University of Dublin

TRINITY COLLEGE

Understanding Soil and Water Sustainability

A simulator to aid in the teaching the impact of farming on soil and water quality

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B.A.(Mod.) Computer Science

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Declaration

I hereby declare that this project is entirely my own work and that it has not been submitted as an exercise for a degree at this or any other university.

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Signed: Emer Murphy Date: 30/04/2023

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Abstract

With the challenges presented by loss of biodiversity, the need to understand sustainability has become more important than ever. Making sustainable choices is crucial to protect the planet, such as maintaining healthy soil and waterways. The health of these resources is important for sustaining life and ensuring global food and nutritional security, as well as for supporting biodiversity. Therefore, it is important to educate people about these issues, to ensure they are equipped with the knowledge to make informed decisions and take actions that promote environmental sustainability.

Microworlds are a type of educational computer simulation in which the learner can engage with a simplified model of a real-world phenomenon in order to come to a deeper understanding of the phenomena in question. The aim of this project is to design, develop and evaluate a Microworld to teach undergraduate Botany students about the impact of farming on soil and water quality. The learner can gain knowledge on both growing crops and preserving the environment by learning how to minimise the impact of farming on soil and water resources. This is done by allowing the learner to select crops, the amount of fertiliser and whether or not to include a vegetative buffer strip, and then simulating what happens over time. This application's design allows the learner to quickly understand the mechanics of the simulation and to easily interact with the microworld. The microworld was implemented as a web application utilising HTML, CSS, JavaScript and P5.js. These technologies provide minimal pre-built functionality, enabling the developer to design and implement visualisations that align with the specific needs and requirements of the application.

To provide triangulation, the microworld was tested by multiple audiences. The audiences evaluated the tool's usability and educational value. The testing group was comprised of an academic from the School of Botany (the project domain expert), Ph.D. Botany students, and non-Botany undergraduates. Both quantitative and qualitative data was collected. (Plans to test the tool with Botany undergraduates did not come to fruition for reasons outside the author's control). From a Human Computer Interaction perspective, data from the System Usability Scale indicated that respondents were satisfied with the overall usability of the tool, with all respondents (N=11) stating they would recommend using the tool in an educational setting. Analysis of other data showed the tool helped learners to understand the topic and raised awareness of environmental issues among the respondents.

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1 Introduction

With the challenges presented by loss of biodiversity, the need to understand sustainability has become more important than ever. Making sustainable choices is crucial to protect the planet, such as maintaining healthy soil and waterways. The health of these resources is important for sustaining life and ensuring global food and nutritional security, as well as for supporting biodiversity. Therefore, it is important to educate people about these issues, to ensure they are equipped with the knowledge to make informed decisions and take actions that promote environmental sustainability.

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1.1 Goal

The goal of this project is to employ visualisation techniques and technologies in Computer Science to create a microworld for undergraduate Botany students to explore the impact of farming on water and soil quality in an engaging way. The project will incorporate Human Computer Interaction (HCI) principles to ensure the design is usable and accessible. The outcome should be a microworld that allows the student to simulate growing crops and explore the relationship between optimising profits and protecting the local soil and water quality.

The evaluation process will employ triangulation which involves cross-checking data from multiple sources. The sources considered include Botany Educators, Ph.D. students studying the topic, and the author's peers. Both questionnaires and user observations will be utilised during the evaluation and testing of the microworld.

1.2 Road Map

This report discusses the development of a microworld designed to teach Botany students about the effects of farming on soil and water quality. The background work, which involved research into the Botany, pedagogical and computer aspects of the project, is described. The report details the specification based on the background research. This is followed by chapters on implementation and testing of the Microworld. The report finishes with a conclusion and a discussion of potential future work, and includes a personal reflection by the author.

2 Background

This chapter presents a comprehensive account of the research conducted to inform and prepare for the design of the microworld. A literature review was undertaken consisting initially of research into soil and water ecosystems, and the effects of farming practices, including vegetative buffer strips. Research concerning the different modelling tools that could be used in the simulation was then conducted. Microworld and related pedagogical theories, Visualisations and HCI were studied. Finally, similar applications were evaluated in order to assess the strengths and shortcomings of each.

2.1 Botany Background

This section provides a literature review of the Botany topics related to soil and water health, the Nitrogen Cycle, effects of fertilisers, plant diversity, crop yield, and multispecies culture. A thorough understanding of these topics is crucial in developing a microworld that educates users about these concepts. Additionally, this section will consider the numerical values and equations that could be used in creating the simulation and generating outputs based on the user's input.

2.1.1 Soil Quality

A healthy soil is one that has a thriving and diverse community of microorganisms. These organisms help to break down organic matter, recycle nutrients, and create a nutrient-rich environment that is ideal for plant growth (Doran & Zeiss, 2000). In soil, the Nitrogen Cycle is the process by which atmospheric Nitrogen is converted by bacteria into a form usable by plants (Killpack & Buchholz, 2022). Nitrogen-fixing bacteria, which reside in nodules on the roots of legumes (beans, lentils, peas, clover, chickpeas, etc.), convert N_2 into ammonia (NH_4^+). Further conversion of NH_4^+ to nitrite (NO_2^-) and ultimately to nitrate (NO_3^-), which is a highly available form of Nitrogen, is facilitated by bacteria of the genera *Nitrosomonas* and *Nitrobacter* (Kimball, 2022).

Farmers use fertilisers to add nutrients to the soil. While artificial fertilisers provide the nutrients that plants need to grow, they also affect the physical and chemical nature of soil leading to depletion of important organisms and bacteria, causing long-term negative effects on soil health (Doran & Zeiss, 2000). Reducing the amount of fertilisers used in agriculture is important not only for soil health but also to maintain the health of local waterways. Runoff of excess fertiliser enters lakes and streams releasing Nitrogen (N) and Phosphorous (P) into the water where these nutrients stimulate microbial growth (algal bloom), which competes with fish and other aquatic life for the dissolved oxygen in the water resulting in the suffocation of the fish and destruction of the aquatic ecosystem (Mishra, et al., 2022).

2.1.2 Plant Diversity

While the use of Nitrogen-fixing legumes reduces the need for fertilisers (Wixey, 2022) due to their Nitrogen-fixing properties, plant diversity is also important, and using legumes in multi-species mixes further increases yield. Multi-species mixtures in intensively managed systems have been shown to achieve not just overyielding (Moloney, et al., 2021), but transgressive overyielding which occurs when a mixture performance exceeds that of the best performing monoculture (Figure 2.1) (Trenbath, 1974). The legume proportion is a key determinant of transgressive overyielding in grass legume mixtures with legume composition of 30% to 50%, and low fertiliser application outyielding a 100% grass swarth with high fertiliser application (Nyfeler, et al., 2009). This effect is achieved through multiple synergistic interactions among species, for example symbiotic Nitrogen-fixing, acquisition of soil nutrients and water, and utilisation of light. Grange, et al (2021) found that a six species mix (two legume, two grass and two herb species) at 150 kg per hectare per year (150N) of fertiliser gave the best yield and matched or exceeded yield from grass monoculture at 300N of fertiliser.

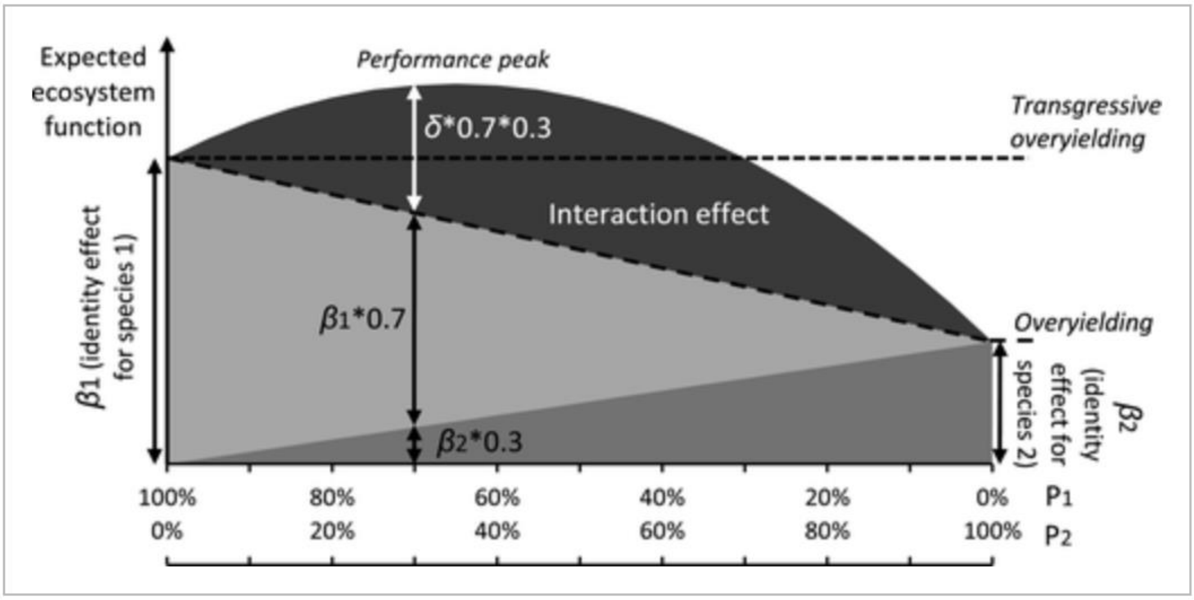


Figure 2.1: Illustration of the Diversity-Interactions modelling approach

(Grange, et al., 2021)

2.1.3 Predicting Yield

Calculating crop yield is difficult and there are different ways to predict yield. It is beyond the scope of this project to investigate how to predict crop yield. Instead, an opportunistic approach was followed. A statistician from the School of Computer Science and Statistics (SCSS) who had collaborated with Teagasc (the state agency providing research in agriculture, horticulture, food and rural development in Ireland) gave insight into research on this topic and provided answers to questions. Grange, et al (2021), working with Teagasc, used Diversity Interactions modelling to predict the yield from a multi-species mix of six species. The mix included two grasses (L. perenna, P. pratense), two legumes (T. pratense, T. repens) and two herbs (C. intybus, P. lanceolata) over a range of proportions from zero to 1 for each species based on the six individual species' identity effects, the interactions within each of the three functional groups (grasses, legumes, and herbs), and the pairwise interactions across the groups. Below shows the model to predict yield (Grange, et al., 2021):

$$Y= [\beta_1 P_{Lp} + \beta_2 P_{Pp} + \beta_3 P_{Tp} + \beta_4 P_{Tr} + \beta_5 P_{Ci} + \beta_6 P_{Pl} + \delta_{GG} P_{Lp} P_{Pp} + \delta_{LL} P_{Tp} P_{Tr} + \\ + \delta_{HH} P_{Ci} P_{Pl} + \delta_{GL}(P_{Lp} + P_{Pp})(P_{Tp} + P_{Tr}) + \delta_{GH}(P_{Lp} + P_{Pp})(P_{Ci} + P_{Pl}) + \delta_{LH}(P_{Ci} + \\ P_{Pl})(P_{Tp} + P_{Tr})]$$

The predicted yield (Y) is calculated using the equation, where P represents the proportion of the species sown, Beta is the expected yield for a monoculture of the species, and delta is a measure of the pairwise interactions within and between the three functional groups (Figure 2.2). The amount one species contributes to the yield is determined by multiplying its proportion in the mix by the expected yield for a monoculture of that species (P multiplied by beta). Pairwise interactions within and between functional groups also contribute to yield (delta multiplied by the product of the two species proportions). See Appendix 1 for a sample calculation.

