Using Systems Thinking, System Dynamics and Simulation for Sustainability Education: A Study Design

Caroline Brennan*, Owen Molloy and Jim Duggan

School of Computer Science, National University of Ireland, Galway

*Correspondence: caroline.brennan@nuigalway.ie

Keywords: Education for Sustainable Development, Systems Thinking, System Dynamics, simulation

8th June 2020

Abstract

Education for Sustainable Development (ESD) is vital to the success of the United Nation's Sustainable Development Goals (SDGs). There is broad consensus that it requires active, participative and experiential learning methods, underpinned by systemic thinking. Goals for ESD include better critical thinking and an improved ability to analyse complex problems, to make judgements and decisions and to act accordingly. And yet, ESD has so far proved difficult to implement. One reason for this is that systemic understanding is required to comprehend the intricate interplay of causal connections typically underlying sustainability issues.

This research describes an experimental approach to investigate whether ESD can be shown to benefit from Systems Thinking and System Dynamics simulation. It attempts to consolidate and build on the body of knowledge that has accumulated since the 1970s around modelling and simulation of complex human-environmental systems, and the use of such models to teach Systems Thinking and sustainability skills.

This paper describes a new study design that builds on a recent pilot study undertaken in the field of Ocean Literacy education. The pilot study, centred on the problem of Sustainable Coastal Tourism, found promising results from combining a Systems Thinking approach with hands-on interactive simulation. This new study is designed to address the broader concept of teaching sustainability. It centres on the problem of Sustainable Deer Herd Management, one that has often been modelled in the System Dynamics field and has the benefit of being relatively simple systemically, with clearly definable sustainability goals. This research is designed to investigate whether the application of Systems Thinking to a well-defined sustainability problem enhances the learner's practical understanding, whether interacting with model simulations also enhances it, whether applying both has the greatest effect, and whether they increase the transfer of skills to another sustainability problem in a different field, that has a similar systemic structure (Sustainable Fisheries Management).

1. Introduction

Major global sustainability challenges include food security, climate change, pollution, water and energy management, biodiversity, marine health, human health and poverty. All are complex issues requiring a systemic approach. All are serious and urgent problems.

The UN has been instrumental in developing the concept of sustainability and sustainable development. It founded The World Commission on Environment and Development (WCED) in 1980 which was responsible for the influential 1987 Brundtland Report (World Commission on Environment and Development, 1987). The definition of sustainability in the Brundtland Report is that most frequently quoted, namely that 'Sustainable development is development that meets the needs of the present without compromising the ability of future generations to meet their own needs.' This combines traditional goals for the UN - fighting poverty and supporting developing countries – with consideration of the need for limits to growth, environmental protection and generational justice.

The UN has also led efforts to formulate concrete targets for action towards sustainability. In 2000 the UN defined the 8 Millennium Development Goals (MDGs) for 2015, of which goal 7 was 'To ensure environmental sustainability'. All 191 United Nations member states, and at least 22 international organizations, committed to these goals. The UN adopted the Decade of Education for Sustainable Development (DESD) from 2005 to 2014. The MDGs were further developed in the 17 Sustainable Development Goals (SDGs), set in 2015 and to be achieved by 2030, and again adopted by all United Nations member states, now 193 in number.

Education for Sustainable Development (ESD) is explicitly recognized in the SDGs as part of Target 4.7 of the SDG on education.

> 'To create a more sustainable world and to engage with issues related to sustainability as described in the Sustainable Development Goals (SDGs), individuals must become sustainability change-makers. They require the knowledge, skills, values and attitudes that empower them to contribute to sustainable development. Education is thus crucial for the achievement of sustainable development …' (Rieckmann et al., 2017: 63).

The goal, as stated above, applies to all citizens. The Council of the European Union sees ESD as 'essential for the achievement of a sustainable society and is therefore desirable at all levels of formal education and training, as well as in non-formal and informal learning'[1]. Thus ESD is seen as a form of lifelong learning.

There is broad consensus in the field of Sustainability Education that it requires active, participative and experiential learning methods, underpinned by systemic thinking and leading to better critical thinking, analysis and ability to make judgements and decisions and to act. Progress, discussions and findings can be found in various UNESCO reports (Nolan, 2012), 'sourcebooks' (United Nations Educational and Scientific and Cultural Organization, 2012) and 'toolkits' (McKeown et al., 2002)[2]. The latter two include many resources including teaching techniques and exercises for ESD.

Regarding ESD in schools, incorporating it into the curriculum is a challenging task. Should it be another 'add-on' subject? Can it be taught like a conventional academic subject, or will it require reorientation of the whole curriculum? (Michelsen and Wells, 2017: 41). How can the values

[1] Council of the European Union. Council conclusions on education for sustainable development. Viewed 5 September 2019. <https://www.consilium.europa.eu/uedocs/cms_data/docs/pressdata/en/educ/117855.pdf>
[2] Available online. Viewed 9 September 2019. < http://www.esdtoolkit.org/default.htm>

underlying efforts towards sustainability be engendered effectively and without indoctrination (Frisk and Larson, 2011: 14)? How can the well-known limitations in human cognitive ability to reason about complex systems (Sterman, 2000: 599) be overcome? These complex reasoning skills must be taught, they are not inherent.

2. Problem Statement

There have been problems with the implementation of ESD, and in her review article, Maria Hofman-Bergholm (Hofman-Bergholm, 2018b) explores possible reasons. She cites factors such as the complexity and lack of clarity in both the terms sustainability and Sustainability Education, a lack of consensus as to the educational content of ESD and its interdisciplinary nature, difficulty for people to leave behind the advantages of unsustainable lifestyles, defensive psychological reactions such as denial and apathy, and low levels of understanding of Systems Thinking in teachers. She draws out the commonalities between the literatures on Sustainability Education and Systems Thinking, in that both require critical thinking, real-world complex problem-solving skills and action. She finds that systemic understanding and Systems Thinking are required to comprehend the intricate connections in sustainable development (Hofman-Bergholm, 2018a: 27).

