regular feedback should be provided to help players assess the gap between their current knowledge level and the desired one.
- Challenge: The game should present challenges that align with the skill levels of the students.
- Autonomy: Students should derive satisfaction from taking initiative during game sessions and having complete control over their decisions.
- Immersion: The game should engage students to the extent that it distorts their perception of time.
- Social interaction: Game tasks should encourage social interactions among students.
- Knowledge acquisition: The game should facilitate the acquisition of knowledge among students.

The 6 other statements left were added to capture other dimensions related to how the lesson/game modality was perceived (Table 1).

Table 1: Additional statements *(not related to the flow)*

I think that the game was easy to use.
I think that playing this game was useful in improving my understanding of agroecology.
For me, working in a group was useful to improve my understanding.
I enjoyed playing this game.
For me, this game and the theoretical lecture are complementary.
I will advise students from my university to play this simulation game.

As mentioned above, the main objective of this study is to assess how much can be delivered in a 4-hour university lesson using SEGAE compared to the previously documented outcomes of a 5-day seminar. The content of the surveys is thus quite similar (De Graeuwe et al., 2020). A noteworthy difference is that 12 additional statements (i.e. not linked to 8 factors of flow) were removed to shorten the length of the post-survey (*see* Appendix 2).

2.4 Analysis of survey results

Before treating the collected data, some outliers were removed from the database. These are students who did not answer all the open-ended questions in both surveys (4, 0, and 1 students, respectively for the March 2021, March 2023, and May 2023 sessions). In addition, three problematic cases must be mentioned: (1) students who explicitly wrote that the 4-hour lesson did not impact their answers for open-ended questions (1 1, and 2 students, respectively for the March 2021, March 2023, and May 2023 sessions); (2) students who did not entirely answer the second knowledge survey (1 student for the March 2023 and 2 students for May 2023 sessions); (3) students who did not answer the open-ended questions for the post-survey (3 and 7 students, respectively for March 2021 and May 2023). In those cases, the answers from their first questionnaire were assumed to be the same as in the pre-survey. Apart from the first case (i.e. where an equal level of knowledge is explicitly reported), this assumption may appear somewhat strong, especially regarding the 10 students in the third case. However, in the context of a pedagogical setting hopefully designed to be effective, it can rather be considered as a conservative hypothesis to assume an absence of knowledge increase after the 4 hour SEGAE lesson. Unlearning is always possible but if it does not reflect the average case, proceeding as we did thus amount to downplaying the overall knowledge impact of the proposed setting. Alternatively, removing those students from the sample could be seen as pushing the results upward.

The pre-survey was done during lesson times. The post-survey was done after the lesson. For the latter, students thus had to complete the online survey by themselves during their free time. It can explain the low matching rates between the surveys (Table 2). As far as the second lesson in March 2023 is concerned, it is worth noting that it was given by the teacher as an invited lecturer (whereas the other two lessons took place within the university in which the teacher is employed). This one-off relation with the concerned teacher provides a complementary potential explanation for the even lower matching rate in this lesson.

The sample distribution by specialization is shown in Table 3.

Table 2: Samples of the 3 lessons (*numbers of students*)

	Knowledge part			**Feedback** part
	Pre-survey	Post-survey	Matching*	
First lesson (March 2021)	68	74	48	74
Second lesson (March 2023)	34	20	20	20
Third lesson (May 2023)	51	49	42	49
Total (all three lessons)	153	143	**110**	**143**

Legend: *accounting for the removal of outliers

Table 3: Study specializations distribution for the knowledge acquisition (*numbers of students, n=110*)

	Agronomy	**Forest**	**International Development**	**Others**
First lesson (March 2021)	16	17		15
Second lesson (March 2023)			20	
Third lesson (May 2023)	18	15		9
Total (all three lessons)	**34**	**32**	**20**	**24**

All statistical data analyses were performed using R software v.4.3.2 (R Core Team, 2022), and a $\alpha = 0.05$ was used for the significance level.

The scores of each student for both the pre- and post-surveys were calculated and registered. For the multiple-choice questions, students received a score of 1 when they had a correct answer, 0 when they did not answer, and -1 if the answer was not correct. For the open-ended questions, students were given a score between 0 and 3 depending on the number of correct answers given, compared to those expected. They received a score of -1 for each incorrect answer. The result of each question was added up to calculate the total score. The maximum score that could be reached is 39 and it was converted into percentages. Final scores were used to calculate descriptive statistics (e.g. average and median). Then, a paired t-test was performed with the null hypothesis of the absence of an increase in the scores before and the scores after the 4-hour lesson. The progress of a student is calculated as the absolute change in knowledge acquisition (i.e. the post-survey score minus the pre-survey score) in percentage points. Subsequently, the aggregate scores of each type of specialization were calculated and the same statistical analysis as previously described was performed. Moreover, two multiple regressions were conducted to try to explain the score reached in the pre- and-post surveys. Following the results of multiple regression, two single regressions were run.

The score for the feedback questions is calculated by converting all answers to each of the 36 statements with a scale from 1 to 4 (1=strongly disagree, 2=disagree, 3=agree, 4=strongly agree). Each flow factor score was calculated by adding up the results of all corresponding statements and dividing them by the number of statements included in the flow factor itself. An overall flow score for each student was computed by adding all the factors of flow and dividing by 8 (the number of factors). Final flow scores were used to calculate descriptive statistics. Mean scores were calculated for the whole sample, by type of lesson and by type of specialization. A two-factor analysis of variance (ANOVA) and a Tukey test have been performed.

Finally, to confirm the results and explore the possible links between flow and absolute change in knowledge, a principal component analysis (PCA) of the mean values of the eight flow factors for each student was performed with their absolute change in knowledge (unit: % of correct answers) and with the type of lesson (added as a supplementary variable). Given the number of variables involved (i.e. a 110 × 10 matrix), the detailed interpretation of these individual relationships is very delicate and fully justifies the use of a principal component analysis.

3. Results

3.1 Results of knowledge acquisition

Overall, a large majority of students (77 of 110) increased their scores after the 4-hour lesson. It can be noticed from Figure 2 that only 4 students had the same scores, and 29 saw their scores decrease slightly.

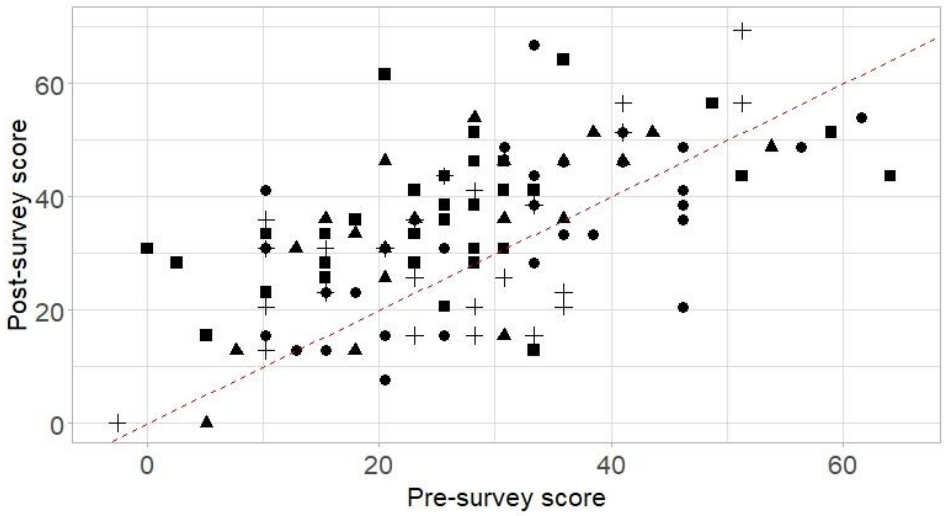

Figure 2. Comparison of students' mean scores on the knowledge pre- and post-surveys, by their specialization: Agronomy ●, Development ▲, Forest ■ and Other +.

On the knowledge pre-survey, the general mean score is 27.6 % of correct answers (Table 4). The score of each specialization type varies from 26 % to 30.5 %. On the knowledge post-survey, the students' general mean score is significantly higher (p<0.001) and reaches 34.5 %. The forest specialization records the highest significative increase: 10.7 percentage points.

The overall knowledge gain achieved through the 4-hour/SEGAE setting is thus of 6.9 percentage points. This is lower than the one achieved through the 5-day seminar, where the gain was 8.7 percentage points (De Graeuwe et al., 2020). However, this seminar involved a wider spectrum of student curricula. Comparing with students of a similar profile (i.e. those listed in the category *multidisciplinary curriculum* in Appendix 3), the achieved gain is of a similar magnitude (6.4 in the workshop and 6.9 in the present study).

An interesting result to underline is that the progress in knowledge acquisition is both higher and significant for open-ended questions (p<0.0001). The increase ranges from 8.8 to 15.9 percentage points (Figure 3). For close-ended questions, the increase is not significant and is much lower (2.8 percentage points).