TABLE 1 Parameter estimates (a) and predictions from selected communities (b) from the mixed model shown in Equation 2; the units are t ha^{-1} $year^{-1}$. The standard errors for the 2-year average values take year-to-year covariance into account. The *Diff* columns give the level of significance of the difference between the rainfed and drought treatments (***$p \le 0.001$, **$p \le 0.01$, *$p \le 0.05$, †$p \le 0.1$, ns: not significant). In part (a), FG interaction estimates in bold indicate significant parameters ($p \le 0.05$). In part (b), 'Monoculture average' is the mean of all 150N species' identity effects. 'Six-species centroid' and 'Four-species' are predictions from equi-proportional mixtures, including both species from each FG. 'Five-species' are three FG mixtures where one species was dropped (0% for the named species, and 20% for each of the five others). For the 2-year average (only), hash signs (#) denote the transgressive overyielding, that is, communities significantly outperforming *P. pratense*, the highest-yielding monoculture ($\alpha = 0.05$)

	2018			2019			2-year average		
	Rainfed	Drought	Diff	Rainfed	Drought	Diff	Rainfed	Drought	Diff
(a) Modelled fixed effects									
Species identity (β)									
Lolium perenne	9.2 ± 0.44	8.3 ± 0.44	*	9.1 ± 0.35	8.6 ± 0.35	†	9.2 ± 0.29	8.4 ± 0.29	*
Phleum pratense	11.1 ± 0.46	10.1 ± 0.46	*	10.2 ± 0.37	9.2 ± 0.37	**	10.7 ± 0.30	9.6 ± 0.30	**
Trifolium pratense	11.7 ± 0.44	8.9 ± 0.44	***	8.3 ± 0.35	7.2 ± 0.35	***	10.0 ± 0.29	8.0 ± 0.29	***
Trifolium repens	10.3 ± 0.44	8.4 ± 0.44	***	9.7 ± 0.35	8.8 ± 0.35	*	10.0 ± 0.29	8.6 ± 0.29	***
Cichorium intybus	8.6 ± 0.44	8.5 ± 0.44	ns	8.5 ± 0.35	7.5 ± 0.35	**	8.5 ± 0.29	8.0 ± 0.29	†
Plantago lanceolata	10.6 ± 0.44	8.8 ± 0.44	***	10.5 ± 0.35	10.2 ± 0.35	ns	10.6 ± 0.29	9.5 ± 0.29	**
FG interaction (δ)									
Grass–Grass	0.5 ± 2.13			2.2 ± 1.81			1.4 ± 1.44		
Legume–Legume	2.9 ± 2.10			2.9 ± 1.79			**2.9 ± 1.43**		
Herb–Herb	−3.0 ± 2.10			1.0 ± 1.79			−1.0 ± 1.43		
Grass–Legume	**6.1 ± 1.75**			**6.7 ± 1.49**			**6.4 ± 1.18**		
Grass–Herb	**4.8 ± 1.75**			2.6 ± 1.49			**3.7 ± 1.18**		
Legume–Herb	**5.8 ± 1.72**			**8.9 ± 1.47**			**7.3 ± 1.17**		
300N *Lolium perenne* (γ)	10.7 ± 0.41	10.4 ± 0.41	ns	10.3 ± 0.32	10.4 ± 0.32	ns	10.5 ± 0.27	10.4 ± 0.27	ns
(b) Selected communities									
Monoculture average	10.3 ± 0.17	8.8 ± 0.17	***	9.4 ± 0.14	8.6 ± 0.14	***	9.8 ± 0.12	8.7 ± 0.12	***
Six-species centroid	12.1 ± 0.23	10.7 ± 0.23	***	11.6 ± 0.19	10.8 ± 0.19	***	11.8 ± 0.15#	10.7 ± 0.15#	***
Four-species Grass–Legume	12.3 ± 0.42	10.6 ± 0.42	***	11.3 ± 0.35	10.4 ± 0.35	***	11.8 ± 0.28#	10.5 ± 0.28#	***
Four-species Grass–Herb	10.9 ± 0.42	9.9 ± 0.42	***	10.4 ± 0.35	9.7 ± 0.35	**	10.7 ± 0.28	9.8 ± 0.28	***
Four-species Legume–Herb	11.7 ± 0.42	10.1 ± 0.42	***	11.7 ± 0.35	10.9 ± 0.35	**	11.7 ± 0.28#	10.5 ± 0.28#	***
Five-species (excluding *L. perenne*)	12.3 ± 0.26	10.4 ± 0.26	***	11.8 ± 0.22	10.9 ± 0.22	***	12.0 ± 0.17#	10.8 ± 0.17#	***
Five-species (excluding *P. pratense*)	11.9 ± 0.25	10.4 ± 0.25	***	11.5 ± 0.21	10.8 ± 0.21	***	11.7 ± 0.17#	10.6 ± 0.17#	***
Five-species (excluding *T. pratense*)	11.6 ± 0.26	10.4 ± 0.26	***	11.4 ± 0.22	10.7 ± 0.22	**	11.5 ± 0.18#	10.4 ± 0.18#	***
Five-species (excluding *T. repens*)	11.9 ± 0.26	10.5 ± 0.26	***	11.1 ± 0.22	10.3 ± 0.22	***	11.5 ± 0.18#	10.4 ± 0.18#	***
Five-species (excluding *C. Intybus*)	12.6 ± 0.26	10.8 ± 0.26	***	11.8 ± 0.22	11.0 ± 0.22	***	12.2 ± 0.18#	10.9 ± 0.18#	***
Five-species (excluding *P. lanceolata*)	12.1 ± 0.26	10.8 ± 0.26	***	11.4 ± 0.26	10.4 ± 0.26	***	11.7 ± 0.18#	10.6 ± 0.18#	***

Figure 2.2: Parameter estimates and predictions from selected communities from the mixed model equation. (Grange, et al., 2021)

2.1.4 Calculating Profit

From the farmer's perspective profit is the ultimate metric. Finding the numbers to predict profit is difficult. In an effort to compile data concerning costs and profits the author met with Guylain Grange, one of the authors of Grange, et al. (2021) discussed above, who provided the images below from a paper that is in preparation by colleagues. Vishwakarma et al. (in prep) calculated profits for mixtures of one, two, or three species, and presented their predictions using species ternary diagrams. Profit was evaluated for one species (the vertices in the ternary diagram), two species (the sides of the ternary diagram), and all three species (all interior points in the ternary diagrams). Their results showed that planting with only one species did not ever yield the highest profit.

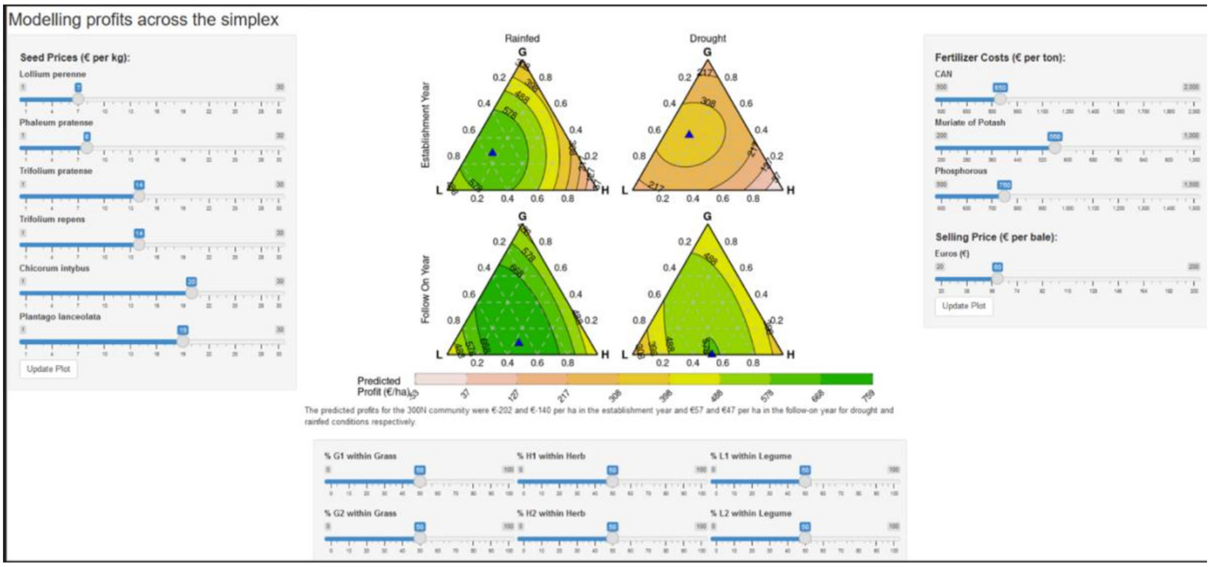


Figure 2.3: Profits for mixtures of species.

(Vishwakarma et al, in prep)

2.1.5 Vegetative Buffer Strips

One method of reducing harmful runoff into rivers is to use Vegetative Buffer Strips (VBS). These are typically comprised of grasses or weeds planted along the edge of agricultural fields to mitigate the impacts of runoff. Many studies have found VBS to be effective at absorbing excess harmful fertilisers from runoff, thus protecting the waterways from pollution (Dosskey, et al., 2010; Cole, et al., 2020).