3. Literature Review

3.1 Defining Sustainability

The most succinct definition of sustainability is simply the capacity to endure or continue. The term originated in the 1800s in the context of managed timber harvesting. In 1804, Georg Hartig described sustainability as utilising forests to the greatest possible extent, but in such a way that future generations will have as much benefit as living generations. Sustainability seeks new ways for human societies and economies to grow without destroying or over-exploiting the environment or the ecosystems on which those societies depend. It involves preserving or maintaining resources over the long term, rather than exhausting them quickly to meet short-term goals. Purvis et al. provide a useful review of the origin and meaning of terms such as 'sustainability' and 'sustainable development', as well as the 'three pillars' conception of sustainability, all of which are often unclear and lack theoretical clarity (Purvis et al., 2018).

Purvis points out that it is possible to take a systems view of the concept of sustainability, in which the three pillars of economy, society and environment represent three systems with competing goals (Purvis et al., 2018: 689). The interactions of these systems must be managed to meet each system goal and the overall goal of sustainability. This involves balancing the systems, setting limits and determining trade-offs. An understanding of sustainability, seen in this way, requires systems literacy. Sustainability, also, is a form of literacy – a set of skills and a fundamental understanding that can be transferred from one problem context to another.

3.2 Systems Thinking, Sustainability and Education

System dynamics modelling was first used to address sustainability in Jay Forrester's 'Word3' model, which formed the basis for the influential book, 'Limits to Growth' (Meadows et al., 1972). There have been many subsequent examples, from environmental models (Ford, 2010) (Bossel, 2007), models for water supply, waste management, air quality, land use (Stave, 2010), fisheries (Martins et al., 2015) (Dudley, 2008), climate change (Sterman et al., 2012), models of social and economic development (Saeed, 2019), reindeer pasture management (Moxnes, 2004) and many more.

The System Dynamics community has seen education as a priority for a long time. The Creative Learning Exchange[3] was founded in 1991 by Jay Forrester 'to encourage the development of systems citizens who use systems thinking and system dynamics to meet the interconnected challenges that face them at personal, community, and global levels'. They provide resources representing experience of teaching Systems Thinking and System Dynamics for real-world problem-solving to school children over nearly thirty years. Diana Fisher has presented a justification for bringing systems concepts into education and an overview of teaching approaches developed and matured over many years (Fisher, 2011).

System Dynamics simulation has frequently been explored for the purpose of environmental education, both for tackling specific problems and in general for its effectiveness in supporting such learning. There are flight simulators for sustainability (Sterman, 2014) and simulation-based learning environments to teach sustainability (Deegan et al., 2014) (Pallant and Lee, 2017). System Dynamics models and simulations have also been used to try to understand why renewable resources are so often over-utilised; this is because of faulty reasoning and systematic misperceptions of the dynamics of complex systems (Moxnes, 2004). Simulation has been shown to improve understanding and performance in a natural resource management task (Kopainsky and Sawicka, 2011). Simulation can serve effectively as the 'problem' in problem-based learning (Anderson and Lawton, 2004), and as an experiential activity it can both increase retention and have a stronger influence on behaviour than declarative learning (Frisk and Larson, 2011: 11).

For an overview of some current initiatives using Systems Thinking for Sustainability Education see Soderquist and Overakker (Soderquist and Overakker, 2010). The authors describe common human deficiencies in building effective mental models of complex environmental problems, and how Systems Thinking is essential for improving these mental models and addressing what they call the adaptive challenges we face. Cavana and Forgie also describe a number of well-established systems education programs and review teaching approaches for Sustainability Education (Cavana and Forgie, 2018). They explore the strong links between systems approaches and sustainability goals, illustrating that the two are so entwined as to be inseparable.

3.3 Sustainability Education

Sustainability education, like sustainability science, is an emerging field. It seeks to address the considerable challenge of training learners not only to solve or understand existing complex problems but to be equipped to solve future problems as they emerge. There have been widespread and urgent calls for innovative sustainability pedagogies (Hardin et al., 2016: 58).

O'Flaherty and Liddy provide a useful summary of approaches so far taken to ESD, evidence of their impact on learners, and methodological and pedagogical questions that remain open (O'Flaherty and Liddy, 2018). Approaches include blended learning, drama, simulation exercises, multi-media, problem-based learning and discussion forums.

Frisk and Larson position Sustainability Education within the broader areas of education for transformative action and behavioural change research. Sustainability Education will only be effective if it combines several forms of knowledge (declarative, procedural, effectiveness and social), and incorporates Systems Thinking, long-term thinking, collaboration and engagement, and action-orientation (Frisk and Larson, 2011). Sustainability, they say, is fundamentally a call to action, and Sustainability Education therefore requires experiential, practical and flexible learning methods. Note

[3] http://www.clexchange.org/

that according to this view, the learning tool that provides the platform for this research, if it is to be effective, would need to be part of a carefully designed program that incorporated these dimensions.

'Sustainability education should enable students to analyse and solve sustainability problems' (Wiek et al., 2011: 204). This requires a particular set of interlinked and interdependent key competencies. Wiek et al. review the literature and provide a taxonomy of sustainability competencies. They define competence as a 'functionally linked complex of knowledge, skills and attitudes that enable successful task performance and problem solving', contrasting this with the prevalence of 'laundry lists'. (Wiek et al., 2011: 204). They identify the five key competencies as: systems-thinking competence, anticipatory competence, normative competence, strategic competence and interpersonal competence.

Faham et al. review a number of studies of sustainability competencies and group them into three main categories (Faham et al., 2017: 308):

1. **Understanding** the general concept of sustainability
2. **Skills** such as critical and creative thinking, Systems Thinking and interdisciplinary collaboration
3. **Attitudes** such as respect for present and future generations

Frisk and Larson (2011) propose four key competencies:

1. Systems Thinking and an understanding of interconnectedness
2. Stakeholder engagement and group collaboration
3. Long-term, foresighted thinking
4. Action-orientation and change-agent skills

The learning tool is designed to teach sustainability principles through Systems Thinking (1), long-term thinking (3), and provides hands-on action learning (4) via simulation and problem-based learning designed to nurture action. It could potentially be used in group learning contexts (2) although this is not part of the current research.