Table 4. Mean of students' scores (% of correct answers) on the knowledge pre- and post-survey, and the increase after the 4-hour lesson (percentage points)

Grouping of Data (and number of students)	*Pre-Survey*	*Post-Survey*	*Increase*
All students	27.6	34.5	6.9***
By type of specialization			
Agronomy (34)	30.5	34.6	4.1
Development (20)	26.5	34.7	8.2**
Forest (32)	26.2	36.9	10.7***
Other (24)	26	30.8	4.8
By type of questions			
Closed-ended questions	34	36.8	2.8
Open-ended questions	20	31.7	11.7***

Legend: *** p < 0.001; ** p < 0.01; * p < 0.05; no symbol p > 0.05

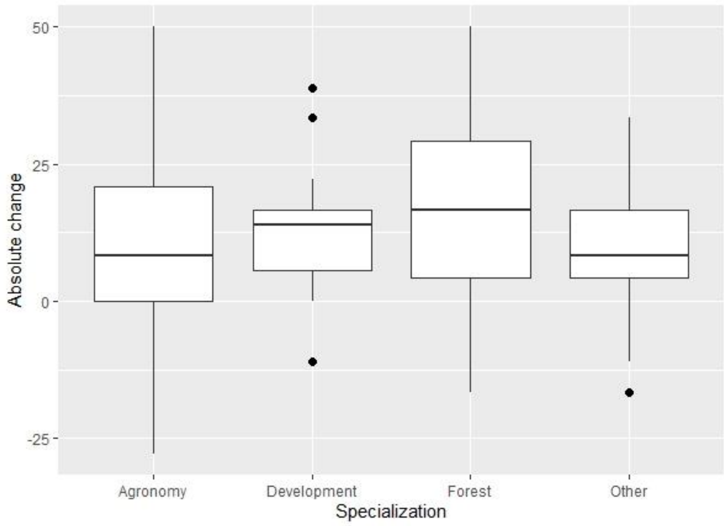

Figure 3: Comparison of the absolute change for the open-ended questions for the knowledge surveys

We could have expected some control variables to play a role. However, according to a multiple regression analysis, the level of scores achieved by a student at the pre-survey could not be explained (p-values>0.05) by any of the following variables: (1) number of ECTS (European Credits Transfer System) in agroecology (2) study specialization (3) childhood living environment. The only profile variable that is very significantly linked is the number of books or scientific articles read about agroecology ($p<0.001$, $R^2=0.08$).

Looking at Table 5, classroom-based lessons appear slightly more effective in increasing knowledge than those given online. However, the regression analysis shows that this variable does not significantly influence the scores achieved by the student at the post-survey. In addition, it seems that the slight difference is mostly driven by one cohort of students (i.e. students in International Development). Another interesting finding is that the gains achieved in the online lesson appear to be somewhat more dispersed than those achieved in face-to-face settings. The only variable that is very highly significantly linked is the score achieved on the first knowledge test ($p<0.0001$, $R^2=0.35$). Each extra point obtained during the pre-survey knowledge test increases the score achieved at the post-survey test by 0.6 % (Figure 4).

Table 5. Mean of students' scores (% of correct answers) on the knowledge pre- and post-survey, and the increase after the 4-hour lesson (percentage points) by type of lesson and specialization

Grouping of Data (and number of students)		Online (n=48) Pre-Survey	Online (n=48) Post-Survey	Online (n=48) Increase	Face-To-Face (n=62) Pre-Survey	Face-To-Face (n=62) Post-Survey	Face-To-Face (n=62) Increase
All students		25	31.6	6.6**	29.5	36.7	7.2***
Except the development specialization (0 /42)					31	37.6	6.6*
By type of specialization							
Agronomy	(16 /18)	30.1	30.1	0	30.9	38.7	7.8*
Development	(0 /20)				26.5	34.7	8.2**
Forest	(17 /15)	20.4	34.4	14***	32.8	39.8	7*
Other	(15 /9)	24.8	30.3	5.5	27.9	31.6	3.7

Legend: *** p < 0.001; ** p < 0.01; * p < 0.05; no symbol p > 0.05

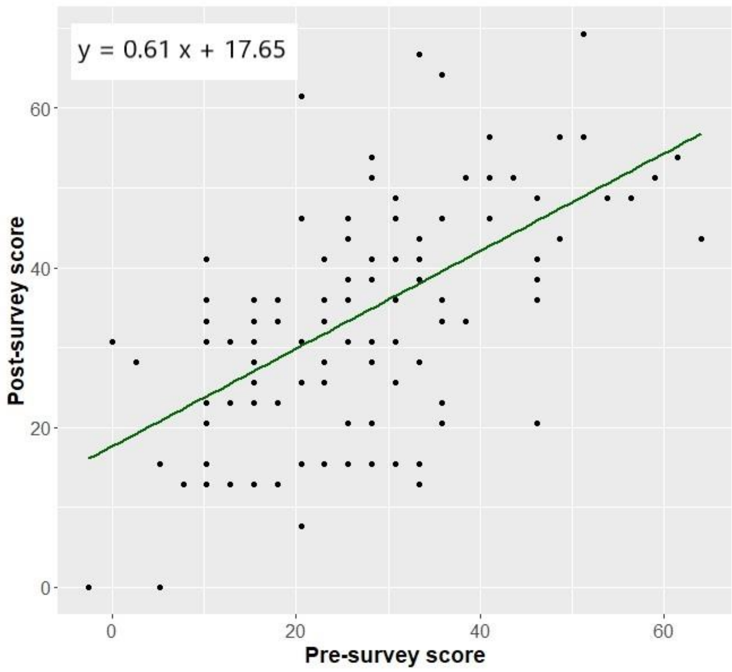

Figure 4: Simple regression

3.2 Perception of SEGAE and its evaluation through flow

In the feedback section of the post-survey, more than 90% of the students "agreed" or "strongly agreed" with the statements (Figure 5):

- "I think that playing this game was useful to improve my understanding of agroecology".

- “I enjoyed playing this game.”
- “I will advise students from my university to play this simulation game”.

Almost 90% of them also “agreed” or “strongly agreed” that (1) the game was easy to play, (2) the theoretical and game sessions are complementary. The lowest value (albeit still above 70%) for the reported extent of agreement relates to the statement that working in a group allows students to increase their understanding. Altogether, these results confirm that the SEGAE game is globally well appreciated by students.

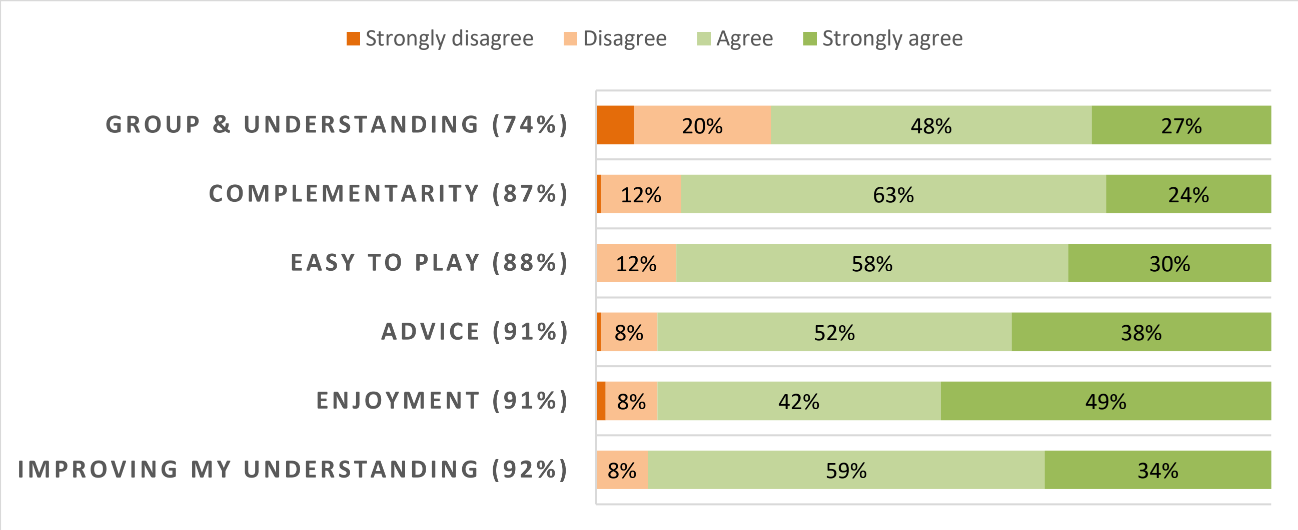

Figure 5: Distribution for additional statements *(n=143)*

The scores for the eight factors of flow show an average of 3.07 points (i.e., > “agree”) out of 4. Most students can then be considered as ‘immersed’ in the game. The factor “social interaction” is graded the lowest (general mean: 2.69). The seven other factors of flow are rated particularly lower in the online lesson compared to the classroom-based lesson (Figure 6). For each specialization, the flow average was calculated and compared with the general mean. A two-factor analysis was performed. The variables ‘Specialization’ and ‘Online’ are highly significant in explaining the level of flow ($p<0.0001$). Only international development students differentiate themselves with an average of around 3.52 points out of 4. This specialization has a flow mean significantly different compared to the others (Tukey-Kramer test with p-values <0.05). The ‘flow’ scores achieved in the online session are very significantly different ($p<0.0001$) than those achieved in classroom-based sessions.