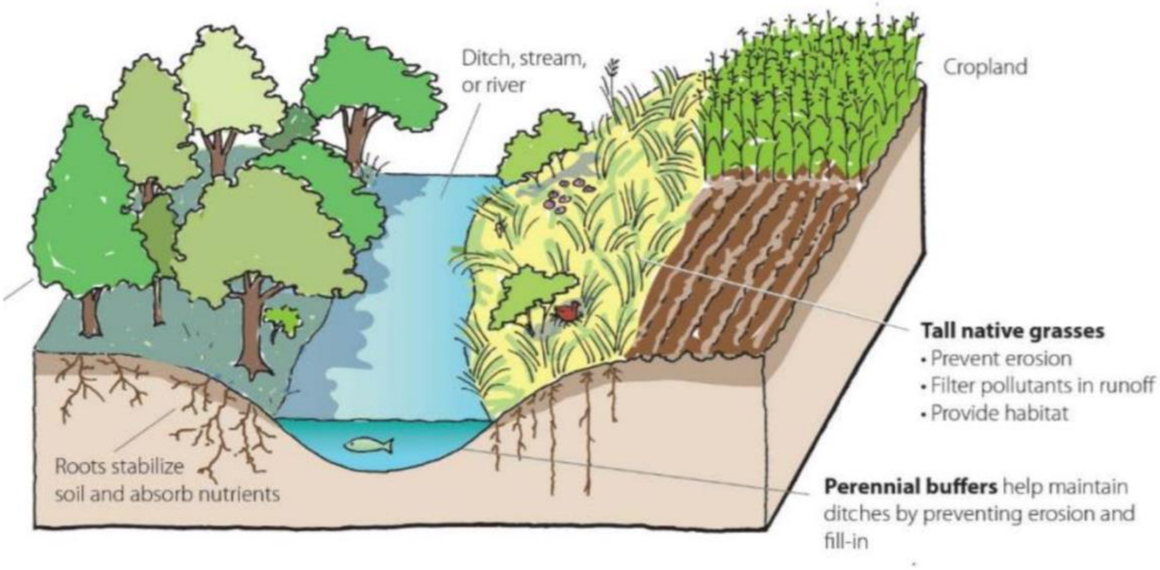


Figure 2.4: Vegetative Buffer Strip

https://bwsr.state.mn.us/alternative-practices-introduction

Aguiar, et al. (2015) found that the amount of N and P removed was proportional to the width of the buffer strip. The composition of the buffer strip was also found to be important, with woody vegetation having a higher nutrient retention capacity compared to grass and shrubs, as seen in Figure 2.5.

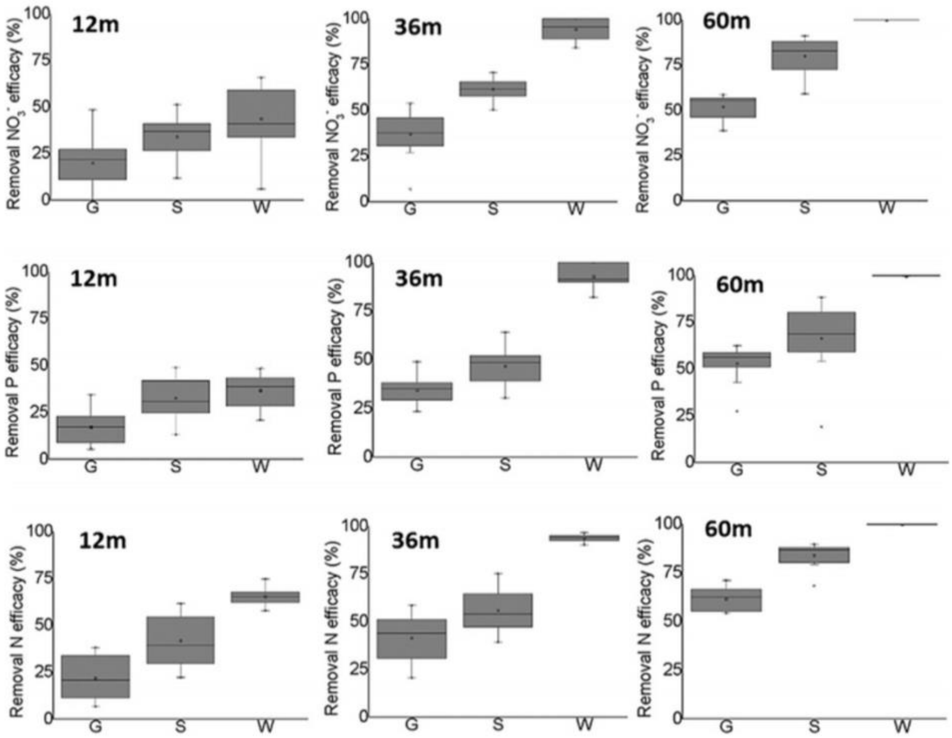


Fig. 3. Removal of N, P and NO_3^- in each study area, where N (nitrogen), P (phosphorus) and Nit (nitrate), S (shrub), G (grasses) and R (woody vegetation). The efficiency was calculated in the following buffer zone widths (A) 0–12 m (B) 0–36 m, and (C) 0–60 m.

Figure 2.5: Proportion of N and P removed for VBSs with different lengths and plants.

(Aguiar, et al., 2015).

This effect is seen due to the higher organic matter content of woody vegetation as a result of the deposition and breakdown of leaves which, in turn, supports a rich microbial population that utilises the nutrients from the runoff in the production of humus (Groffman, et al., 2002; Young, et al., 1980) (Cahn, et al., 1992). The trees and associated biomaterial provide protection to the soil, reducing the impact of rain and reducing nutrient runoff into nearby waterways. In contrast, areas with grasses and shrubs have less organic soil matter and lower microbial activity. Additionally, the lower soil protection and higher runoff in these areas result in less contact time between pollutants, vegetation, and soil (Sharpley, et al., 1994).

2.1.6 Summary

This section provides insight into the fundamental Botany concepts that the microworld aims to teach including healthy soil, multispecies cropping, and the importance of VBS. In addition, research and meetings provided the author with numbers and equations needed to simulate yield and VBS absorption.

2.2 Modelling Tools

To simulate the effects of VBS, fertilisers, and the Nitrogen Cycle, a modelling tool is required. There is a wide range of conventional modelling approaches available, ranging from complex mathematical models to more flexible agent-based models. In this study, two commonly used modelling techniques are analysed, namely process-based models and agent-based modelling. The choice of the appropriate modelling approach depends on the complexity of the problem and the project's requirements.

2.2.1 Process-Based Models

Process-based modelling is a method of using mathematical representation to predict the function of a specific biological system. The models are based on first principles, or empirical knowledge, and describe how key parameters, inputs, and outputs of each process change over time. (Buck-Sorlin, 2012). These models are valuable in the study of ecological systems, where accurate predictions of responses to environmental changes are critical. By understanding the underlying mechanisms of an ecosystem, scientists can predict how changes to the system will impact its functioning, and can design strategies to mitigate the negative effects of such changes. (Mäkelä, et al., 2000)

2.2.2 Agent-Based Modelling

Agent-based modelling, similar to process-based modelling, is a method to study and make predictions about complex systems. However, they differ in how they are constructed and focus. Unlike process-based modelling, agent-based modelling involves building models from the bottom-up, where individual agents are assigned attributes and programmed to behave and interact with each other and the environment. These interactions among agents produce emergent effects that may differ from the effects of individual agents. Agent-based modelling is used to study interactions between people, things, places, and time, and allows for exploration of complex systems that display non-independence. (Macal & North, 2009; Haer, et al., 2020)

2.2.3 Summary

Process-based modelling and agent-based modelling are two approaches to modelling complex systems, each with their own strengths and weaknesses. While process-based modelling is useful in making accurate predictions of responses to environmental changes in high-fidelity situations, it falls short when representing the behaviour of individual agents. On the other hand, agent-based modelling is particularly useful for modelling complex systems where the behaviour of individual agents is critical to understanding the behaviour of the system as a whole. Agent-based modelling provides more flexibility in representing the behaviour of individual agents and their interactions, leading to engaging and nuanced simulations that are suitable for low-fidelity applications that focus on teaching concepts rather than predicting behaviour for decision-making strategies.

2.3 Microworld and Pedagogical Theories

Microworlds are a type of educational computer simulation in which the learner can engage with a simplified model of a real-world phenomenon in order to come to a deeper understanding of the phenomena in question (Hoyles, et al., 2002). Microworlds are complex, dynamic, and opaque. They require learners to consider multiple goals and trade-offs. The dynamic nature of a microworld means that they change as a direct result of the learner's actions. As a result of the opaque character of microworlds, not everything is initially visible, and learners must form hypotheses and test them as part of the activity. These features make microworlds effective for learning (Brehmer & Dörner, 1993).

Constructionism and constructivism are two pedagogical educational philosophies that emphasise the role of active learning in the educational process. Constructivism states that learning is an active process in which learners construct new knowledge and meaning through their experiences, interactions, and reflections. Learners construct knowledge themselves rather than just receiving it (Fosnot & Perry, 2005). It emphasises the importance of providing learners with opportunities to construct their own understanding of the world and to connect new knowledge to their existing knowledge. Constructionism, on the other hand, emphasises the importance of creating learning environments in which learners are actively engaged in constructing something tangible, such as a project or artifact. It emphasises the importance of learning by doing and creating, and encourages learners to take an active role in the educational process (Kynigos, 2015). A microworld can support both types of learning, as it allows learners to interact with and gain experience in different environments through various methods (Jong & Njoo, 1992). Research has consistently shown that active learning approaches such as constructionism and constructivism are effective in improving the learner's understanding, engagement, and long-term retention of knowledge (Prince, 2004).

2.4 Human Computer Interaction

The field of Human Computer Interaction (HCI) focuses on designing, accessing, and implementing computer systems that are interactive and easy for humans to use (Sinha, et al., 2010). To achieve this goal, HCI researchers study how people interact with computer systems and seek to understand their needs and preferences. HCI aims to create systems that are not only innovative and useful but also engaging and accessible (Gross, 2014).

Figure 2.6: HCI focuses on creating systems that are easy for humans to use.

https://www.interaction-design.org/literature/topics/human-computer-interaction

One important aspect of designing user-friendly systems is considering how people typically communicate and interact in their day-to-day activities. This requires involving users in the design process to ensure systems are efficient, safe, and easy to learn and remember how to use. A good system should have good utility, meaning that it serves its intended purpose well and is easy to use even after interruptions or distractions (Gross, 2014).

Universal Design in HCI refers to designing digital products and interfaces that can be used by a diverse range of people, regardless of their abilities or disabilities. By using Universal Design principles, developers can ensure that interactive computer systems are user-friendly for all, regardless of their age or disability (Gross, 2014).