All the frameworks for Sustainability Education above feature Systems Thinking prominently, and normative and strategic competence, variously named. Frisk et al. emphasise action, although its importance is implicit in all of them.

Core competencies are general and transferable; for example, the ability to analyse a problem, arrive at a sustainable solution and take action are skills that can be applied to sustainability challenges in different fields. Sustainability competencies provide a reference framework for developing knowledge and skills and for evaluation of learning tools.

3.4 Pilot Study

The Ocean Literacy online learning tool[4] used Sustainable Coastal Tourism as the case study. Analysis of the causes and effects of unsustainable Coastal Tourism employed Systems Thinking concepts such as stocks and flows, causal loop diagrams, feedback loops, loop dominance, structure and behaviour, leverage points and systems archetypes ('overshoot and collapse' in particular). The term 'sustainability' was defined, and learners were given a practical task: to interact with a simulation to attempt to bring the system into a sustainable state by manipulating three key variables. Knowledge

---

[4] Available at <http://responseable.nuigalway.ie/st>, viewed 8 June 2020.

transfer was tested by questions inviting identification of other systems demonstrating the 'overshoot and collapse' dynamic behaviour pattern.

The pilot study was conducted in December 2018 at the National University of Ireland, Galway (Brennan et al., 2019). 15 adults participated in the study and effectiveness was evaluated using the results of pre- and post-survey questionnaires, facilitator observations and semi-structured interviews.

Respondents all indicated that the simulations helped them understand the dynamics of the system. The study used a framework of Ocean Literacy dimensions, comprising awareness, knowledge, attitude, communication, behaviour and activism. All dimensions increased, particularly intended behaviour and communication, as well as knowledge and attitude. These dimensions are predictors of behaviour change. Respondents scored well on the sustainability task and identifying systems with similar structure. These results provided motivation for further research.

3.5 Conceptual Approach to the Sustainability Learning Tool

Designed to support a teaching approach that combines case studies with simulation, the learning tool explores two specific sustainability problems to increase understanding of the issues and how to formulate sustainable solutions – deer herd management and sustainable fisheries. These are illustrated with historic cases of overshoot and collapse, namely the Kaibab deer herd collapse in the 1920s, and the Grand Banks cod fishery collapse in 1992. It is not a simulation game or flight simulator in the sense that learners are not asked to take the role of an actor in the scenario. The Systems Thinking and simulation elements in the learning tool offer the 'big picture' of the system as a whole and offer insights into its essential structure and dynamics. The emphasis is thus on systemic understanding and policy making.

The System Dynamics model used in the learning tool represents a sustainability challenge with well-defined guiding principles for finding solutions, namely the population dynamics of a deer herd. Given that the term 'sustainability' is so often used in a broad and imprecise way, the use of well-defined problems and a small model is deliberate – indeed, it has been shown that 'small models can yield accessible, insightful lessons for policy making' (Ghaffarzadegan et al., 2011).

The following key Systems Thinking concepts, tools and techniques were chosen from the literature (Kim, 1999) (Arnold and Wade, 2017) (Meadows, 2008) for their appropriateness as tools for analysis of the two sustainability problems under consideration:

- Feedback Loops
- Causal Loop Diagrams
- Behaviour Over Time graphs
- Stock and Flow Diagrams
- Identifying Common Patterns of Behaviour in Systems
- Identifying Leverage Points for Effective Change

The concept of system stability when in a state of dynamic equilibrium is included in the last point above. Delays are an important systems concept but not covered, owing to time limitations on learning tool session length.

Integrated into the tool are questions testing understanding of: sustainability in general and in context, calculations of stock changes over time, limits and carrying capacity, dynamics of the systems that cause unsustainability, and assessment of strategies for moving towards sustainability. The learning tool is designed to measure whether the use of Systems Thinking and simulation increases performance in these tests, and whether and to what extent sustainability skills gained from learning about the first problem are transferred to the second.

4. Research Questions & Methodology

4.1 Research Questions and Hypothesis

The work is designed to answer the following research questions, in the context of Sustainability Education:

RQ1: Does the application of Systems Thinking tools and techniques to a sustainability problem enhance the learner's practical understanding of sustainability?

RQ2: Does interacting with System Dynamics simulations representing the same sustainability problem enhance the learner's practical understanding of sustainability?

RQ3: Does adding both Systems Thinking and simulation result in higher sustainability task performance than Systems Thinking only, simulation only, or a non-systemic treatment?

RQ4: What effect do Systems Thinking and simulation have in increasing the transferability of skills from one sustainability problem to another with a similar systemic structure?

The hypothesis is:

The Systems Thinking (ST) and simulation group will register a higher performance in defined sustainability tasks than the ST-only treatment group, the simulation-only treatment group, and the control group.

4.2 Study Design

Since this is a study concerning comparison of educational outcomes, the design is drawn from established practices in the field of Social Sciences research. The investigation will be an experimental study using a combined repeated measures and two-by-two factorial design. The two factors are Systems Thinking and simulation (see Table 1). The study will aim to discover the main effects, i.e. the effect of each factor on the learning outcome, and the interaction effect, or the combined effect, of both.

Table 1 Two-by-two factorial design

Factors	No Systems Thinking	Systems Thinking
No Simulation	Control Group	Group 1
Simulation	Group 2	Group 3

Participants will be randomly assigned to one of four groups: a control group, a Systems Thinking only group (group 1), a simulation only group (group 2), and a Systems Thinking and simulation group (group 3). The design uses repeated measures in the form of quizzes that test sustainability skills and knowledge, repeated for comparison after different treatments of the deer problem (see Figure 1).