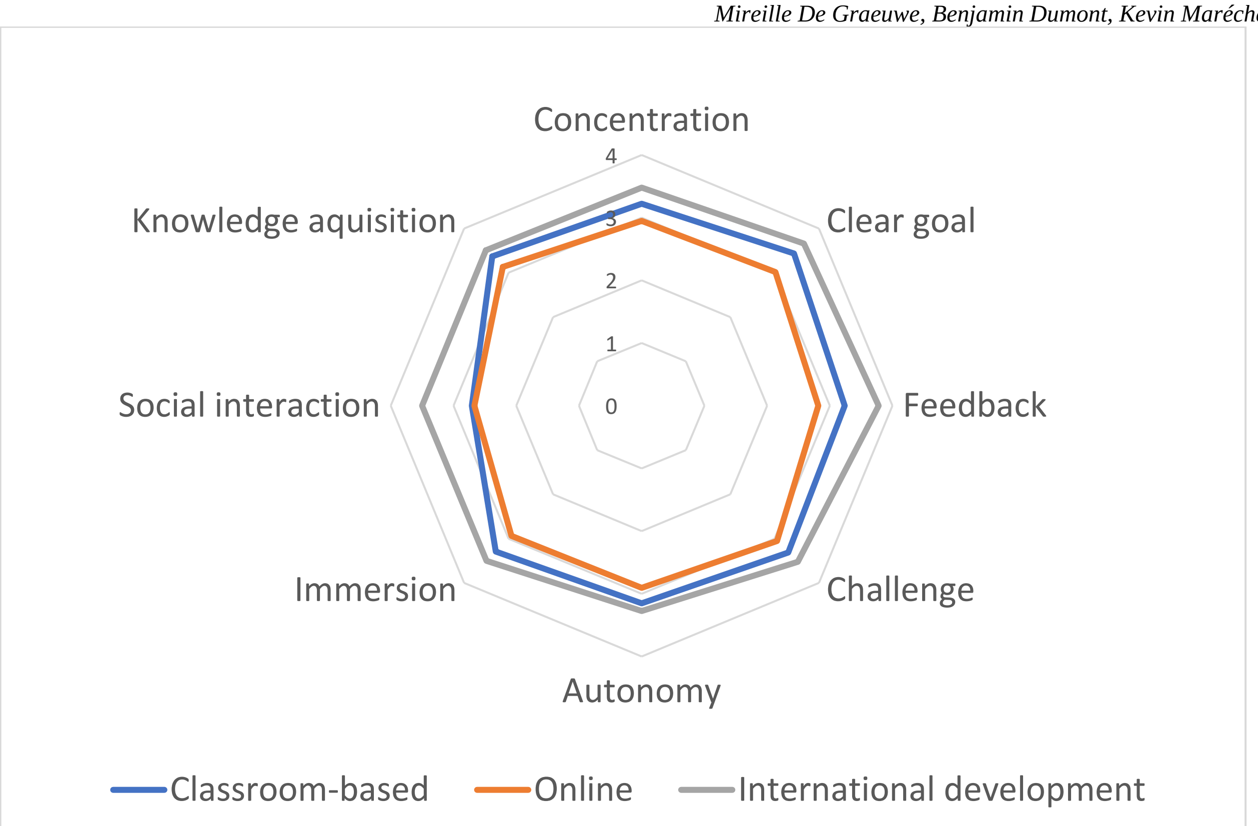

Figure 6. Comparison with a radar chart on eight mean flow factors

3.3 Perception of flow and absolute knowledge score increase

The first dimension of the Principal Component Analysis (inertia of 49.6%, see the "Variable-PCA" graph on Figure 7) is correlated significantly ($p < 0.0001$) with the eight flow factors (1."Concentration", 2. "Clear goal", 3. "Feedback", 4. "Challenge", 5. "Autonomy", 6. "Immersion", 7. "Social interaction", and 8. "Knowledge acquisition") , all of which had $r > 0.63$. Students provided comparable ratings for most of the flow factors, with scores tending to be either predominantly high or predominantly low. The online type of lesson (added as a qualitative variable under the form of a dummy, taking the value "1" it was an online course and "0" if it was a classroom-based session) is significantly negatively correlated ($r= -0.39$) with this first dimension ($p < 0.0001$), *see* the "Individuals-PCA" graph on Figure 7. The second dimension of the PCA (inertia of 14.2%) was correlated with the absolute change in knowledge acquisition and two factors of flow: feedback and social interaction ($p < 0.0001$), all of which had $r > 0.53$ (see the "Variable-PCA" graph on Figure 7). The third dimension was not analyzed because of its low inertia (<10%). This choice was confirmed by the analysis of the screeplot of the eigenvalues.

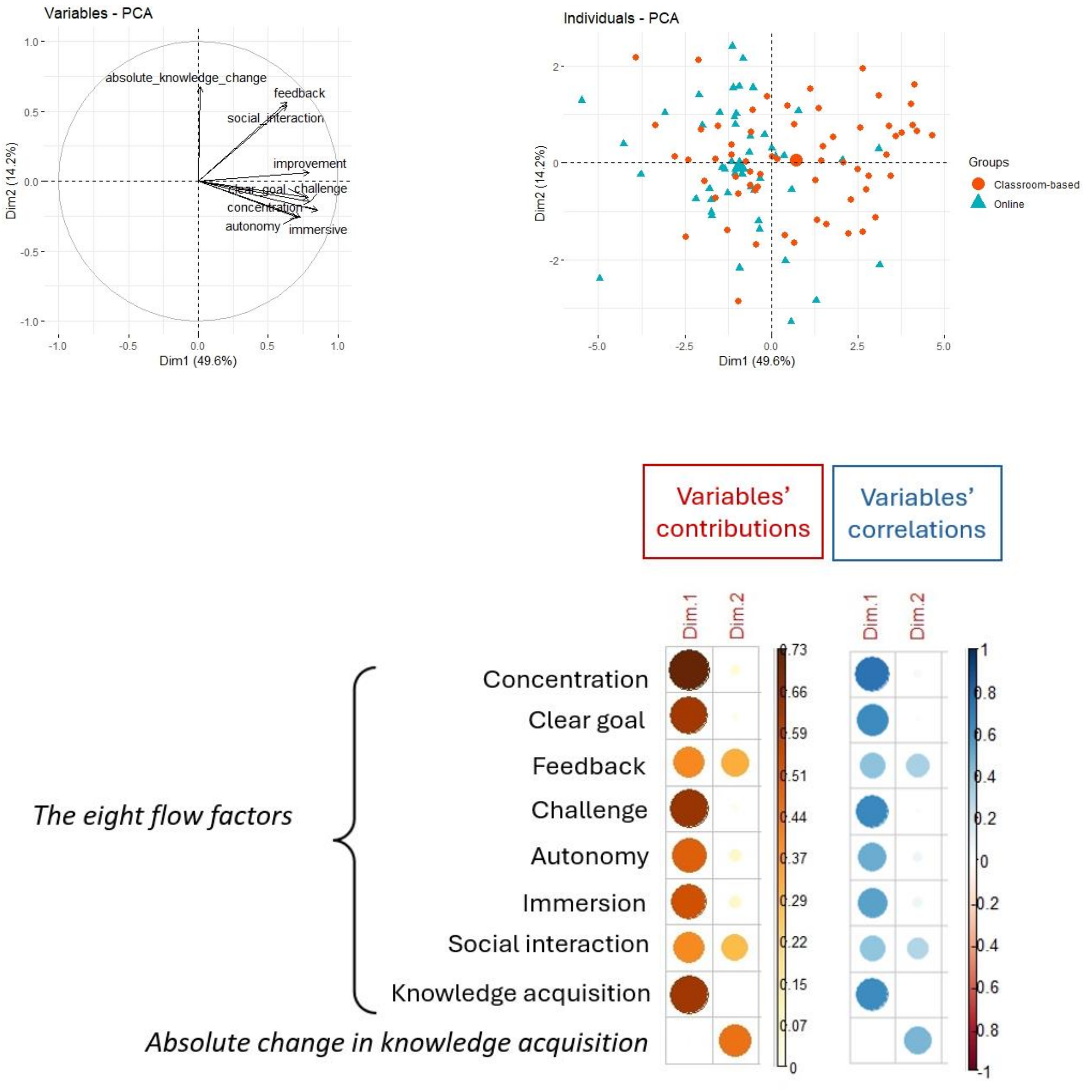

Figure 7. Computed figures from the Principal Component Analysis (PCA)

4. Discussion

The primary objective of this study is to contribute to the ongoing efforts of integrating agroecology into university curricula, which is deemed essential for addressing the contemporary challenges in agriculture.

Including agroecology in undergraduate bioengineering programs is indeed necessary to equip future professionals with the required systems-thinking approach and interdisciplinary skills.