The cognitive loop refers to the iterative process of perception, interpretation, and action that occurs in HCI. The user perceives information from the system, interprets its meaning, and decides on an appropriate action to take. The chosen action further generates new information that feeds back into the cognitive loop and restarts the process. The cognitive loop is central to the success of HCI because it allows users to develop a mental model of the system and its functionality. This mental model allows the user to anticipate the system's response to their actions and adjust their behaviour accordingly, creating a sense of control and understanding over the technology. By understanding and supporting the cognitive loop, designers can create systems that are intuitive, user-friendly, and seamlessly integrated into the user's activity (Kaptelinin, 1996).

2.5 Visualisation Techniques

Visualisation is a particularly interesting method of transforming data into computer graphics when applied in the context of pedagogical theories. Visualisation techniques can be used to create powerful tools that leverage the innate visual processing abilities of the human brain. Visualisations shift the emphasis from cognitive processes to perceptual processes, enabling users to extract a deeper understanding of data in a shorter amount of time (Murray, 2017; Ware, 2008). As this project involves modelling soil and water this section will present a range of common visualisation techniques used to visualise soil and water quality.

2.5.1 Soil Texture Triangle

A Soil Texture Triangle refers to the proportion of sand, silt, and clay particles etc. in the soil. It is a graphical representation of soil texture which can help determine soil quality. The triangle helps to identify the texture class of a soil based on the percentage of sand, silt, and clay in the soil.

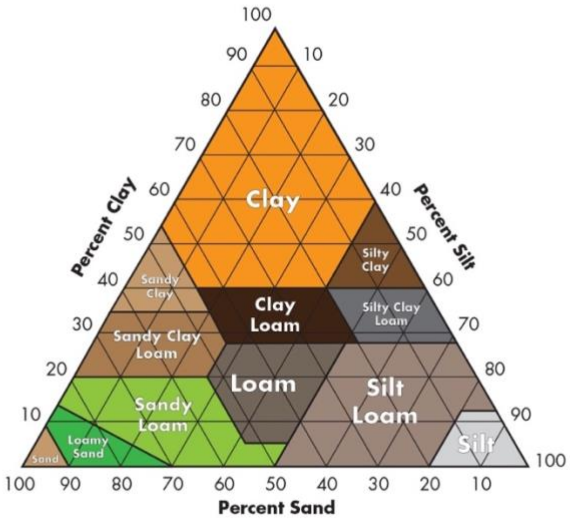


Figure 2.7: Example of a soil texture triangle.

https://www.trugreen.com/lawn-care-101/learning-center/grass-basics/dig-deeper/soil-texture?new18=1&var301=v1

2.5.2 Soil Horizons

A soil horizon is a vertical cross-section that shows the layers of the soil, each with varying physical and chemical properties. Evaluating a soil profile can provide valuable information about soil quality.

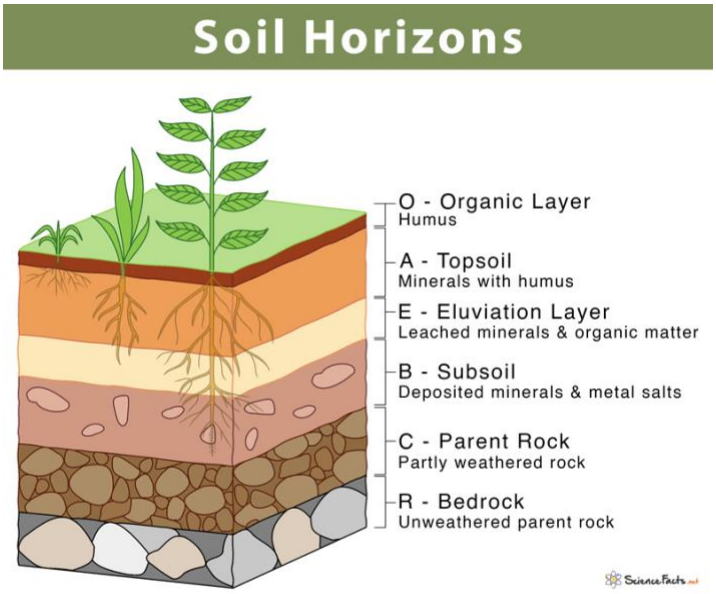


Figure 2.8: Example of a soil horizon.

https://www.sciencefacts.net/soil-horizons.html

2.5.3 Digital Mapping Technology

Digital mapping technology such as Geographic Information Systems (GIS) are used to visualise soil and water quality, creating maps that depict soil properties such as pH, organic matter, and nutrient levels. These maps facilitate the identification of areas that may require management interventions due to low soil quality (Figure 2.9), while also providing insight into spatial patterns in water quality data (Figure 2.10). As digital mapping technologies offer high fidelity representations of data, they are ideally suited to scientific analysis and decision-making.

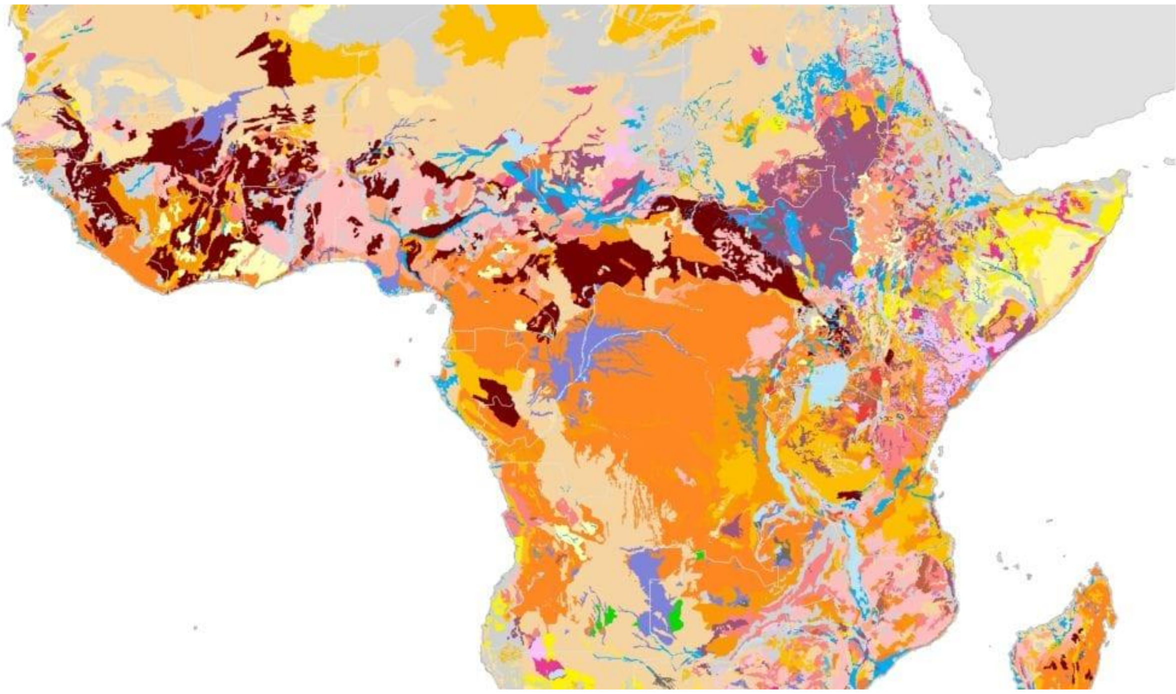


Figure 2.9: GIS used to visualise soil quality.

https://www.scidev.net/sub-saharan-africa/news/soil-quality-maps-created-to-assist-african-farmers/

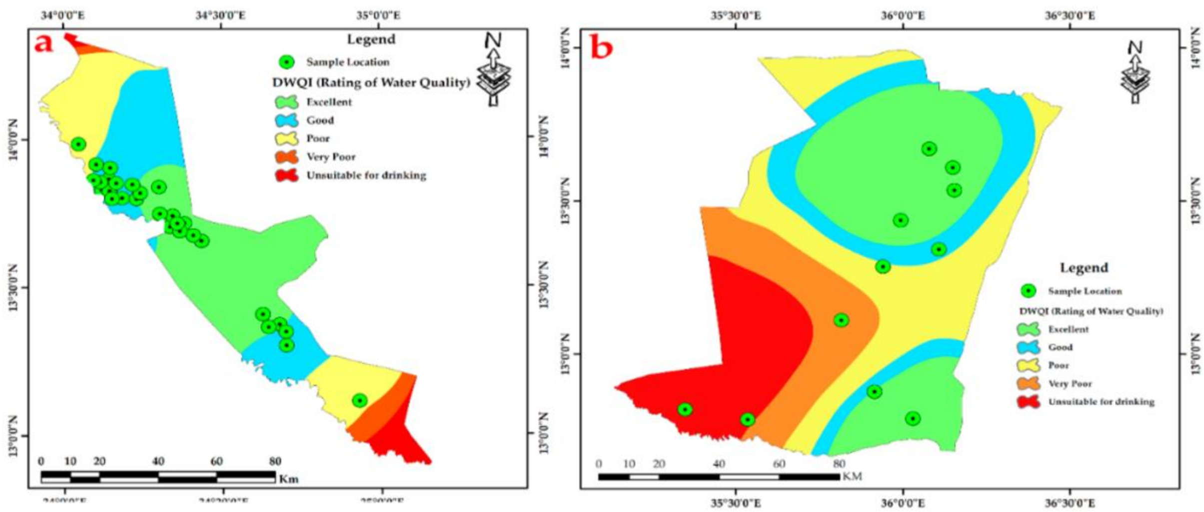


Figure 2.10: Example of GIS used to visualise water quality.

https://www.mdpi.com/1660-4601/16/5/731

Unlike soil horizons and soil texture triangles, which provide specific information and display the unique characteristics of individual soil layers of a particular soil, digital mapping technology provides a comprehensive view of soil quality across a geographic area. The visualisation techniques discussed provide a diverse range of methods used to visualise soil and water quality. Elements from these visualization techniques were integrated and modified to inform the design process of this project, discussed further in this report.

2.6 Similar Applications

A number of educational tools have been developed to teach various aspects of water and soil sustainability, including the Nitrogen Cycle, VBS, fertilisers, etc. Some of the identified applications provide engaging visuals or interactive elements, inspiring and informing the design of the microworld developed in this project.

2.6.1 Video/Non-interactive Simulations

This section examines several educational videos that feature captivating visualisation but lack any interactive components for users.

2.6.1.1 Understanding Our Soil: The Nitrogen Cycle, Fixers, and Fertiliser

Figure 2.11 shows a YouTube video by the channel "Jimi Sol" that answers the questions, "What are Nitrogen-fixing plants?", and "Why use them over Nitrogen fertiliser?". The answers are taught with clear explanations and engaging simulations of the Nitrogen Cycle.