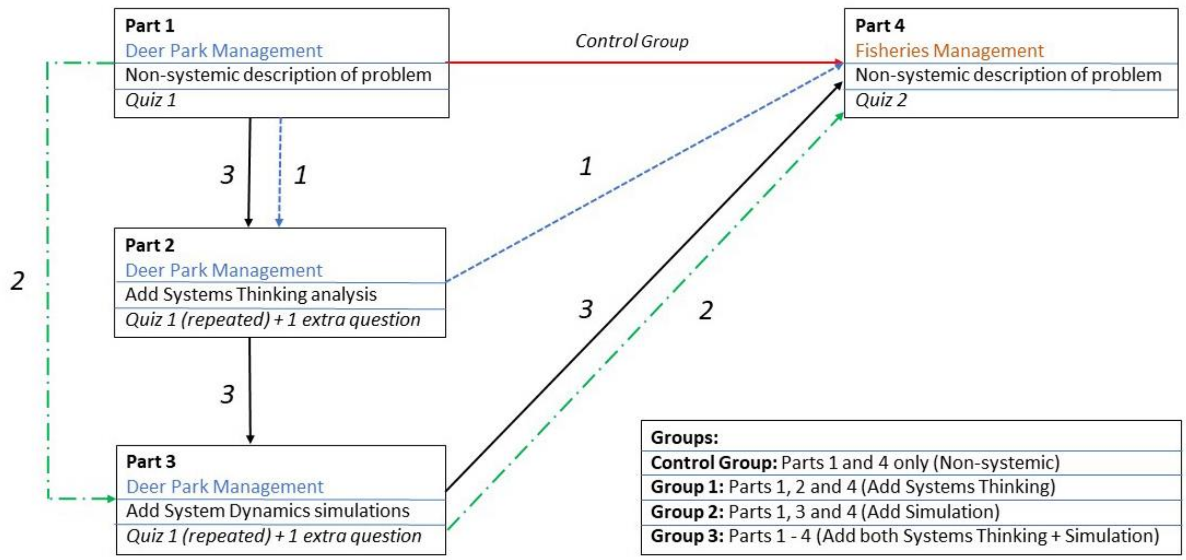

Figure 1 Elements and sequence of the online learning tool presented to the four groups of participants

The control group will receive the non-systemic treatment only for each of the two sustainability problems. This consists of a description of each problem, using facts, figures, text and videos only, together with definitions of terms such as sustainability and carrying capacity (see Figures 2 and 5 for sample pages). Group 1 will also work through Part 2, which provides a Systems Thinking analysis of the deer problem (see Figure 3). Group 2 will work through Part 3, which adds interactive simulation to explore the deer problem (see Figure 4). Finally, Group 3 will receive the full treatment, i.e. Systems Thinking plus simulation treatments.

Each part is followed by a short survey or quiz. Each of the deer quizzes will ask similar questions (repeated measures), and the degree of confidence (or extent of guessing) when answering the questions. The quizzes for parts 2 and 3 will also ask how useful the Systems Thinking or simulation elements were found to be. The fisheries quiz, after part 4, is designed to test similar concepts to the deer quiz, but in the context of fisheries.

Part 1 survey results will serve as the baseline for participants' understanding about sustainability for the deer park, after exposure to the basic information only, without systemic interpretation.

For groups 1 and 3, a comparison of Part 1 and Part 2 survey results will test the main effect of adding Systems Thinking to the learning tool, by comparing the quality of answers to questions and levels of confidence (RQ1).

Similarly, for group 2, a comparison of Part 1 and Part 3 survey results will test the main effect of adding System Dynamics simulation to the learning tool (RQ2).

Similarly, for group 3, a comparison of Part 1 and Part 3 survey results will test the interaction effect of adding both Systems Thinking and simulation to the learning tool, in that order (RQ3).

The control group will work through Part 1 and then go directly to Part 4, and so will not have had exposure to the Systems Thinking and System Dynamics simulation elements in Parts 2 and 3. Performance of the four groups in Part 4 survey results will be compared. Better performance for groups 1, 2 and 3 in Part 4 will indicate an increase in transferrable skills after exposure to Systems Thinking alone, simulation alone, or both (RQ4). The main effects and interaction effects of the two factors on transferability will be tested, as per the hypothesis.

4.3 Content of the Sustainability Learning Tool

The primary scenario represents deer herd management in a bounded area of land. It can be used to illustrate a number of useful concepts in sustainability and ecological systems management such as population dynamics, carrying capacity of the environment, the effect of predators or the lack of them, the limits imposed by dependence on resources such as food, and looking for ways to bring a system to a state of equilibrium in order to find sustainable solutions. The historic case of overshoot and collapse of the Kaibab deer population is used to illustrate the problem[5]. After removal of predators and a hunting ban, the deer population increased sharply from 4,000 in 1905 and peaked at about 100,000 deer in 1924. Shortly after that time, the deer population began to decline sharply. By the mid-1920s, many deer were starving to death. The range itself was damaged, and its carrying capacity was greatly reduced. These days the deer population is carefully managed with regulations on management of predators and hunting designed to keep the number of deer near the carrying capacity of the range.

The deer model is adapted slightly from the original model of deer population as documented in Breierova (Breierova, 1997), which was prepared for the MIT System Dynamics in Education Project under the supervision of Jay Forrester.

The second scenario represents fisheries management, which can suffer a similar pattern of overshoot and collapse. The Grand Banks cod fishery collapse of 1992 is used to illustrate the problem. The non-systemic treatment does not require a model.

4.3.1. Specific Learning Objectives

The two simplified sustainability problem scenarios have a similar systemic structure. Both concern sustainable management of natural resources, where there is a need to place limits on their use in order to safeguard supply into the future. Both have the potential for overshoot and collapse because of the systemic structure (an exponentially growing stock that depends on a second, renewable, stock, delays in response to overuse of resources, and erodable limits). The dynamics of the two systems have key similarities and also some differences. The key similarities will be used to test transfer of knowledge from one problem to the other.

Learning objectives are listed in tables 2 and 3 below, grouped according to the simple framework of key sustainability competency categories described by Faham (Faham et al., 2017).

Table 2: Sustainable management of a deer herd	
Scenario*: To manage a deer herd in a bounded area (a deer park), for conservation and recreational purposes. There are no predators and hunting is banned. Facts given: initial number of deer and units of vegetation, normal deer birth and death rates, vegetation regeneration rate, and normal consumption of vegetation per deer per year.	
Competency category	**Topics**
Understanding	Sustainability in general, and what it means in this scenario.
	Decide which population graphs show sustainable growth in deer population.
	Overgrazing – what it is and how it can undermine the herd.
	Case study: the Kaibab deer population in the 1920s.
	Maximum capacity of the deer park.