More particularly, this study aims to assess the merits of a concise pedagogical setting which consists in a 4-hour lesson using the serious game SEGAE and that can easily be integrated into an existing course. The interest of SEGAE in effectively raising student awareness of systems thinking, interdisciplinarity, and agroecology has already been demonstrated in De Graeuwe et al. (2020). However, the setting presented in this paper offers a more feasible option compared to the requirements of a 5-day international workshop in terms of logistics and financial resources.

Building on SEGAE for teaching agroecology echoes previous research showing that serious games provide an immersive learning experience, facilitating a deeper understanding of complex systems (Hauge et al., 2013; Sajjadi et al., 2022). The idea is to see whether our pedagogical setting could deliver similar educational benefits, thereby contributing to a growing body of evidence (Hainey and Baxter, 2024; Severengiz et al., 2020) that supports the use of serious games as an effective pedagogical tool in higher education.

In parallel, there has been a growing use of serious games for agronomic purposes in the last two decades (Dolinska, 2017; Espinosa-Curiel and De Alba-Chávez, 2024; Farrié et al., 2015; Martin, 2021; Orduña Alegría et al., 2020; Ryschawy et al., 2018; Speelman et al., 2014). For a better engagement, research emphasize the need to tailor the game length and, the sequence of pedagogical activities to the targeted audience, and enabling the achievement educational goals, and enhancing long-term learning. A quick look at those studies reveals significant variability in their design and application, but most puzzling is the lack of details needed to recreate the game experiences, as reported by Espinosa-Curiel and De Alba-Chávez (2024). For example, Jones et al. (2023) mention the research period (6 weeks) for the Lameness game without mentioning the frequency or number of game-played sessions (even approximate). In the case of Agritainment (Yoo and Kim, 2014, 2010), no information could be found regarding game duration. The Crownking game (Szilágyi et al., 2017) is based on feedback from 30 users, but the context of their participation, whether voluntary, mandatory, or compensated, is not specified. In AgriVillage (Yongyuth et al., 2010), the authors do not mention which pedagogical theory the serious game is based on. This uncertainty surrounding their use makes it difficult to accurately assess their impact on learning and enable a comparison. This is the reason why we were keen on providing as much detail as possible to ensure the pedagogical activity is clear and understandable to the reader. Transparency, regarding the course materials, game scenarios and surveys, is crucial to warrant replicability and potential refinement by others.

It also is worth mentioning that most games in agriculture have not been specifically designed for educational purposes aimed at students (e.g Role-playing game of Salvini et al., 2016), SIPA game in Moojen (2022b, 2022a), LAITCONOMIE of Dolinska (2017) or Lameness game of Jones et al. (2023)). In contrast, our study explores the potential of a game-based approach within an academic setting and specifically targeting students (such as Game of Piglets in Klit et al. (2018)). As shown in the results section, the proposed pedagogical setting resorting on a game-based approach did generate a (statistically significant) increase of knowledge in agroecology among the surveyed students. This finding aligns with other studies, such as Blasko-Drabik et al. (2013), De Alba-Chávez et al. (2024) and Martin et Shen (2014), where positive learning outcomes were measured. This more largely echoes the conclusions made in previous studies which suggest that games can contribute to fostering the transition towards sustainability (Meunier et al., 2022; Moojen et al., 2022a, 2022b; Salvini et al., 2016) as well as agroecology (De Graeuwe et al., 2020; Sari et al., 2024; Seegers et al., 2023).

Although positive, the achieved gains in knowledge must obviously be put into perspective as the mean scores for both the pre- and post-surveys are relatively low. However, what is more important to underline from our perspective is that the proposed pedagogical setting allowed students to achieve an absolute change in knowledge acquisition that is of a similar magnitude as the one enabled through a 5-days workshop (see De Graeuwe et al.(2020)), although the latter requires significantly more organization and is therefore much more time-, money-, and energy-consuming. In the classroom-based modality, which more closely resembles the in-person workshop setting, the overall increase recorded through the 4-hour lessons even reached 7.2 percentage points which is slightly higher than the 6.4 increase observed in the workshop for the students of a similar profile (i.e., those under the 'multidisciplinary). Although the starting levels of knowledge are lower, the 4-hour setting generated a comparable impact on knowledge. The same goes for the level of satisfaction (for instance, students in both modalities enjoyed the game with scores of agreement or strong agreement above 85%) as well as for the extent of immersion (i.e. the overall mean for the factors capturing the notion of 'flow' in this study is 3.07 while it was 2.96 in the 5-days workshop). Altogether, a condensed 4-hour session led by a single teacher thus emerges as a promising avenue for effective learning in agroecology.

Going more deeply into the results, students notably exhibited marked enhancements in their aptitude to tackle open-ended questions, necessitating nuanced analyses within a broader framework. This aligns with observations made in De Graeuwe et al. (2020), and in Moojen (2022a, 2022b) that game-based simulations are effective in instilling and refining system reasoning. The game appears to increase the ability of students to articulate both pre-existing and newly acquired knowledge, fostering the integration of diverse concepts concurrently. The findings underscore the potential of SEGAE in nurturing metacognitive learning, particularly evident in the enhanced handling of open-ended inquiries.

Moreover, the study unveils a notable influence of prior knowledge on post-test scores, corroborating findings from prior research by Zumbach et al. (2020) and Beier and Ackerman (2005). Remarkably, even incorrect prior knowledge impacts negatively final scores. As it was explained for each incorrect answer in a multiple-choice question or an incorrect element in an open-ended question, students received a score of -1. Therefore, a high score implies that students have substantial prior knowledge, while a lower score may suggest the presence of misconceptions rather than an absence of knowledge, as students who did not answer would receive a score of zero rather than -1. This highlights a nuanced relationship between prior knowledge and performance outcomes, reinforcing the necessity for targeted interventions to rectify misconceptions and bolster foundational understanding (Lipson, 1982).

Bearing this result in mind, it may seem surprising that the number of ECTS in agroecology does not feature among the significant explanatory factors. One potential explanation is that, as reported by several students in informal post-lesson discussions, assigning credits was not an easy task given the various extent of integration of agroecological concepts in courses. Estimating credits may thus be more prone to subjectivity than the numbers of books and scientific articles read, the latter being significant (albeit with a low explanatory power).

Overall, 31% of the students either demonstrated no improvement or even showed lower scores in the second survey. Since it seems quite unlikely that a lesson would induce students to unlearn, one explanation could be that some students were not fully focused and completed the end-of-post-survey questionnaire rather on the fly. It was thus decided to check the respective time taken by each student to fill out the questionnaire, but it turned out to be insignificant in explaining the results. This corroborates the finding of Bolsinova et al. (2017), which indicates that there are strong differences in the ways individuals process questionnaires and that the time taken to do so can thus not assess either their extent of concentration or the ensuing quality of their responses. The lack of improvement can also be attributed to the insignificant progress observed in closed-ended questions. These questions are linked to sub-indicators within the game, necessitating students to delve deeply into their comprehension of technical aspects to acquire previously unknown knowledge. A 4-hour lesson is likely insufficient for them to fully grasp these intricacies and consequently acquire new insights.

Furthermore, the study delineates distinct trajectories of knowledge acquisition among different student specializations. Agronomy students, already equipped with prior knowledge of agroecology and breeding systems, exhibited marginal improvements, possibly hindered by reduced concentration levels. Conversely, students with only a basic understanding of agroecology fundamentals demonstrated more pronounced gains, suggesting that limited foundational knowledge provided a more ample room for improvement, as shown by the case of students in forestry. However, some other groups (i.e. students in chemistry and environmental sciences) do not seem to follow the same path of improvement, indicating the need for tailored instructional strategies to address diverse learning needs adequately (Burruss and Popkess, 2013).

This appears even more critical given an intriguing aspect of the study which pertains to the differentiated impact of instructional modalities on knowledge acquisition. While both online and classroom-based sessions yielded similar knowledge gains, distinct patterns emerged according to student specializations. Forestry students enrolled in the online lesson recorded significant improvements (14 percentage points, $p < 0.001$), whereas the other students exhibited negligible changes in scores. This disparity highlights the need for a thorough understanding of the contextual factors that determine learning outcomes within the same educational environment.

In exploring potential avenues for enhancing the efficiency of game-based learning, it is useful to turn to insights relative to the notion of flow. While no direct link could be found between flow indicators and post-survey knowledge tests, the study does underscore the importance of harnessing flow to enhance learning satisfaction, a positive link already demonstrated by Burke (2010). Moreover, the observed high levels of flow among students specializing in international development highlight the role of contextual factors, such as cohort size and classroom dynamics, in shaping the learning experience. The study could have been strengthened by including a fully digitalized class for students in international development, and future research could explore their responses to an online SEGAE session while controlling for other variables.

As digitalization continues to reshape educational landscapes (Allen and Seaman, 2013; Young and Duncan, 2014), our analysis puts the systematic use of online courses into perspective. More precisely, it points out the need for careful consideration of instructional design principles and alignment with pedagogical objectives (Caliskan et al., 2020). While online education offers unprecedented flexibility and accessibility, its effectiveness in fostering critical components of learning, such as feedback (Anderson et al., 2010) and social interaction (Azmat and Ahmad, 2022), remains questionable.