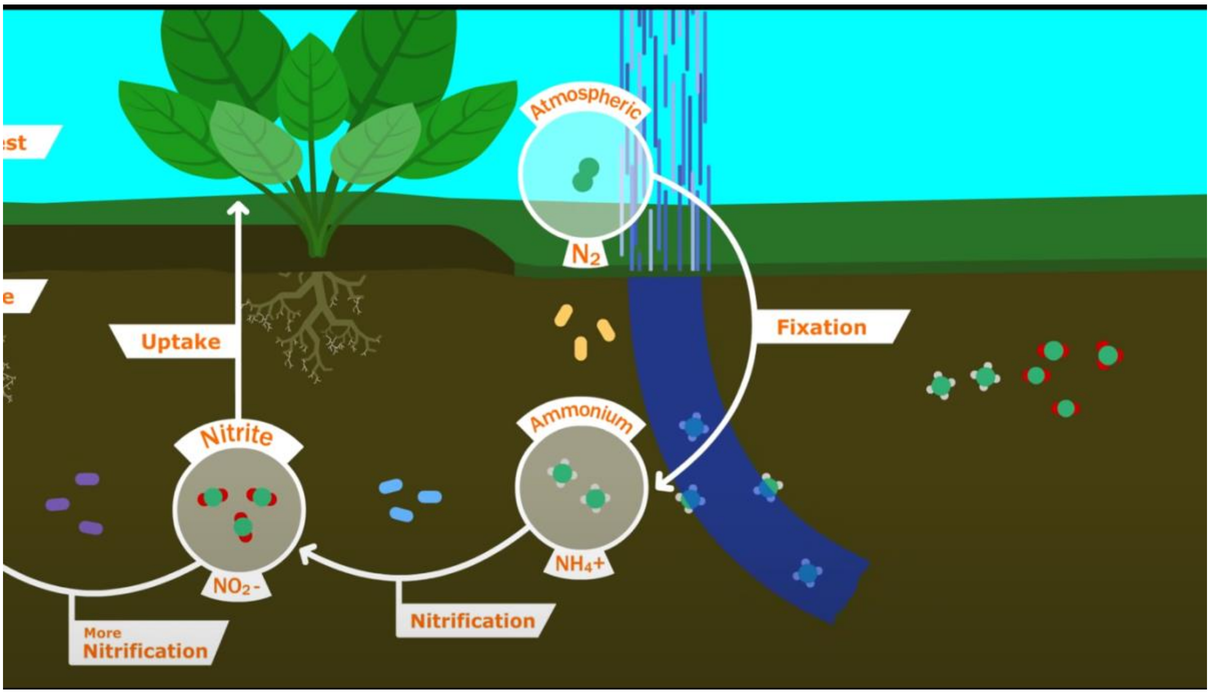


Figure 2.11: "Understanding Our Soil: The Nitrogen Cycle, Fixers, and Fertilisers " video

https://youtu.be/A8qTRBc8Bws

The video uses animation to explain the Nitrogen Cycle and compares Nitrogen-fixing plants to fertilisers. Initially, the creator introduces Nitrogen-fixing plants and then poses the question, "Well, doesn't Nitrogen fertiliser do the same thing?" This leads to a discussion about the Nitrogen Cycle and its significance. Although the video uses chemical names, the explanations are delivered in a manner that is easy for the audience to understand. For example, the video describes how various species of bacteria "eat atmospheric Nitrogen and poop out ammonium." Because of the accessible language used, important information is conveyed effectively and accurately. The video concludes with an explanation of how Nitrogen exits soil through runoff, and revisits nitrogen-fixing plants, highlighting their advantages over fertilisers in light of new understanding of the Nitrogen Cycle. The video is concise and features engaging visualisations that intuitively explain the topic. The explanations flow together in a narrative style, akin to a story. However, the video falls short in its explanation of VBS, which leaves a gap in understanding for the viewer. Additionally, as a passive video it does not have any interactive features to consolidate learning.

2.6.1.2 Riparian Buffer

Figure 2.12 is a YouTube video by the channel "North Carolina DEQ" that explains how VBS provide flood control and cleans water. The video achieves this through clear explanations and engaging simulations.

Figure 2.12: "Riparian Buffer" video

https://youtu.be/KIhZEfMGTxI

The video begins by emphasising the importance of clean water for our environment and communities, highlighting the critical role of VBS in protecting waterways. The video showcases the numerous benefits of VBS, such as stabilizing banks, filtering pollutants, providing natural flood control, and keeping drinking water clean. Throughout the video, viewers are shown clear and informative visuals of VBS in action. The video concludes by encouraging viewers to support VBS by leaving them undisturbed or planting more native vegetation, emphasising that the healthier the buffer, the healthier the water. Overall, the video is informative, and the animations are clear. However, like “Understanding Our Soil: The Nitrogen Cycle, Fixers, and Fertiliser" this video is not interactive.

Although "Understanding Our Soil: The Nitrogen Cycle, Fixers, and Fertiliser" and "Riparian Buffer" are two different videos addressing different subjects, there is some overlap between them. The "Riparian Buffer" video addresses the gap in knowledge of VBS indentified in the discussion of the former video. Together these videos provide a comprehensive introduction to the topic and serve as a starting point before engaging with the simulation of the topic.

2.6.2 Interactive Tools

This section looks at tools which offer an element of interactivity.

2.6.2.1 Cornucopia

Cornucopia is a digital game developed by the California Academy of Sciences. It aims to teach students ages 10-16 years old about growing food while managing the water and land that the crops are using.

Figure 2.13: "Cornucopia" game

https://www.calacademy.org/cornucopia

In Cornucopia, the user must manage a plot of land by planting crops, taking into account multiple factors to meet various food orders and other demands. The game requires monitoring of water levels and crop yields, as well as earning technology upgrades to maximise the farms success before the season ends. Playing Cornucopia allows the user to analyse and compare the water and land needs of different crops and animal food sources, understand how weather and climate changes affect water availability and food production, and explore the impact of agricultural technologies on water use.

The game is engaging and visually appealing. However, the game is designed for students aged 10 – 16 years old and this is reflected in the level of detail of the content.

2.6.2.2 Top Crop: Farming the Future Educator's Guide

Top Crop is a digital game developed by National Geographic to teach students aged 11-14 years old. Similarly to Cornucopia, Top Crop aims to teach the learner about growing food while at the same time alleviating the environmental impact and preserving the natural ecosystem.

Figure 2.14: “Top Crop: Farming the Future Educator’s Guide”

https://education.nationalgeographic.org/resource/top-crop-farming-future-educators-guide/

Top Crop is an interactive tool and visually appealing. However, Top Crop has the same drawbacks as Cornucopia; because the target user is school aged children it does not provide a sufficient level of detail for the undergraduate Botany students.

2.6.2.3 Covid-19 Microworld

The Covid-19 microworld is a simulator tool designed to enhance the comprehension of viral disease transmission dynamics and facilitate the exploration of the essential decision-making trade-offs involved in managing pandemics. It uses Agent-Based modeling. The learner can adjust parameters to configure the population, its environment, and interact with individual characteristics and behavior of the agents. The resulting high level of interactivity within the simulator offers vast flexibility to the learner to experiment and see the effects of their decisions.

Figure 2.15: Covid-19 Microworld

https://github.com/LukeFeely/Final-Year-Project-Covid-Simulator-

Although the Covid-19 microworld is teaching a completely different topic it serves as an example of a simulation tool for teaching using simple graphics and agent-based modelling.

2.6.3 Comparison of Similar Applications

Table 2B shows a comparative analysis of the applications reviewed in this chapter. The comparison is based on a set of specific criteria which were informed by the research discussed above. Given the importance of active learning, interactivity was a criteria. Challenge based learning was also included to provide learners with engaging activities that highlight the key learning outcomes. Visual aids were also deemed necessary to leverage the innate visual processing abilities of the human brain. As the tool is intended to teach undergraduate Botany students, the level of detail provided for explaining the Nitrogen Cycle and VBS must match their educational level.

Table 2-A: Table comparing a sample of similar applications

	Interactivity	Engaging Visual Aid	Challenge Based Learning	Suitable for Botany University Students	Explains the Nitrogen Cycle	Explains VBSs
Understanding Our Soil Video	No	Yes	No	Yes	No	No
Riparian Buffer Video	No	Yes	No	Yes	Yes	Yes
Cornucopia	Yes	Yes	Yes	No	No	No
Top Crop	Yes	Yes	Yes	No	No	No
Covid-19 Microworld	Yes	Yes	Yes	No	No	No

The analysis identified useful functionalities as well as the drawbacks and limitations of existing systems. The findings were utilised to shape the development of the microworld, drawing inspiration from the most effective features and enhancing areas for improvement.

2.7 Discussion

This chapter discussed the research carried out to gain an understanding of the Botany concepts that the microworld aims to teach. This research included consulting experts involved in researching these topics. Numbers and formulae were given for predicting yield, profit and the efficiency of VBS in absorbing runoff, from work that was published and in preparation, which are essential for developing the simulation. Research in modelling, microworlds and pedagogical theory, HCI and visualisation techniques, and how they can be used to create powerful tools that teach complex concepts in an intuitive and engaging manner was completed. Finally, the analysis included examining similar applications that aimed to teach the concepts related to soil and water quality. While some of the visualisations used by the applications were effective, the applications lacked the necessary depth for undergraduate Botany students and failed to incorporate all essential information into a single simulation.

3 Project Specification

This chapter presents the project specification, including the design, the simulation variables, the challenges, and the simulation modelling. The functional and non-functional requirements are listed. It also details the incorporation of the domain expert's feedback throughout the design process, to create an effective teaching tool. Additionally, it highlights the contribution of prior research to ensure good project design.

3.1 Project Considerations:

The learning is intended to be used by third and fourth-year undergraduate Botany students, but it may also be useful to other groups. Therefore, specific factors were considered during the design phase.

Prior Knowledge: As the intended students are third and fourth-year undergraduate Botany students, it is expected that they have a certain level of knowledge of the factors that affect soil and water quality and VBS.

Learning environment: The learning tool is primarily designed to be utilised in a classroom setting with computers. Nevertheless, as it may also be used by individuals outside of the formal classroom context it is crucial that the tool is self-explanatory.

Accessibility: To ensure that the learning tool can be used by all students, including students with disabilities and varying technical abilities, it is essential that it is intuitive, accessible, and user-friendly. Drawing upon the principles of HCI theory, the system should be designed in a manner that allows learners seamless understanding and navigation.