[5] A video of Donella Meadows' lecture on the Kaibab deer, given at Dartmouth College in the 1970s, is available at http://donellameadows.org/donella-meadows-legacy/envisioning-a-sustainable-world/

	Carrying capacity of the deer park.
	Maximum sustainable herd size.
	Renewable resources and application of Herman Daly's rule, renewable resources must be used no faster than the rate at which they regenerate.
	Objectives of management are to work out the maximum sustainable herd size and make sure the population does not exceed it.
	Judge whether the herd is sustainable given the figures*.
	Choose from a selection of management policies those likely to be most effective in achieving the goal of sustainability.
	Decide on the main reasons why the Kaibab deer population was not sustainable.
	Decide, from looking at graphs that show carrying capacity, when overgrazing began.
Skills	Calculate growth in deer population over time, taking into account birth and death rates.
	Calculate growth in vegetation over time, and loss through consumption by deer.
	Calculate units of vegetation eaten by deer population per year.
	Calculate maximum capacity of deer park (number of deer).
	Calculate how long it will take the deer population to reach the maximum capacity of the deer park.
	Calculate (or estimate) the carrying capacity of the deer park (number of deer).
Attitudes (implicit)	It is undesirable to allow the deer population to grow unchecked to the extent that they overconsume the natural resource that they depend on, leading to suffering and collapse of the deer population or unnecessary culling.
	Good management results in, and requires, a stable system.
	Long-term thinking.

Table 3: Sustainable fisheries management	
Scenario**: To manage a fishery in order to maintain the supply of fish in the long term. Initial fish stock figures and shipping vessels are given, together with fish population growth rates, estimated growth rate for numbers of fishing vessels, and normal catch rate per vessel per year.	
Competency category	**Topics**
Understanding	What sustainability means in this scenario.
	Decide which fish catch graphs show sustainable growth.
	Overfishing – what it is and how it can undermine the fish stocks, and the fishing industry that depends on it.
	Case study: the Grand Banks cod fishery collapse in 1992.
	Maximum sustainable yield.
	Renewable resources and application of Herman Daly's rule, renewable resources must be used no faster than the rate at which they regenerate.
	Objectives of management are to work out the maximum sustainable yield and make sure the fishing catch does not exceed it.
	Judge whether the fishery is sustainable given the figures**.
	Choose from a selection of management policies those likely to be most effective in achieving the goal of sustainability.
	Decide on the main reasons why the Grand Banks cod catch rates were not sustainable.
	Decide, from looking at graphs that show maximum sustainable yield, when overfishing begins.
Skills	Calculate growth in fish population over time.

	Calculate growth in shipping vessels over time.
	Calculate (or estimate) the maximum sustainable yield (number of fish).
	Calculate the number of shipping vessels that could operate within the maximum sustainable yield limit.
	Calculate how long it will take before the catch reaches the maximum sustainable yield.
Attitudes (implicit)	It is undesirable to allow the fishing fleet and/or annual catch to grow unchecked to the extent that they overconsume the natural resource that they depend on, leading to possible collapse of the fish population and the industry that depends on it.
	Good management results in, and requires, a stable system.
	Long-term thinking.

Table 4 below outlines the Systems Thinking and simulation contributions added in Parts 2 and 3 of the tool for the deer park scenario only.

Table 4: Addition of Systems Thinking and Simulation to Analysis of Deer Park Scenario	
Learning tool part	Concepts and techniques used in context to analyse the deer park problem
Part 2: Systems Thinking	• Feedback Loops, including the power of exponential growth • Causal Loop Diagrams • Behaviour Over Time graphs • Stock and Flow Diagrams • Common System Patterns (Overshoot and Collapse / Limits to Growth) • Leverage Points (including Dynamic Equilibrium) • Policy Evaluation
Part 3: System Dynamics Simulation	• Exercises to demonstrate deer population and vegetation growth rates over time • Demonstrate Overshoot and Collapse pattern • Exercises to stabilise deer stock (several attempts using different approaches, demonstrating the importance of birth and death rates) • Task: Find maximum sustainable herd size (carrying capacity of park)

All participants will answer survey questions testing learning objectives in Tables 2 and 3. Groups 1, 2 and 3 will answer them more than once. Participants are told they can give the same or different answers.

4.4 Data collection

The following data will be collected from participants:

- Basic information such as age, email, gender, degree subject and/or occupation, and prior knowledge of sustainability.
- Survey (quiz) answers: data collected will be a mix of quantitative and qualitative data, for example, numeric answers to questions about population growth, and textual answers to questions about the meaning of specific terms such as sustainability. The surveys will also attempt to measure self-reported confidence in the answers at each stage, to see whether confidence grows after Systems Thinking and simulation are introduced. The data will be analysed to test whether the quality of answers improved, whether participants' confidence

grew (leading to less self-reported guessing), and whether an increase in confidence correlates with better performance.

- Simulation data: variable values set by participants will be stored and can then be compared with answers given to relevant survey questions.
- Participants will be invited to participate in semi-structured interviews or focus groups after interaction with the learning tool.

4.5 Platform

Stella Architect interface with authentication and data collection, integrated with SurveyMonkey surveys, and published to the ISEE Exchange. Desktop, laptop or tablets are recommended, not mobile devices.

5. Next Steps

- Pilot testing is currently in progress to test and refine the contents and design of the learning tool, survey questions and data collected.
- Due to current Covid-19 restrictions, the training has been designed for online unsupervised individual interaction, and voluntary follow-up with remote interviews and/or focus groups.
- Undergraduates and/or postgraduates in various disciplines at the National University of Ireland Galway will be recruited for the study, including trainee secondary school teachers. A two-by-two factorial design requires a minimum of 20 participants per group, so at least 80 subjects will be recruited (Bhattacherjee, 2012: 87).