The present study indeed shows the potential added value of classroom-based lessons (as evidenced by the PCA results) in facilitating rapid peer and teacher feedback, underscoring the multifaceted nature of effective knowledge acquisition. This added benefit of face-to-face engagement is called "joint reality" by García-Barrios et al. (2008). By jointly exploring scenarios, participants reframe problems and develop a shared reality, fostering stronger engagement and a more sustainable learning experience through co-created solutions. Ditzler et al. (2018) found similar results, highlighting the role of serious games in fostering collaborative learning environments where diverse stakeholders can engage and co-create knowledge.

Taking these considerations further, Ryschawy et al. (2022) highlight the importance of co-designing games with the targeted participants, such as farmers, in their study. Extending this approach, co-designing pedagogical settings with students indeed appears promising for improving educational outcomes, as it would enable the creation of learning environments that are more tailored to the needs of learners and therefore more effective. This approach would further reinforce the effectiveness of games in agricultural education.

5. Conclusion

This study confirms that the format of the SEGAE serious game integrated into a 4-hour lesson with a single teacher is a relevant tool for the learning and teaching of agroecology. Students can achieve similar absolute changes in knowledge acquisition and flow level compared to those achieved through a longer workshop, which requires much more organization. Also, students widely report having appreciated learning using this game. Therefore, the development of serious games appears to be a credible avenue for the future of agroecology learning.

This study also provides some evidence of a link between the observed increase in absolute knowledge and two factors of flow: feedback and social interaction. Further study would be useful to unveil the precise levers to activate a game-based learning experience in agroecology to be as efficient as possible.

Although comparable to those achieved in the workshop, the knowledge gains observed in this study are still relatively modest. Although it can be partially explained by the use of negative marking, future research should explore how the proposed pedagogical setting could be improved to yield higher gains. For instance, it could be interesting to include a 'group homework session' into the overall pedagogical setting and see whether it would induce any differences in knowledge acquisition. This added activity would indeed provide a temporal space for the students to explore the indicators more deeply and maybe yield better results on closed-ended questions. Another option that could potentially enhance the results obtained would be to start from a similar structure of the lesson but to duplicate the sessions to have a maximum of 30 students by lesson or have more teachers for the serious game session to allow for more effective feedback. This would enable shaping the learning experience and tailoring it to the specific needs of students with distinct disciplinary profiles, for instance.

From a methodological point of view, organizing semi-structured, narrative, or qualitative interviews could also be an interesting approach for capturing the learning experience of students more comprehensively. In their literature review, Connolly et al. (2012) do indeed report that only 11.6% of papers on serious games rely on a qualitative study design. This would undoubtedly generate useful insights to complement and refine the existing knowledge regarding the effective methods of teaching intrinsically interdisciplinary and systemic contents such as agroecological ones. It would also provide a useful basis for increasing the participation of students into the co-designing of the pedagogical setting, which has been shown to generate positive outcomes.

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8. References

Al Hakim, V.G., Yang, S.-H., Liyanawatta, M., Wang, J.-H., Chen, G.-D., 2022. Robots in situated learning classrooms with immediate feedback mechanisms to improve students' learning performance. Computers & Education 182, 104483. https://doi.org/10.1016/j.compedu.2022.104483

Allen, I.E., Seaman, E., 2013. Changing Course: Ten Years of Tracking Online Education in the United States. MA: Babson Survey Research Group and Quahog Research Group, Babson Park.

Anderson, D., Imdieke, S., Standerford, N.S., 2010. Feedback in the Online Classroom: We Need It, Too., in: The Eighth International Conference on Self-Study of Teacher Education Practices. Presented at the The Eighth International Conference on Self-Study of Teacher Education Practices, pp. 313–325.

Azmat, M., Ahmad, A., 2022. Lack of Social Interaction in Online Classes During COVID-19. Journal of Materials and Environmental Science 13, 185–196.

Beier, M.E., Ackerman, P.L., 2005. Age, Ability, and the Role of Prior Knowledge on the Acquisition of New Domain Knowledge: Promising Results in a Real-World Learning Environment. Psychology and Aging 20, 341–355. https://doi.org/10.1037/0882-7974.20.2.341

Blasko-Drabik, H., Blasko, D.G., Lum, H.C., Erdem, B., Ohashi, M., 2013. Investigating the Impact of Self-Efficacy in Learning Disaster Strategies in an On-Line Serious Game. Proceedings of the Human Factors and Ergonomics Society Annual Meeting 57, 1455–1459. https://doi.org/10.1177/1541931213571325

Bolsinova, M., Tijmstra, J., Molenaar, D., De Boeck, P., 2017. Conditional Dependence between Response Time and Accuracy: An Overview of its Possible Sources and Directions for Distinguishing between Them. Front. Psychol. 8. https://doi.org/10.3389/fpsyg.2017.00202

Boulestreau, Y., Casagrande, M., Navarrete, M., 2023. A method to design coupled innovations for the agroecological transition. Implementation for soil health management in Provencal sheltered vegetable systems. Agricultural Systems 212, 103752. https://doi.org/10.1016/j.agsy.2023.103752

Boyle, E., Connolly, T.M., Hainey, T., 2011. The role of psychology in understanding the impact of computer games. Entertainment Computing 2, 69–74. https://doi.org/10.1016/j.entcom.2010.12.002

Burke, R.J., 2010. Flow, Work Satisfaction and Psychological Well-Being at the Workplace.

Burruss, N., Popkess, A., 2013. The diverse learning needs of students., in: Teaching in Nursing: A Guide for Faculty. pp. 15–33.
Caliskan, S., Kurbanov, R.A., Platonova, R.I., Ishmuradova, A.M., Vasbieva, D.G., Merenkova, I.V., 2020. Lecturers Views of Online Instructors about Distance Education and Adobe Connect. Int. J. Emerg. Technol. Learn. 15, 145. https://doi.org/10.3991/ijet.v15i23.18807
Campbell, B.M., Beare, D.J., Bennett, E.M., Hall-Spencer, J.M., Ingram, J.S.I., Jaramillo, F., Ortiz, R., Ramankutty, N., Sayer, J.A., Shindell, D., 2017. Agriculture production as a major driver of the Earth system exceeding planetary boundaries. E&S 22, art8. https://doi.org/10.5751/ES-09595-220408
Connolly, T.M., Boyle, E.A., MacArthur, E., Hainey, T., Boyle, J.M., 2012. A systematic literature review of empirical evidence on computer games and serious games. Computers & Education 59, 661–686. https://doi.org/10.1016/j.compedu.2012.03.004
Csikszentmihalyi, M., 2014. Flow and the Foundations of Positive Psychology. Springer Netherlands, Dordrecht. https://doi.org/10.1007/978-94-017-9088-8
David, C., Bell, M.M., 2018. New challenges for education in agroecology. Agroecology and sustainable food systems 42, 612–619. https://doi.org/10.1080/21683565.2018.1426670
De Graeuwe, M., Jouan, J., Carof, M., Baccar, R., Bareille, N., Bastian, S., Brogna, D., Burgio, G., Couvreur, S., Cupiał, M., Dumont, B., Jacquot, A.-L., Magagnoli, S., Makulska, J., Maréchal, K., Pérès, G., Ridier, A., Salou, T., Tombarkiewicz, B., Sgolastra, F., Godinot, O., 2020. Learning Interdisciplinarity and Systems Approaches in Agroecology: Experience with the Serious Game SEGAE. Sustainability 12, 2–15. https://doi.org/10.3390/su12114351
DeLonge, M., Basche, A., 2017. Leveraging agroecology for solutions in food, energy, and water. Elementa: Science of the Anthropocene 5, 6. https://doi.org/10.1525/elementa.211
Dernat, S., Dumont, B., Vollet, D., 2023. La Grange®: A generic game to reveal trade-offs and synergies among stakeholders in livestock farming areas. Agricultural Systems 209, 103685. https://doi.org/10.1016/j.agsy.2023.103685
Ditzler, L., Klerkx, L., Chan-Dentoni, J., Posthumus, H., Krupnik, T.J., Ridaura, S.L., Andersson, J.A., Baudron, F., Groot, J.C.J., 2018. Affordances of agricultural systems analysis tools: A review and framework to enhance tool design and implementation. Agricultural Systems 164, 20–30. https://doi.org/10.1016/j.agsy.2018.03.006
Dolinska, A., 2017. Bringing farmers into the game. Strengthening farmers' role in the innovation process through a simulation game, a case from Tunisia. Agricultural Systems 157, 129–139. https://doi.org/10.1016/j.agsy.2017.07.002
Espinosa-Curiel, I.E., De Alba-Chávez, C.A.G., 2024. Serious Video Games for Agricultural Learning: Scoping Review. IEEE Trans. Learning Technol. 17, 1155–1169. https://doi.org/10.1109/TLT.2024.3364086
Farrié, B., Jouven, M., Launay, F., Moreau, J.-C., Moulin, C.-H., Piquet, M., Taverne, M., Tchakérian, E., Thénard, V., Martin, G., 2015. Rangeland Rummy – A board game to support adaptive management of rangeland-based livestock systems. Journal of Environmental Management 147, 236–245. https://doi.org/10.1016/j.jenvman.2014.08.018
Fernández González, C., Ollivier, G., Bellon, S., 2021. Transdisciplinarity in agroecology: practices and perspectives in Europe. Agroecology and Sustainable Food Systems 45, 523–550. https://doi.org/10.1080/21683565.2020.1842285
Francis, C.A., Jordan, N., Porter, P., Breland, T.A., Lieblein, G., Salomonsson, L., Sriskandarajah, N., Wiedenhoeft, M., DeHaan, R., Braden, I., Langer, V., 2011. Innovative Education in Agroecology: Experiential Learning for a Sustainable Agriculture. Critical Reviews in Plant Sciences 30, 226–237. https://doi.org/10.1080/07352689.2011.554497
Francis, C.A., Lieblein, G., Breland, T.A., Salomonsson, L., Geber, U., Sriskandarajah, N., Langer, V., 2008. Transdisciplinary Research for a Sustainable Agriculture and Food Sector. Agron. J. 100, 771–776. https://doi.org/10.2134/agronj2007.0073
Fu, F.-L., Su, R.-C., Yu, S.-C., 2009. EGameFlow: A scale to measure learners' enjoyment of e-learning games. Computers & Education 52, 101–112. https://doi.org/10.1016/j.compedu.2008.07.004
García De Alba-Chávez, C.A., Espinosa-Curiel, I.E., Michel-Nava, R.M., 2024. Exploring the Impact of a Persuasive Serious Video Game (Farmily) on Promoting Home Gardening Among Novices: Design and Randomized Controlled Trial. JMIR Serious Games 12, e60771. https://doi.org/10.2196/60771