Ethics: When designing, the developer has the responsibility to promote inclusivity and equality by facilitating as many users as possible to access the application including students with disabilities and varying technological literacy. In addition, ensuring accessibility can benefit not only individuals with disabilities, but can improve the overall user experience for all students (Adams, 2000). Despite specifically searching for issues with race implication for the project, none were found. Farming is traditionally considered a masculine role despite the fact that in developing countries the majority of farming is done by women. Farmers can be both male and female thus it is important to use gender neutral language in this project when referring to farmers. The learning tool should teach the students the relevant information about the topic; it is not propaganda and should avoid bias, allowing the student to form their own informed opinions on the topic. In addition, it should clearly state the limitations and potential biases within the model.

This project involves the handling of data from research participants. Thus ethical approval for this project was granted by the School of Computer Science & Statistics.

3.2 Project Scope

Due to time limitations and the complexity of modelling factors that affect soil and water quality, some limitations had to be applied to the scope of the project. Assumptions will be made when modelling factors affecting soil and water, resulting in a low fidelity system that focuses on key concepts instead of precise modelling. This prevents overwhelming the learner with complexity and instead enhances educational benefits. In addition, due to the required screen size, development efforts will be focused on ensuring accessibility for PCs and laptops.

3.3 Functional Requirements

- The learner must be able to clearly distinguish between the different nutrients and bacteria in the soil.
- The learner must be able to witness the change from one type of Nitrogen to another.
- The learner must be able to configure the variables and observe the impact of their decisions on the outcome.
- The simulations must have stochastic elements so that the outcomes of the simulations vary with each run, the agents (Nitrogen Cycle components), initial position and direction in the soil should be random.
- The tool should set a series of challengers for the user to achieve the learning outcomes.
- When the simulation ends after each year, the results of the simulation should automatically be displayed.
- The Dashboard should be updated so that the user can see the quality of the soil, the quality of the water and the amount of money made at the end of each year.

3.4 Non Functional Requirements

- The tool should operate effectively on a standard laptop or PC.
- The tool should be compatible with at least the 4 most used internet browsers (Google Chrome, Safari, Mozilla Firefox, Edge).
- The tool should be able to handle multiple users on the site at once and should be scalable for further growth if needed.
- The tool should provide instructions on how to use the simulation page.
- The tool should gradually introduce new elements to the simulation.
- The tool should be suitable for undergraduate Botany students.
- The tool should incorporate HCI principles including universal design, on providing prompts and scaffolding.
- The tool should be useful for an individual learner as well as in a collaborative learning environment.
- The tool should be intuitive and not present a steep initial learning curve to its users.

3.5 Simulation Design

During the initial meeting, the domain expert, Dr Carla Harper, Assistant Professor of Environmental Science in the School of Botany, Trinity College Dublin, expressed her expectations and objectives for the learning tool. These included improving learners' understanding of topics such as the Nitrogen Cycle, soil health, the impact of artificial fertilisers on soil and water quality, and the effectiveness of VBS in reducing water pollution.

Following an initial brainstorming session, the domain expert created a mock-up for what the tool might look like (Figure 3.1).

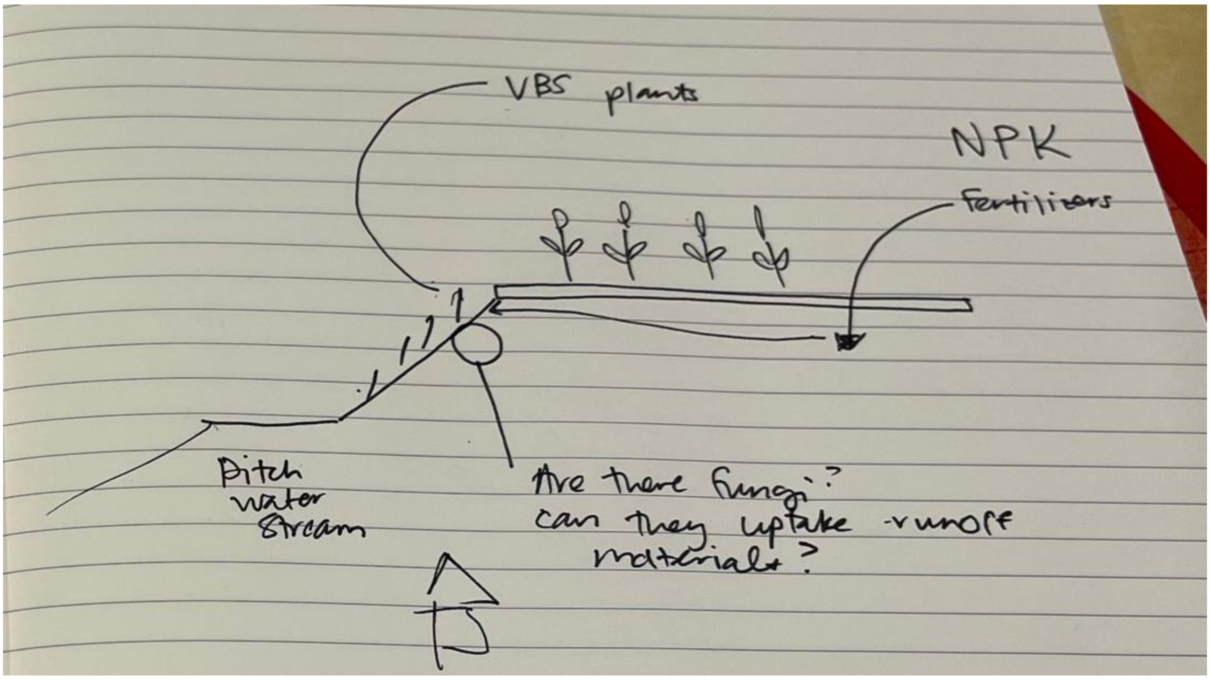


Figure 3.1: The domain expert's mock-up of the microworld

From the comparative analysis of a sample of similar applications using specific criteria outlined in Table 3B, and drawing on knowledge of pedagogical theories, the decision was made to create a microworld. As discussed in Chapter 2, microworlds align with constructivism and constructionism by allowing learners to engage with various environments and methods. The goal was to design a microworld that not only built upon the features of similar applications but also incorporated new elements such as challenge-based learning, while adhering to sound pedagogical principles.

Table 3-A: Table comparing a sample of similar applications to proposed system

	Interactivity	Engaging Visual Aid	Challenge Based Learning	Suitable for Botany University Students	Explains the Nitrogen Cycle	Explains VBSs
Understanding Our Soil Video	No	Yes	No	Yes	No	No
Riparian Buffer Video	No	Yes	No	Yes	Yes	Yes
Cornucopia	Yes	Yes	Yes	No	No	No
Top Crop	Yes	Yes	Yes	No	No	No
Covid-19 Microworld	Yes	Yes	Yes	No	No	No
Proposed System	Yes	Yes	Yes	Yes	Yes	Yes

3.6 Choosing Variables

Microworlds provide users with the opportunity to observe the effects of changing variables, enabling them to construct their own understanding of concepts. During the initial meeting, the domain expert listed the input and output variables (Figure 3.2) that could be used to model this ecological system.

The goal of this microworld is to teach concepts rather than precise modelling, as a result, a subset of these variables were chosen to implement. Variables such as climate change and fungi are beyond the scope of this project.

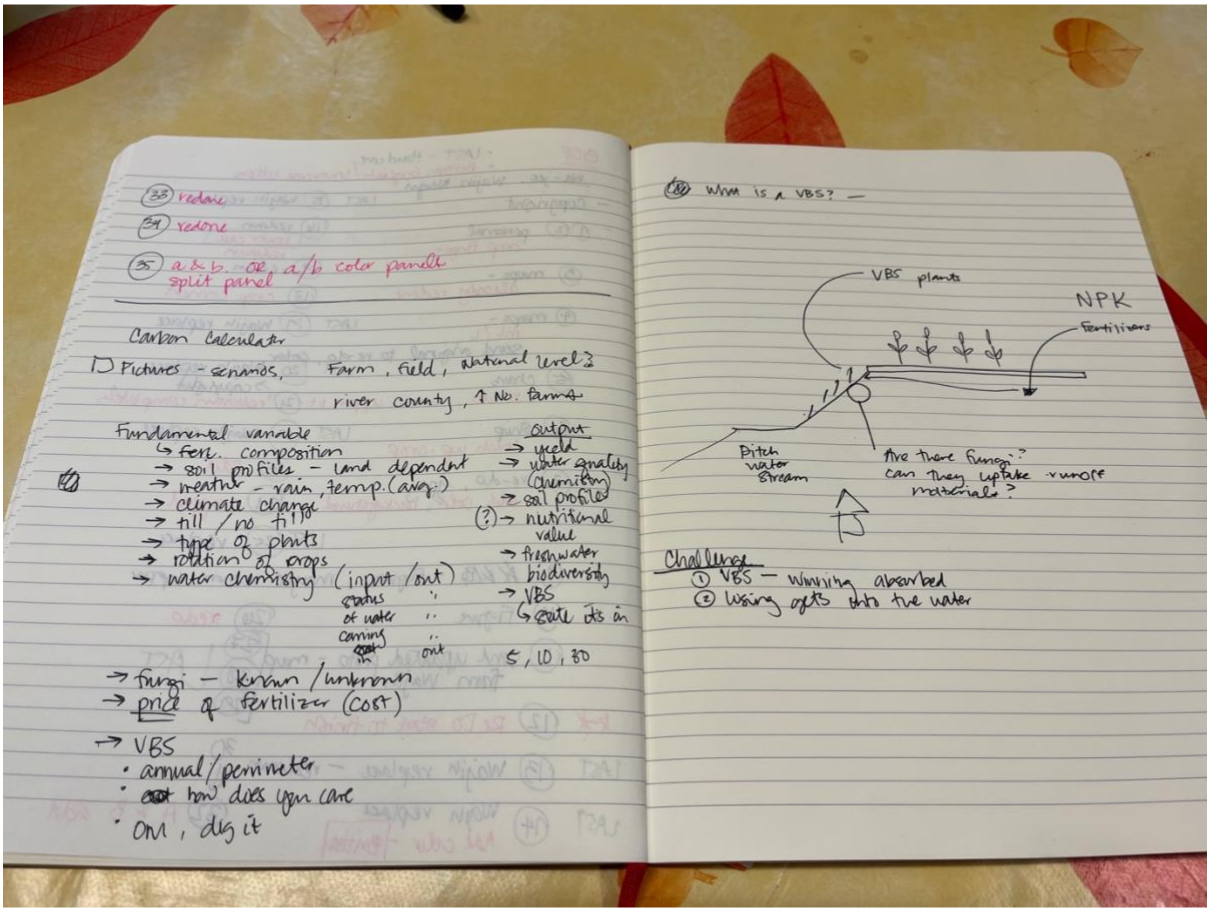


Figure 3.2: The domain expert's list of variables

The chosen input variables were soil quality, type of plants, crop rotation, and VBS. Soil quality and plant types were selected to demonstrate the benefits of Nitrogen-fixing plants on soil. Fertiliser was included to show the impact on plant growth, soil, and water quality. Three different concentrations of fertilisers were used as a variable to illustrate the effect of VBS in absorbing runoff. VBS width and composition were chosen as they determine the amount of fertiliser absorbed. Instead of using crop rotation as a variable, an opportunistic approach was taken, and multi-species mixing was used instead (refer to Chapter 2). The output variables chosen were soil quality, water quality, and yield. By choosing to only use these variables, the design resulted in a low-fidelity system that prioritises teaching the concepts rather than making accurate predictions, and attempts to encourage the learner to construct their own understanding of soil and water quality.