6. Bibliography

Anderson, P. H. & Lawton, L. Simulation exercises and problem based learning: Is there a fit? Developments in Business Simulation and Experiential Learning: Proceedings of the Annual ABSEL conference, 2004.

Arnold, R. D. & Wade, J. P. 2017. A Complete Set of Systems Thinking Skills. *INSIGHT,* 20**,** 9-17.

Bhattacherjee, A. 2012. Social Science Research: Principles, Methods, and Practices. Scholar Commons.

Bossel, H. 2007. *System Zoo 2 Simulation Models: Climate, Ecosystems, Resources*, BoD–Books on Demand.

Breierova, L. 1997. Generic structures: Overshoot and collapse. *Cambridge, Massachusetts, USA: Massachusetts Institute of Technology,[online],* *http://sysdyn.clexchange.org/sdep/Roadmaps/RM9/D-4480.pdf*.

Brennan, C., Ashley, M. & Molloy, O. 2019. A System Dynamics Approach to Increasing Ocean Literacy. *Frontiers in Marine Science,* 6.

Cavana, R. Y. & Forgie, V. E. 2018. Overview and Insights from 'Systems Education for a Sustainable Planet'. *Systems,* 6**,** 5.

Deegan, M., Stave, K., Macdonald, R., Andersen, D., Ku, M. & Rich, E. 2014. Simulation-Based Learning Environments to Teach Complexity: The Missing Link in Teaching Sustainable Public Management. *Systems,* 2**,** 217.

Dudley, R. G. 2008. A basis for understanding fishery management dynamics. *System Dynamics Review,* 24**,** 1-29.

Faham, E., Rezvanfar, A., Movahed Mohammadi, S. H. & Rajabi Nohooji, M. 2017. Using system dynamics to develop education for sustainable development in higher education with the emphasis on the sustainability competencies of students. *Technological Forecasting & Social Change,* 123**,** 307-326.

Fisher, D. M. 2011. "Everybody thinking differently": K–12 is a leverage point. *System Dynamics Review,* 27**,** 394-411.

Ford, A. 2010. *Modeling the environment,* Washington, DC, Washington, DC : Island Press.

Frisk, E. & Larson, K. L. 2011. Educating for sustainability: Competencies & practices for transformative action. *Journal of Sustainability Education,* 2**,** 1-20.

Ghaffarzadegan, N., Lyneis, J. & Richardson, G. P. 2011. How small system dynamics models can help the public policy process. *System Dynamics Review,* 27**,** 22-44.

Hardin, R., Bhargava, A., Bothner, C., Browne, K., Kusano, S., Golrokhian, A., Wright, M., Zeng, P. Z. & Agrawal, A. 2016. Towards a revolution in sustainability education: Vision, architecture, and assessment in a case-based approach. *World Development Perspectives,* 1**,** 58-63.

Hofman-Bergholm, M. 2018a. Changes in Thoughts and Actions as Requirements for a Sustainable Future: A Review of Recent Research on the Finnish Educational System and Sustainable Development. *Journal of Teacher Education for Sustainability,* 20**,** 19-30.

Hofman-Bergholm, M. 2018b. Could Education for Sustainable Development Benefit from a Systems Thinking Approach? *Systems,* 6.

Kim, D. H. 1999. *Introduction to systems thinking*, Pegasus Communications Waltham, MA.

Kopainsky, B. & Sawicka, A. 2011. Simulator-supported descriptions of complex dynamic problems: experimental results on task performance and system understanding. *System Dynamics Review,* 27**,** 142-172.

Martins, J. H., Camanho, A. S., Oliveira, M. M. & Gaspar, M. B. 2015. A system dynamics model to support the management of artisanal dredge fisheries in the south coast of Portugal. *International Transactions in Operational Research,* 22**,** 611-634.

Mckeown, R., Hopkins, C. A., Rizi, R. & Chrystalbridge, M. 2002. *Education for sustainable development toolkit*, Energy, Environment and Resources Center, University of Tennessee Knoxville.

Meadows, D. H. 2008. *Thinking in Systems: A Primer*, Chelsea Green Publishing.

Meadows, D. H., Meadows, D. L., Randers, J. & Behrens, W. W. 1972. *The Limits to Growth: a Report for the Club of Rome's Project on the Predicament of Mankind,* New York, Universe Books.
Michelsen, G. & Wells, P. J. 2017. *A Decade of progress on education for sustainable development: reflections from the UNESCO Chairs Programme*, UNESCO Publishing.
Moxnes, E. 2004. Misperceptions of basic dynamics: the case of renewable resource management. *System dynamics review.,* 20**,** 139-162.
Nolan, C. 2012. *Shaping the education of tomorrow: 2012 report on the UN decade of education for sustainable development, abridged*, UNESCO.
O'flaherty, J. & Liddy, M. 2018. The impact of development education and education for sustainable development interventions: a synthesis of the research. *Environmental Education Research,* 24**,** 1031-1049.
Pallant, A. & Lee, H.-S. 2017. Teaching Sustainability Through System Dynamics: Exploring Stocks and Flows Embedded in Dynamic Computer Models of an Agricultural Land Management System. *Journal of Geoscience Education,* 65**,** 146-157.
Purvis, B., Mao, Y. & Robinson, D. 2018. Three pillars of sustainability: in search of conceptual origins. *Sustainability Science,* 14**,** 681-695.
Rieckmann, M., Mindt, L. & Gardiner, S. 2017. *Education for Sustainable Development Goals. Learning Objectives*, UNESCO.
Saeed, K. 2019. *Towards sustainable development: Essays on system analysis of national policy*, Routledge.
Soderquist, C. & Overakker, S. 2010. Education for sustainable development: a systems thinking approach. *Global Environmental Research,* 14**,** 193-202.
Stave, K. 2010. Participatory system dynamics modeling for sustainable environmental management: Observations from four cases. *Sustainability,* 2**,** 2762-2784.
Sterman, J. 2000. *Business dynamics : systems thinking and modeling for a complex world,* Boston, Boston : Irwin/McGraw-Hill.
Sterman, J. 2014. Interactive web-based simulations for strategy and sustainability: The MIT Sloan LearningEdge management flight simulators, Part I. *System Dynamics Review,* 30**,** 89-121.
Sterman, J., Fiddaman, T., Franck, T., Jones, A., Mccauley, S., Rice, P., Sawin, E. & Siegel, L. 2012. Climate interactive: the C-ROADS climate policy model. *System Dynamics Review,* 28**,** 295-305.
United Nations Educational & Scientific and Cultural Organization 2012. The education for sustainable development sourcebook. UNESCO Paris.
Wiek, A., Withycombe, L. & Redman, C. L. 2011. Key competencies in sustainability: a reference framework for academic program development. *Sustainability science,* 6**,** 203-218.
World Commission on Environment and Development 1987. *Our common future*, Oxford University Press.