García-Barrios, L.E., Speelman, E.N., Pimm, M.S., 2008. An educational simulation tool for negotiating sustainable natural resource management strategies among stakeholders with conflicting interests. Ecological Modelling 210, 115–126. https://doi.org/10.1016/j.ecolmodel.2007.07.009

Geelhoed, E., 2022. Agroecology and EU law: finding potential for agroecology at the nexus between biodiversity law and human rights law. University of Strathclyde.

Gerten, D., Heck, V., Jägermeyr, J., Bodirsky, B.L., Fetzer, I., Jalava, M., Kummu, M., Lucht, W., Rockström, J., Schaphoff, S., Schellnhuber, H.J., 2020. Feeding ten billion people is possible within four terrestrial planetary boundaries. Nat Sustain 3, 200–208. https://doi.org/10.1038/s41893-019-0465-1

Gliessman, S., 2014. Agroecology : The Ecology of Sustainable Food Systems, Third Edition. CRC Press. https://doi.org/10.1201/b17881

Godfray, H.C.J., Beddington, J.R., Crute, I.R., Haddad, L., Lawrence, D., Muir, J.F., Pretty, J., Robinson, S., Thomas, S.M., Toulmin, C., 2010. Food Security: The Challenge of Feeding 9 Billion People. Science 327, 812–818. https://doi.org/10.1126/science.1185383

Hainey, T., Baxter, G., 2024. A Serious game for programming in higher education. Computers & Education: X Reality 4, 100061. https://doi.org/10.1016/j.cexr.2024.100061

Hauge, J.M.B., Pourabdollahian, B., Riedel, J.C.K.H., 2013. The Use of Serious Games in the Education of Engineers, in: Emmanouilidis, C., Taisch, M., Kiritsis, D. (Eds.), Advances in Production Management Systems. Competitive Manufacturing for Innovative Products and Services, IFIP Advances in Information and Communication Technology. Springer Berlin Heidelberg, Berlin, Heidelberg, pp. 622–629. https://doi.org/10.1007/978-3-642-40352-1_78

Heeter, C., 2000. Interactivity in the Context of Designed Experiences. Journal of Interactive Advertising 1, 3–14. https://doi.org/10.1080/15252019.2000.10722040

Hilimire, K., Gillon, S., McLaughlin, B.C., Dowd-Uribe, B., Monsen, K.L., 2014. Food for Thought: Developing Curricula for Sustainable Food Systems Education Programs. Agroecology and Sustainable Food Systems 38, 722–743. https://doi.org/10.1080/21683565.2014.881456

Holt-Giménez, E., Altieri, M.A., 2013. Agroecology, Food Sovereignty and the New Green Revolution. Journal of Sustainable Agriculture 120904081412003. https://doi.org/10.1080/10440046.2012.716388

IPES-FOOD, M., 2020. The added value(s) of agroecology: Unlocking the potential for transition in West Africa.

Jones, M.L., Barnish, M.S., Hughes, R.R., Murray, A.K., Mansour, O., Loni, T., Vickery, H.M., Evans, M.L., Green, L., Verdezoto, N., 2023. Exploring the potential of using simulation games for engaging with sheep farmers about lameness recognition. Frontiers in Veterinary Science. https://doi.org/10.3389/fvets.2023.1079948

Jouan, J., Carof, M., Baccar, R., Bareille, N., Bastian, S., Brogna, D., Burgio, G., Couvreur, S., Cupiał, M., Dufrêne, M., Dumont, B., Gontier, P., Jacquot, A.-L., Kański, J., Magagnoli, S., Makulska, J., Pérès, G., Ridier, A., Salou, T., Sgolastra, F., Szeląg-Sikora, A., Tabor, S., Tombarkiewicz, B., Węglarz, A., Godinot, O., 2021a. SEGAE: An online serious game to learn agroecology. Agricultural Systems 191, 103145. https://doi.org/10.1016/j.agsy.2021.103145

Jouan, J., Carof, M., Baccar, R., Bareille, N., Bastian, S., Brogna, D., Burgio, G., Couvreur, S., Cupiał, M., Dufrêne, M., Dumont, B., Gontier, P., Jacquot, A.-L., Kański, J., Magagnoli, S., Makulska, J., Pérès, G., Ridier, A., Salou, T., Sgolastra, F., Szeląg-Sikora, A., Tabor, S., Tombarkiewicz, B., Węglarz, A., Godinot, O., 2021b. A dataset for sustainability assessment of agroecological practices in a crop-livestock farming system. Data in Brief 36, 107078. https://doi.org/10.1016/j.dib.2021.107078

Kiili, K., 2005. Digital game-based learning: Towards an experiential gaming model. The Internet and Higher Education 8, 13–24. https://doi.org/10.1016/j.iheduc.2004.12.001

Klit, K.J.M., Pedersen, K.S., Stege, H., 2018. A prospective cohort study of game-based learning by digital simulation of a pig farm to train agriculture students to reduce piglet mortality. Porc Health Manag 4, 28. https://doi.org/10.1186/s40813-018-0105-6

Lieblein, G., Østergaard, E., Francis, C., 2004. Becoming an Agroecologist through Action Education. International Journal of Agricultural Sustainability 2, 147–153. https://doi.org/10.1080/14735903.2004.9684574

Lipson, M.Y., 1982. Learning New Information from Text: The Role of Prior Knowledge and Reading Ability. Journal of Reading Behavior 14, 243–261. https://doi.org/10.1080/10862968209547453

Martin, J.-P., 2021. À la Confédération paysanne, des paysans écologistes… mais pas végans: Histoire & Sociétés Rurales Vol. 55, 155–190. https://doi.org/10.3917/hsr.055.0155

Martin, M.W., Shen, Y., 2014. The Effects of Game Design on Learning Outcomes. Computers in the Schools 31, 23–42. https://doi.org/10.1080/07380569.2014.879684

Meunier, C., Casagrande, M., Rosiès, B., Bedoussac, L., Topp, C.F.E., Walker, R.L., Watson, C.A., Martin, G., 2022. Interplay: A game for the participatory design of locally adapted cereal–legume intercrops. Agricultural Systems 201, 103438. https://doi.org/10.1016/j.agsy.2022.103438

Moojen, F.G., De Faccio Carvalho, P.C., Dos Santos, D.T., Neto, A.B., Vieira, P.C., Ryschawy, J., 2022a. A serious game to design integrated crop-livestock system and facilitate change in mindset toward system thinking. Agron. Sustain. Dev. 42, 35. https://doi.org/10.1007/s13593-022-00777-5

Moojen, F.G., Ryschawy, J., Dos Santos, D.T., Barth Neto, A., Vieira, P.C., Portella, E., De Faccio Carvalho, P.C., 2022b. The farm coaching experience to support the transition to integrated crop–livestock systems: From gaming to action. Agricultural Systems 196, 103339. https://doi.org/10.1016/j.agsy.2021.103339

Mousseau, F., 2015. The Untold Success Story of Agroecology in Africa. Development 58, 341–345. https://doi.org/10.1057/s41301-016-0026-0

Orduña Alegría, M.E., Schütze, N., Zipper, S.C., 2020. A Serious Board Game to Analyze Socio-Ecological Dynamics towards Collaboration in Agriculture. Sustainability 12, 5301. https://doi.org/10.3390/su12135301

Petit, S., Alignier, A., Allart, R., Aviron, S., Boussard, H., Franck, P., Gibert, C., Ladet, S., Lavigne, C., Lecuyer, L., Moncamp, M., Muneret, L., Poggi, S., Ricci, B., Rusch, A., Vialatte, A., Young, J., 2023. Building capacities for the design of agroecological landscapes: The added-value of Landscape Monitoring Networks. Agriculture, Ecosystems & Environment 342, 108263. https://doi.org/10.1016/j.agee.2022.108263

Rosset, P., Altieri, M.A., 2017. Agroecology: science and politics. Fernwood Publishing ; Practical Action Publishing, Black Point, Nova Scotia, Warwickshire, UK.