A critical aspect of the simulation is to calculate the effect of VBS in absorbing Nitrogen compounds in runoff during rainfall. This effectiveness depends on the VBS plant type and width, as explained in Chapter 2. Without a VBS any fertiliser that has not been absorbed by plants will runoff during rainfall polluting the waterways. If a VBS is in place the system will calculate the reduced amount of fertiliser reaching the water, using the proportion of fertiliser absorbed by the VBS from Figure 2.5, subtracted from 100 percent. The yield is calculated using the equation for predicting yield, and profit is then calculated using numbers supplied by Grange (see Chapter 2).

3.7 Setting Challenges

Expanding on the principles of active learning, it is important to provide learners with engaging activities that stimulate their cognitive abilities and encourage them to consider their choices and underlying reasoning. To achieve this, three challenges were created for the simulator, with the aim of highlighting key learning outcomes and delivering instructive value to the tool. The three challenges follow a consistent format, but with increasing numbers of input and output variables. At the beginning of year one, learners select their inputs. They observe the effects of their decisions and the changes over the following months. At the end of the year, they can assess the resulting output variables. In years two and three, learners make similar decisions and can view the results at year-end. However, the VBS length and width selection made in year one will remain unchanged for the three years, as recommended by the domain expert. The chosen input variables are crops, artificial fertilisers, and VBS length and width, and the chosen output variables include soil quality, water quality, biodiversity, and yield. Twenty fish are used to represent a healthy ecosystem, and the threshold for distinguishing between healthy and polluted ecosystems is arbitrarily set at 17.

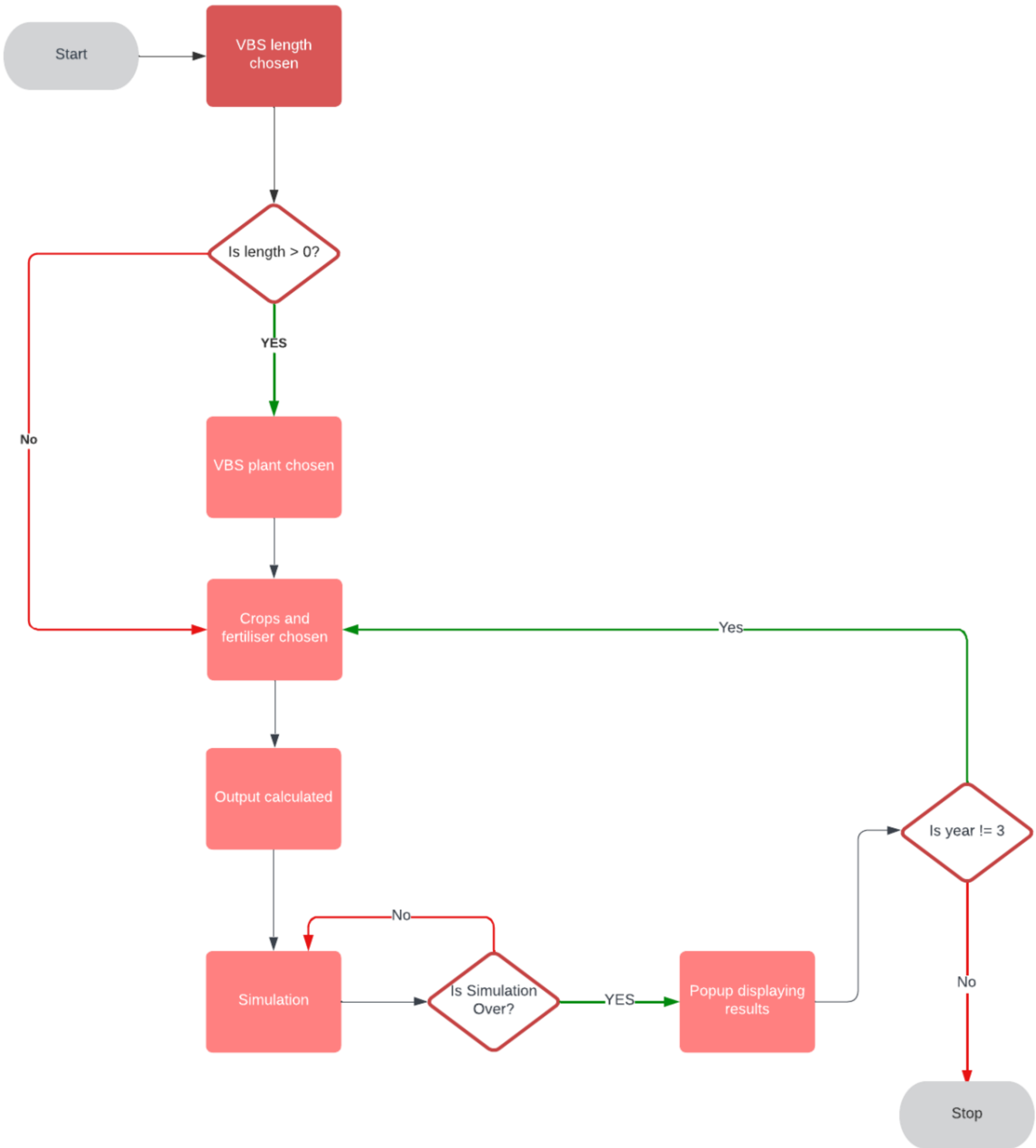


Figure 3.3: Challenge 2 flow chart

Challenge 1: Enhance soil quality from 50% to 75%. The aim is to encourage the learner to construct their own understanding of the role of Nitrogen-fixing plants in improving soil health, and the adverse effect of artificial fertiliser. This introductory challenge enables users to become familiar with the simulator's layout and mechanisms without overwhelming them with too much information. The variables for this challenge are the crops sown and the application or non-application of artificial fertilisers, and the concentration at which they are applied. At the end of the year, they can assess the resulting soil state, represented as a percentage and the activity of microorganisms and worms in the soil bed.

Challenge 2: Enhance soil quality from 50% to 75% while keeping 17 fish alive - The learning objective is to understand the effects of VBS in protecting waterways by absorbing runoff. In this challenge, the simulator becomes more complex by the addition of two further variables, namely VBS width and VBS plant type. Building on the concepts learned in Challenge 1 the learner must now consider the length and makeup of the VBS necessary to protect the water. The output variables for Challenge 2 are the output variables from challenge 1, as well as the health of the water and aquatic life, which is indicated by the colour of the water and the number of healthy fish.

Challenge 3: Keep 17 fish alive while generating maximum revenue – To achieve the learning objective of understanding how multi-species mixes can increase yield and reduce cost, the simulator presents a more complex scenario in the third challenge. This challenge introduces a cost to the crops and fertilisers. The input variables in this challenge are carried forward from challenge two, while output variables such as yield, and profit are introduced. By using multispecies cultures, it is possible to increase yield without a corresponding increase in fertiliser usage, thereby keeping costs low and yields high and minimising environmental damage. The user is encouraged to apply the knowledge gained from the previous challenges and to construct their own understanding on the benefits of using multispecies cultures.