7. Appendix

Sample Screenshots from the Learning Tool

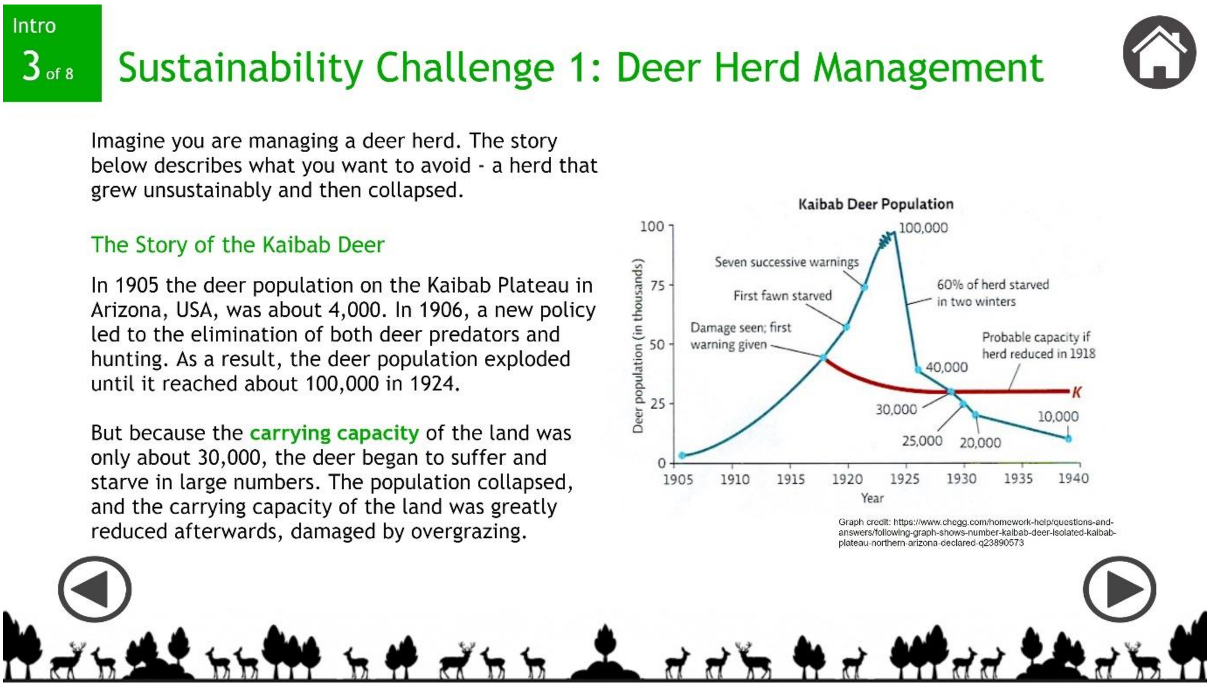

Figure 2 Sample screenshot of Part I (Non-systemic description of the deer park management problem)

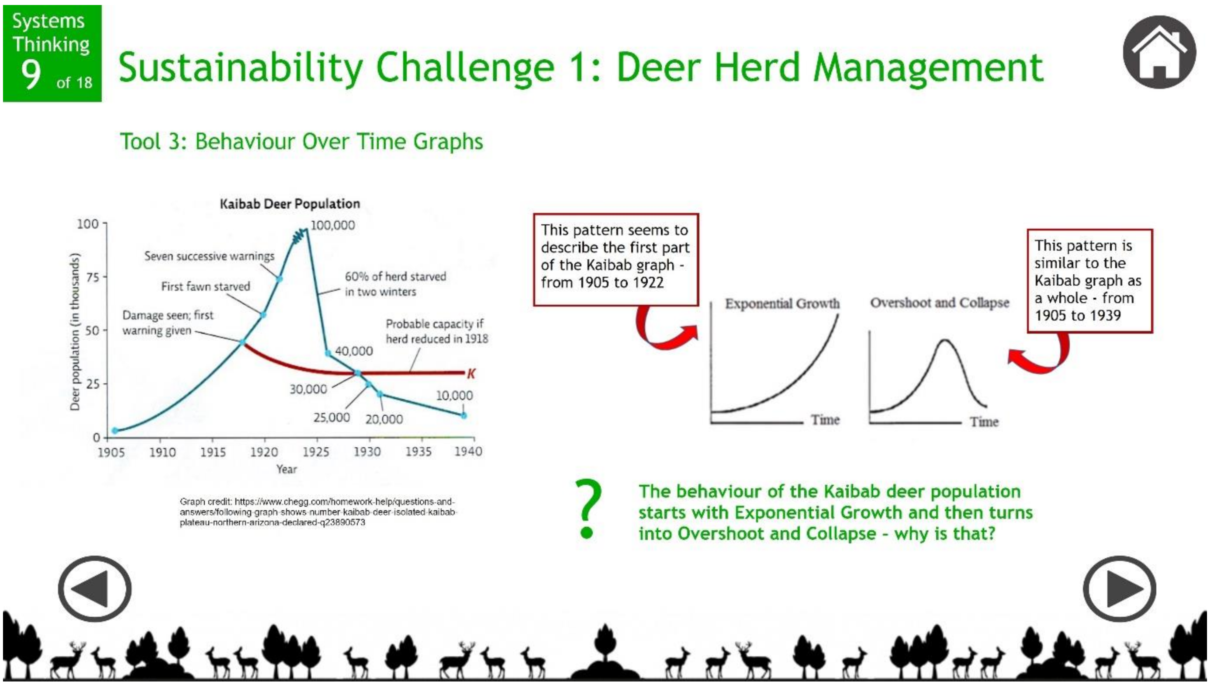

Figure 3 Sample screenshot of Part II (Systems Thinking analysis of deer park management problem)