Ryschawy, J., Charmeau, A., Pelletier, A., Moraine, M., Martin, G., 2018. Dynamix, un « jeu sérieux » pour concevoir des scénarios d'achat-vente entre céréaliers et éleveurs : une application en Ariège.

Ryschawy, J., Grillot, M., Charmeau, A., Pelletier, A., Moraine, M., Martin, G., 2022. A participatory approach based on the serious game Dynamix to co-design scenarios of crop-livestock integration among farms. Agricultural Systems 201, 103414. https://doi.org/10.1016/j.agsy.2022.103414

Sajjadi, P., Bagher, M.M., Myrick, J.G., Guerriero, J.G., White, T.S., Klippel, A., Swim, J.K., 2022. Promoting systems thinking and pro-environmental policy support through serious games. Front. Environ. Sci. 10, 957204. https://doi.org/10.3389/fenvs.2022.957204

Salvini, G., Van Paassen, A., Ligtenberg, A., Carrero, G.C., Bregt, A.K., 2016. A role-playing game as a tool to facilitate social learning and collective action towards Climate Smart Agriculture: Lessons learned from Apuí, Brazil. Environmental Science & Policy 63, 113–121. https://doi.org/10.1016/j.envsci.2016.05.016

Sari, R.R., Tanika, L., Speelman, E.N., Saputra, D.D., Hakim, A.L., Rozendaal, D.M.A., Hairiah, K., Van Noordwijk, M., 2024. Farmer Options and Risks in Complex Ecological-Social systems: The FORCES game designed for agroforestry management of upper watersheds. Agricultural Systems 213, 103782. https://doi.org/10.1016/j.agsy.2023.103782

Schroeder-Moreno, M.S., 2010. Enhancing Active and Interactive Learning Online - Lessons Learned from an Online Introductory Agroecology Course. NACTA Journal.

Seegers, R., Winter, E., Grote, U., 2023. Exploring the effectiveness of serious games in strengthening smallholders' motivation to plant different trees on farms: evidence from rural Rwanda. BAE 12, 69–81. https://doi.org/10.36253/bae-13479

Severengiz, M., Seliger, G., Krüger, J., 2020. Serious Game on Factory Planning for Higher Education. Procedia Manufacturing 43, 239–246. https://doi.org/10.1016/j.promfg.2020.02.148

Speelman, E.N., García-Barrios, L.E., Groot, J.C.J., Tittonell, P., 2014. Gaming for smallholder participation in the design of more sustainable agricultural landscapes. Agricultural Systems 126, 62–75. https://doi.org/10.1016/j.agsy.2013.09.002

Sutherland, L.-A., Burton, R.J.F., Ingram, J., Blackstock, K., Slee, B., Gotts, N., 2012. Triggering change: Towards a conceptualisation of major change processes in farm decision-making. Journal of Environmental Management 104, 142–151. https://doi.org/10.1016/j.jenvman.2012.03.013

Szilágyi, T., Kovács, Nagy, Várallyai, 2017. Development of Farm simulation application, an example for gamification in higher education. JAI 8. https://doi.org/10.17700/jai.2017.8.2.373

van der Ploeg, J.D., Barjolle, D., Bruil, J., Brunori, G., Costa Madureira, L.M., Dessein, J., Drąg, Z., Fink-Kessler, A., Gasselin, P., Gonzalez de Molina, M., Gorlach, K., Jürgens, K., Kinsella, J., Kirwan, J., Knickel, K., Lucas, V., Marsden, T., Maye, D., Migliorini, P., Milone, P., Noe, E., Nowak, P., Parrott, N., Peeters, A., Rossi, A., Schermer, M., Ventura, F., Visser, M., Wezel, A., 2019. The economic potential of agroecology: Empirical evidence from Europe. Journal of Rural Studies 71, 46–61. https://doi.org/10.1016/j.jrurstud.2019.09.003

Vanloqueren, G., Baret, P.V., 2009. How agricultural research systems shape a technological regime that develops genetic engineering but locks out agroecological innovations. Research Policy 38, 971–983. https://doi.org/10.1016/j.respol.2009.02.008

Wezel, A., Casagrande, M., Celette, F., Vian, J.-F., Ferrer, A., Peigné, J., 2014. Agroecological practices for sustainable agriculture. A review. Agronomy for Sustainable Development 34, 1–20. https://doi.org/10.1007/s13593-013-0180-7

Wu, J.S., Lee, J.J., 2015. Climate change games as tools for education and engagement. Nature Clim Change 5, 413–418. https://doi.org/10.1038/nclimate2566

Yongyuth, P., Prada, R., Nakasone, A., Kawtrakul, A., Prendinger, H., 2010. AgriVillage: 3D multi-language internet game for fostering agriculture environmental awareness, in: Proceedings of the International Conference on Management of Emergent Digital EcoSystems. Presented at the MEDES '10: The International Conference on Management of Emergent Digital EcoSystems 2010, ACM, Bangkok Thailand, pp. 145–152. https://doi.org/10.1145/1936254.1936280

Yoo, H.-S., Kim, S.-W., 2014. Virtual Farmers Training: Realistic Simulation with Amusements using Historic Simulation and Game Storyline. IJMUE 9, 121–130. https://doi.org/10.14257/ijmue.2014.9.5.11

Yoo, H.-S., Kim, S.-W., 2010. Agritainment: 3D Collaborative Space for Training Agricultural Experience with Entertainment Elements.

Young, S., Duncan, H.E., 2014. Online and Face-to-Face Teaching: How Do Student Ratings Differ? 10.

Zumbach, J., Rammerstorfer, L., Deibl, I., 2020. Cognitive and metacognitive support in learning with a serious game about demographic change. Computers in Human Behavior 103, 120–129. https://doi.org/10.1016/j.chb.2019.09.026

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9. Appendix

9.1 Appendix 1: Surveys design

<u>Profile section :</u>

Which specialization have you chosen this year? [open-ended question]
How old are you? [open-ended question which required a numeric answer]
Where have you spent your childhood? Urban area (in a city or town) Suburban area (peripheral area mixing housing and countryside) Rural area (in or like the countryside)
Have you followed some classes about agroecology? A lot (> 20 ECTS - European Credit Transfer and Accumulation System-) Some (10–20 ECTS - European Credit Transfer and Accumulation System-) A few (< 10 ECTS - European Credit Transfer and Accumulation System-) None (0 ECTS - European Credit Transfer and Accumulation System-)
Have you read some books/scientific articles about agroecology? A lot (> 4) Some (3 or 4)

A few (1 or 2) None (0)

Knowledge section:

The knowledge section of the serious game SEGAE consists of the following questions. When students were filling in the survey, all questions were shuffled randomly, and the themes of the questions (e.g., Crop production) were not disclosed. Correct answers are highlighted in green in the survey. For the open-ended questions, all responses similar to ours were accepted. The use of the exact same keywords as those provided in the answers was not required. Regarding the expected responses, they were derived from the Excel matrix available in the supplementary material of the scientific article "A dataset for sustainability assessment of agroecological practices in a crop-livestock farming system" by Jouan et al. (2021b). The type of sources varies and may come from either scientific publications or the opinion of scientific experts. By way of illustration, the expected answer to the first question in the table below draws on scientific publications (Bertrand et al., 2015; Cluzeau et al., 2012; Hoeffner et al., 2021) while, for the second question, it is based on an expert.

Detailed scientific references used for the first question:

- Bertrand, M., Barot, S., Blouin, M., Whalen, J., de Oliveira, T., Roger-Estrade, J., 2015. Earthworm services for cropping systems. A review. Agron. Sustain. Dev. 35, 553–567. https://doi.org/10.1007/s13593-014-0269-7
- Cluzeau, D., Guernion, M., Chaussod, R., Martin-Laurent, F., Villenave, C., Cortet, J., Ruiz-Camacho, N., Pernin, C., Mateille, T., Philippot, L., Bellido, A., Rougé, L., Arrouays, D., Bispo, A., Pérès, G., 2012. Integration of biodiversity in soil quality monitoring: Baselines for microbial and soil fauna parameters for different land-use types. Eur. J. Soil Biol. 49, 63–72. https://doi.org/10.1016/j.ejsobi.2011.11.003
- Hoeffner, K., Hotte, H., Cluzeau, D., Charrier, X., Gastal, F., & Peres, G. (2021). Effects of temporary grassland introduction into annual crop rotations and nitrogen fertilisation on earthworm communities and forage production. *Applied Soil Ecology*, *162*, 103893.