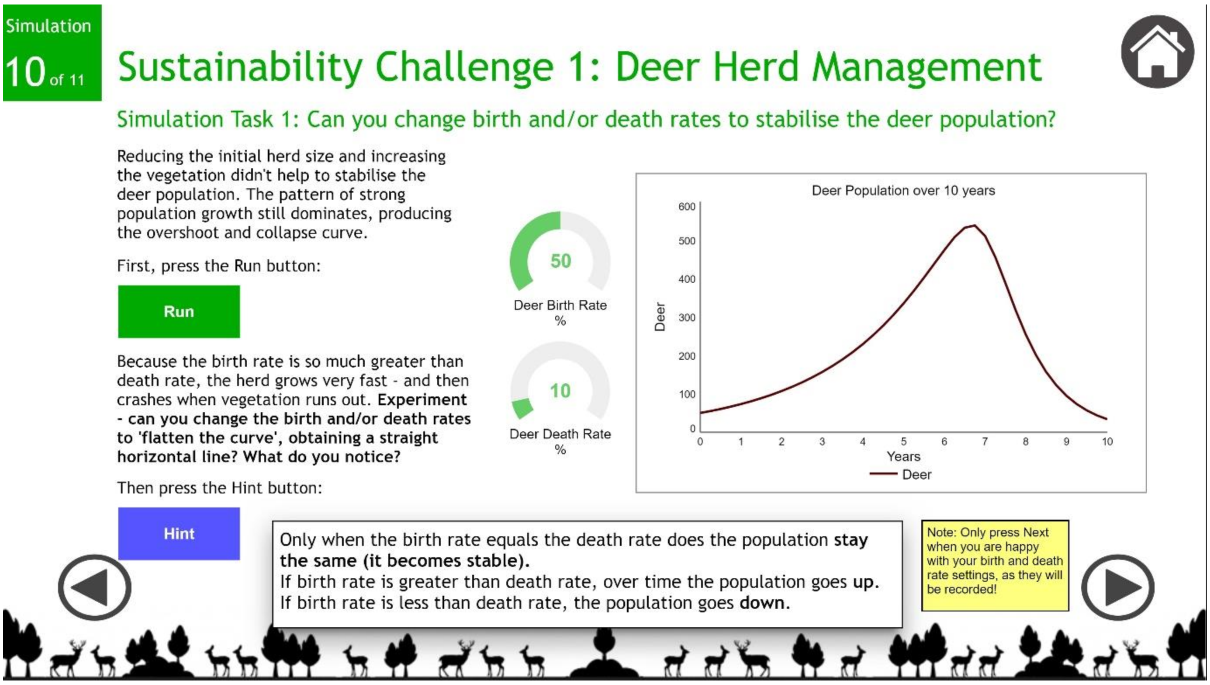

Figure 4 Sample screenshot of Part III (System Dynamics simulations for exploration of deer park management problem)

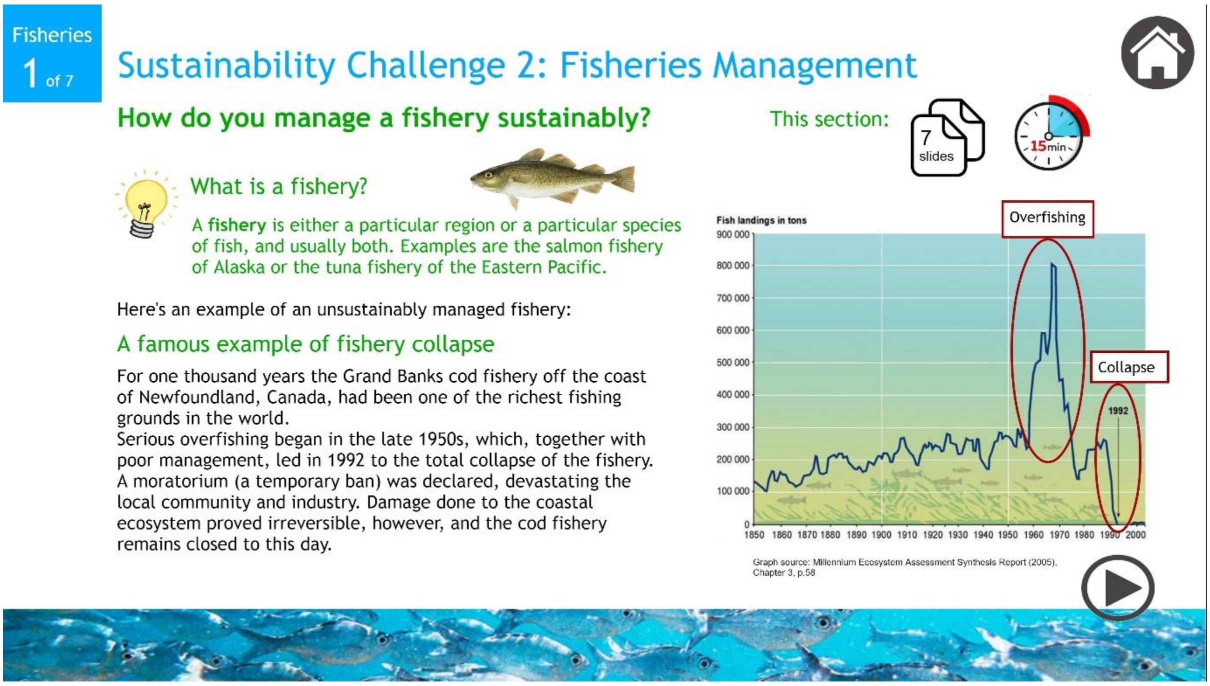

Figure 5 Sample screenshot of Part IV (Non-systemic description of fisheries management problem)