Crop production
Impact of permanent grassland on earthworm abundance ✓ **Positive** ☒ Negative I don't know
Choose practice(s) to fight erosion ✓ **Agroforestry** ✓ **Diverse crop rotation** ✓ **Residues left on soil** I don't know
Which tillage system will have the most positive effect on soil fauna? ☒ Reduced tillage ☒ Conventional tillage ✓ **No tillage** I don't know
Can agroforestry reduce pesticides use? ✓ **Yes** ☒ No I don't know

Introducing a three-year grassland period into cereal rotation will increase total crop production value but does it increase farmer income too?

- ✓ **Yes**
- ☒ No
- I don't know

How will input costs change when introducing legumes in grasslands?

- ✓ **Decrease**
- ☒ Stay at the same level
- ☒ Increase
- I don't know

How does your annual work time change if you go from conventional tillage to no tillage?

- ✓ **Decrease**
- ☒ Stay at the same level
- ☒ Increase
- I don't know

Can biocontrol products pose health risks to their users?

- ✓ **Yes**
- ☒ No
- I don't know

Name 3 benefits of intercropping

[open-ended question]

Accepted responses:

- ✓ Increased overall yield (or increase Land Equivalent Ratio)
- ✓ Enhanced biodiversity
- ✓ Reduced needs for synthetic fertilizer
- ✓ Reduced pest and disease pressure, leading to decreased pesticide use
- ✓ Diversification of farm outputs
- ✓ Mutual benefits between crops (e.g., legumes fix nitrogen, while cereals provide structural support)

Name 3 benefits of cover crops

[open-ended question]

Accepted responses:

- ✓ Reduces soil erosion
- ✓ Prevents nutrient leaching
- ✓ Reduces the need for nitrogen fertilizers
- ✓ Stores Carbon in the soils
- ✓ Decreases weed pressure
- ✓ Might break pest and/or disease cycles
- ✓ Provides forage for livestock
- ✓ Supports soil (micro)biology
- ✓ Promotes earthworm activity

Animal production

The feeding system does not influence greenhouse gas emissions. ✓ **I disagree** ☒ I agree I don't know
Cow housing can increase milk yield. ✓ **Yes** ☒ No I don't know
What is/are the effect(s) of using local cow breeds? ☒ Higher yield ✓ **Lower yield** ✓ **Resilience** ☒ Intensification ☒ Higher veterinary costs I don't know
Which practice(s) can improve animal welfare? ✓ **Pasture grazing** ✓ **Once a day milking** ✓ **Antibiotic treatments** ☒ Reduced age at first calving ☒ Increased cow density on the farm ☒ Nome of them I don't know
General
The implantation of hedges will increase biodiversity, but at the expense of productivity loss. ✓ **True** ☒ False I don't know
Agroecological practices tend to increase labor costs. ✓ **Yes** ☒ No I don't know
How will pollinators influence wheat yield? ☒ Decrease ✓ **Stay at the same level** ☒ Increase I don't know
How can agroforestry practices improve crop and animal productivity? (at least 3 elements) [open-ended question] *Accepted responses:* Crop Production: ✓ Increases biodiversity ✓ Promotes natural enemies of pests ✓ Reduces pest and disease pressure ✓ Enhances water

- ✓ Decreases soil erosion
- ✓ Boosts overall productivity and income
- ✓ Contributes to organic matter (e.g., leaf litter)

Animal Production:

- ✓ Improves animal welfare through the provision of shade
- ✓ Offers alternative sources of forage
- ✓ Enhances productivity and economic returns

How can we benefit from low-production landraces and cultivars in agroecological systems? (at least 3 elements)

[open-ended question]

Accepted responses:

Crop Production:

- ✓ Enhances resilience to environmental stresses
- ✓ Provides more resistant cultivars for pest and disease management
- ✓ Supports specific markets with high-quality products, adding economic value
- ✓ Increases biodiversity within the system

Animal Production:

- ✓ Dual-purpose breeds (e.g., for both meat and milk) provide multifunctional benefits
- ✓ Enhances resilience and sustainability in production systems
- ✓ Provides more resistant landraces for pest and disease management

Does a diversified agroecosystem tend to be more stable? (Give arguments against and for this proposition (at least 3 elements)

[open-ended question]

Accepted responses:

FOR:

- ✓ Increased resilience to emerging diseases and pest outbreaks due to greater biodiversity
- ✓ Reduced dependence on external inputs (e.g., fuel, fertilizers, soybean meal), lowering vulnerability to price fluctuations
- ✓ Enhanced soil conservation, improving plant nutrition and drought resistance
- ✓ Diversified income streams from various sources
- ✓ Breaks pests and/or diseases cycles, lowering pressure on crop productivity
- ✓ Reduces weeds impacts, lowering pressure on crop productivity
- ✓ Lower labor peaks

AGAINST:

- ✓ No single model is universally applicable; localized adaptations are necessary
- ✓ Farmers require extensive expertise across multiple areas/crop management techniques, necessitating more technical knowledge
- ✓ Increased labor demands
- ✓ Higher initial investments in specific machinery or certain practices (e.g., agroforestry)

Name 3 constraints of organic fertilization (at least 3 elements)

[open-ended question]

- ✓ Potentially higher ammonia, N2O and CO2 emissions: Organic fertilizers can release significantly greater GHG emissions, contributing to air pollution.

- ✓ Complex management: It might be difficult to precisely perform the applications rates of organic fertilizers. The uncontrolled rates of mineralization can lead to mismatch between crop needs and nutrient releases, causing crop lower productivity and potential nitrogen leaching, which may result in eutrophication of water bodies.
- ✓ Pest and weeds contamination risks: Organic fertilizers, particularly those derived from non-composted animal manure, may introduce parasites, posing a risk to both crops and animals and increase the risk to contribute to weedbanks.
- ✓ Reduced palatability of grasslands for grazing animals: Organic fertilization may decrease the attractiveness of pastures, impacting grazing efficiency.
- ✓ Nitrogen starvation: When the carbon-to-nitrogen (C/N) ratio is too high, nitrogen is drawn from the soil by microorganisms communities to break down carbon, leading to nitrogen starvation for plants.

Feedback section:

The feedback questionnaire for the serious game SEGAE comprises the following statements. Upon completion of the survey by students, all statements were randomly reorganized, and categories of statements (e.g., Concentration) were not provided.

Give your opinion about the following statements	**Strongly disagree**	**Disagree**	**Agree**	**Strongly agree**
Concentration				
The game provides content that stimulates my attention.				
I am not distracted from the tasks that the player should concentrate on.				
Generally speaking, I can remain concentrated during the game.				
I become unaware of my surroundings while playing the game.				
The workload in the game is adequate.				
Feedback				
Cooperation between players is an appropriate way to receive feedback.				
I have received immediate feedback on my actions from the indicators (income, sustainability, etc.).				
Challenge				
I enjoy the game without feeling bored or anxious.				
The more I play the game, the more my skills improve.				
Teachers provide new challenges with an appropriate timing.				
Autonomy				
I feel that I can use strategies freely.				

I feel a sense of control over the game.				
Immersion				
I forget about time passing by while playing the game.				
I experience an altered sense of time.				
I can become involved in the game.				
Social interaction				
I strongly collaborate with the other students.				
Cooperation during the game is helpful to learn.				
The game encourages social interactions between players (discussion about strategies, decisions, etc.).				
Knowledge acquisition				
The game increases my knowledge.				
I understand the basic ideas of the knowledge taught.				
I try to apply my knowledge in the game.				
The game motivates the player to integrate the agroecology knowledge taught.				
I want to know more about the knowledge taught.				
Clear Goal				
The overall game goals were presented clearly.				
I understand the learning goals through the game.				
The overall game goals were presented at the beginning of the game.				
Additional				
I think that the game was easy to use.				
I think that playing this game was useful in improving my understanding of agroecology.				
For me working in a group was useful to improve my understanding.				
I enjoyed playing this game.				
For me this game and the theoretical lecture are complementary.				
I will advise students from my university to play this simulation game.				

Give your opinion about the following questions	[Open-ended questions]
What are the 2 strengths of the theoretical session?	

What are the 2 weaknesses of the theoretical session?	
What are the 2 strengths of the Serious Game that you have played?	
What are the 2 weaknesses of the Serious Game that you have played?	

9.2 Appendix 2: removal of statements

1. I would like to use this kind of game more often in my university classes.

2. I would have preferred to use the given time to read an educational book about agroecology rather than playing the game.

3. I needed some time to get familiar with the game.

4. I learn about agroecology, as a scientific discipline.

5. I learn about agroecology, as an interactive set of agricultural practices.

6. I feel cooperative toward the other students.

7. I think that without the teacher's lectures I would not have been able to learn as much content as I did.

8. I learn about agroecology, as a societal movement.

9. I understand the interactions among the actors in the agricultural sector.

10. I learn about an integrated vision of agriculture.

11. I know a lot of things about other European countries.

12. I am aware of the day-to-day life of farms in Europe.

9.3 Appendix 3: Previous results of a 5-day seminar

Table Appendix 3. 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 **

Note: *** $p < 0.001$; ** $p < 0.01$; * $p < 0.05$.

Source: Table A1 of De Graeuwe et al. (2020, p. 13)

10. Tables

11. Figures