3.8 Screen Design

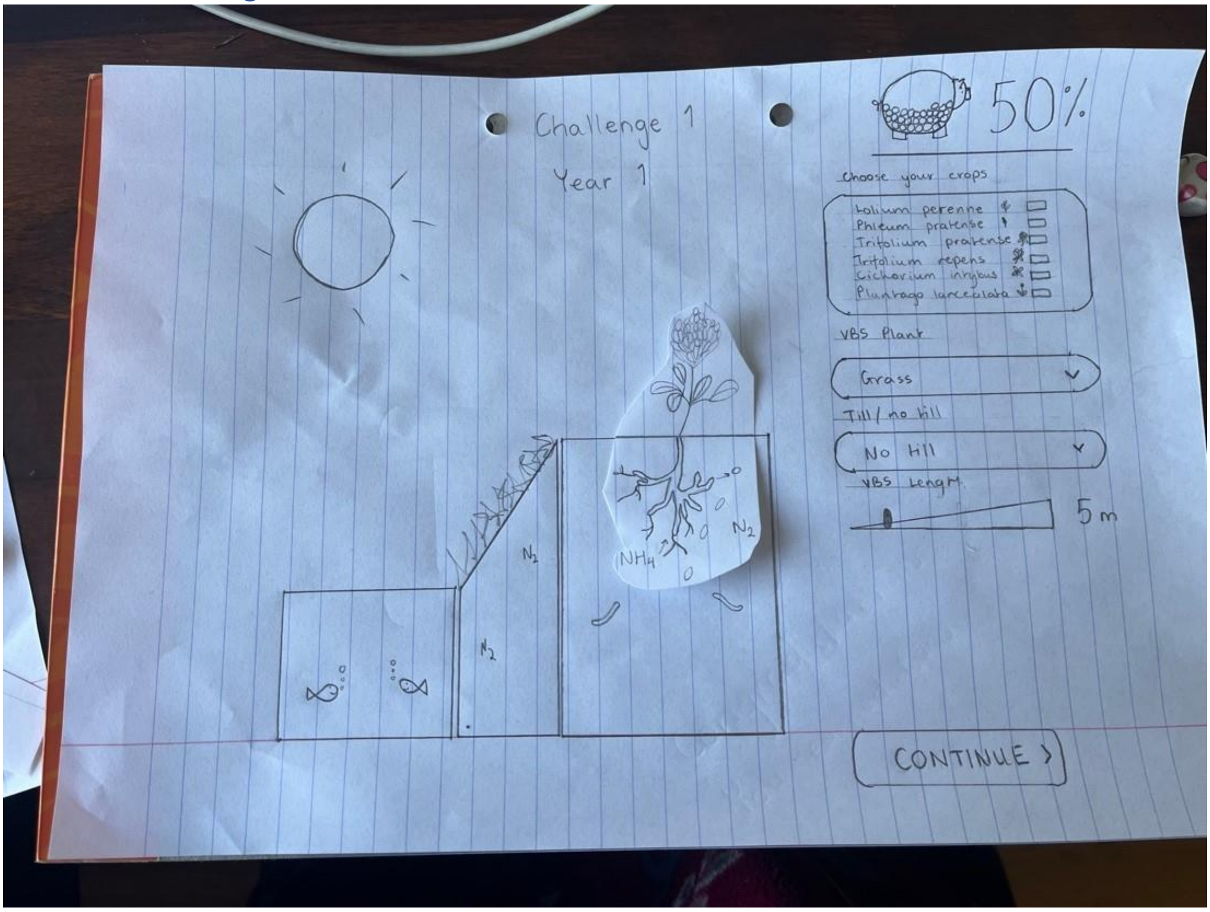


Figure 3.4: Microworld mock up

A mock-up of the microworld, as shown in Figure 3.4, was created by the author after considering the domain expert's initial ideas and the chosen input and output variables. The mock-up provides a preliminary design for the microworld, featuring sliders and check boxes on the right-hand side of the screen to allow users to control variables that affect the simulation in the centre. The challenge and year are displayed prominently at the top of the screen. The design builds upon similar applications previously explored and extends their features, while introducing new elements such as challenge-based learning. The domain expert reviewed and approved this mock-up.

3.9 Modelling

To simulate the ecological system, modelling of several components was required. This included three distinct regions on the landscape: the rectangular farm region, the trapezoidal VBS region, and the rectangular waterway region. As discussed the width of the VBS region depends on the user's input. To preserve the farmland area for crops, the simulation is designed to decrease the size of the waterway instead of shrinking the farmland as the VBS region expands. The decision to implement this design was based on the suggestion of the domain expert who explained that VBSs are usually wasteland and machinery cannot easily traverse VBSs because of the slant. As such, the simulation adjusts the landscape by altering the size of the waterway as the VBS region grows larger.

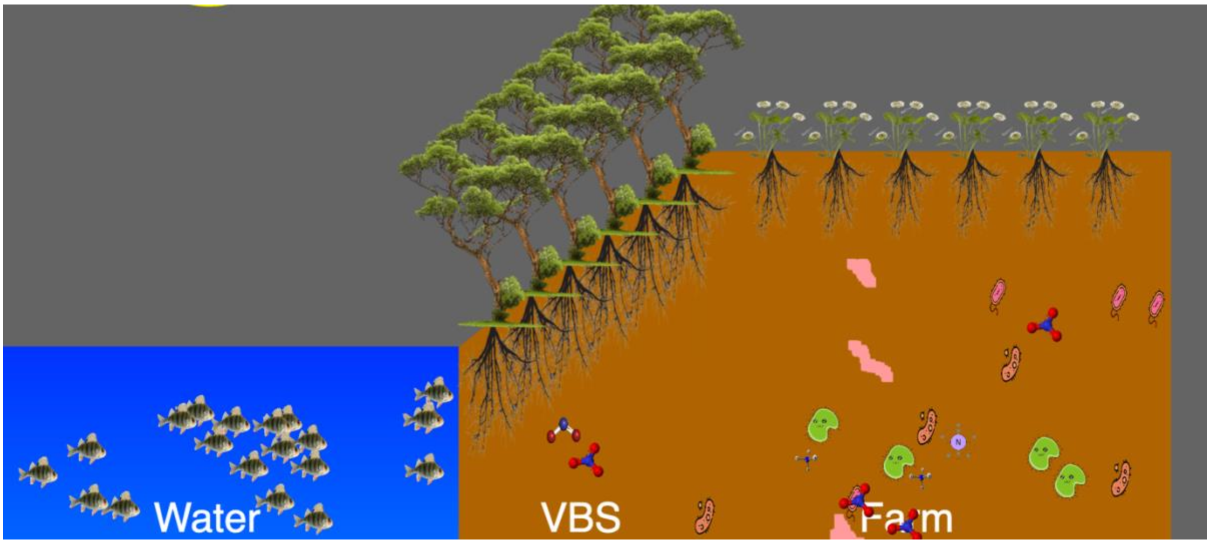


Figure 3.5: Screen shot from finished tool showing water, VBS, and farmland

As explained in Chapter 2, agent-based modelling is a powerful tool for modelling complex systems where the behaviour of individual agents plays a critical role in understanding the overall behaviour of the system. In the case of simulating the Nitrogen Cycle, each agent represents a bacteria or a form of Nitrogen. By simulating the behaviour of individual agents and their interactions with each other, learners can observe how the system behaves as a result of these interactions. The same approach was taken for modelling the fish in the simulation, with each fish acting as an agent that moves around the water and changes state from healthy to dead when the water becomes polluted.

When designing the visual components of the simulation, Universal Design principles were used to ensure that the information could be communicated effectively to all users, including those with colour blindness. Different shapes and colours were used to distinguish between the different components of the simulation, allowing users to easily identify and track different agents and their behaviours. Additionally, detailed information on each component could be accessed by hovering over the corresponding icon.

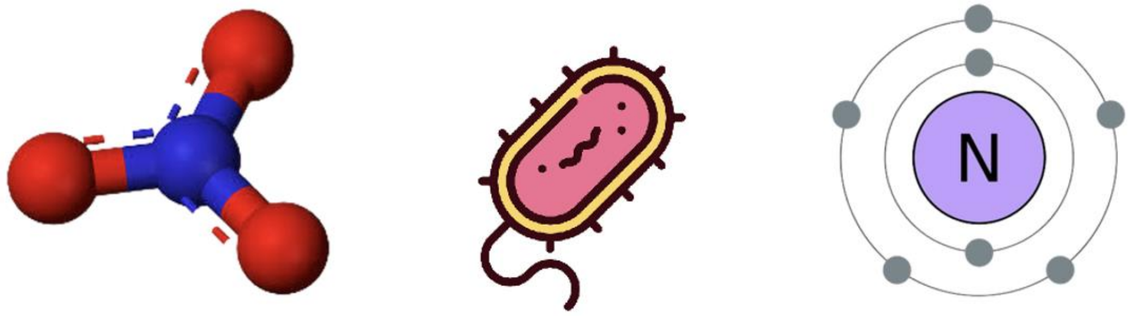


Figure 3.6: Examples of the visualisations used to represent the compounds in soil. (L to R: Nitrate, *Nitrobacter*, Nitrogen)

In terms of the fish, the initial visual representation was a tropical fish. However, after consulting with the domain expert, it was determined that a freshwater fish would be a more appropriate choice.

3.10 Screen Design

The final design draws heavily on HCI theory. The user interface focuses on providing only the relevant information exactly at the time it is needed. The tool aims to integrate with the learner's thought process, while minimising interference. To guide the user through the tool scaffolding techniques, such as process constraints are used which only allow for the next step to become accessible once the previous step is finished.

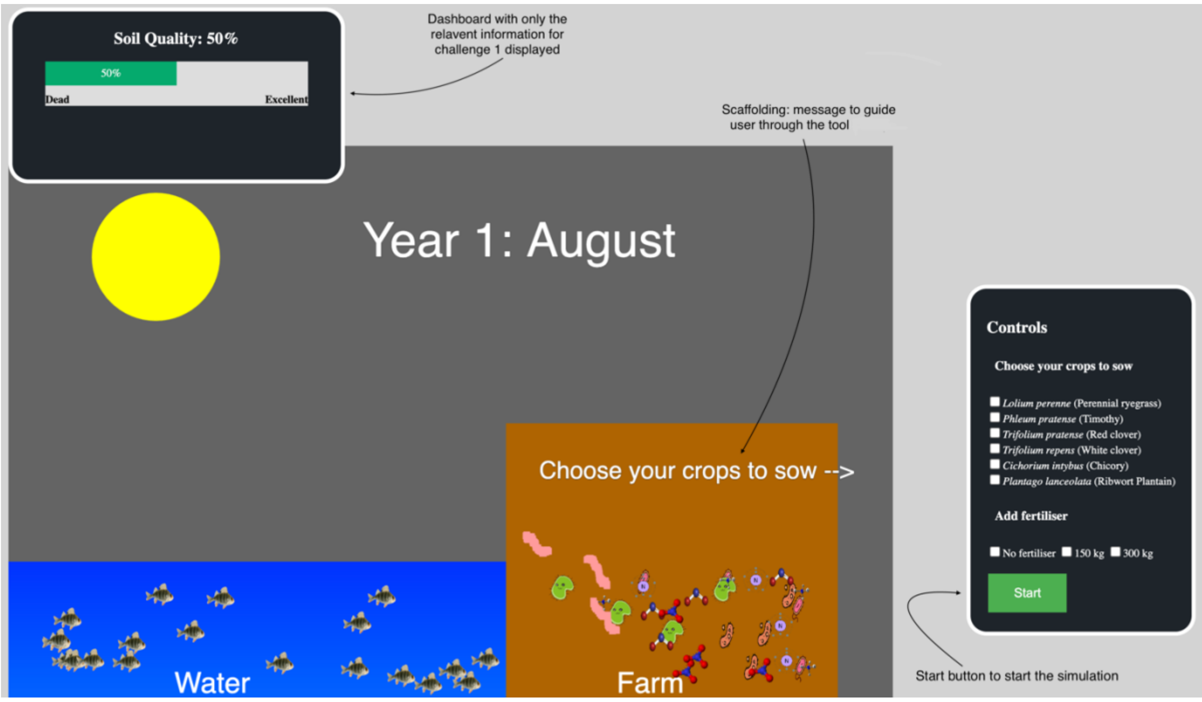


Figure 3.7: Challenge 1 (before crops are chosen)

In Figure 3.7 the Start button is visible at the beginning of the year when it is needed. However, as seen in Figure 3.8, the Start button is hidden and only reappears when the user needs it at the start of the next year.

Figure 3.8: Challenge 1 (after crops are chosen)

The application prompts users to take action, making the interface accessible to a range of users, including those who are new to the application. For the challenge outcome popup, instead of using generic labels such as "Continue" or "OK", the message displays "Choose next year's crops," which directs the user to engage with the controls (Figure 3.9).

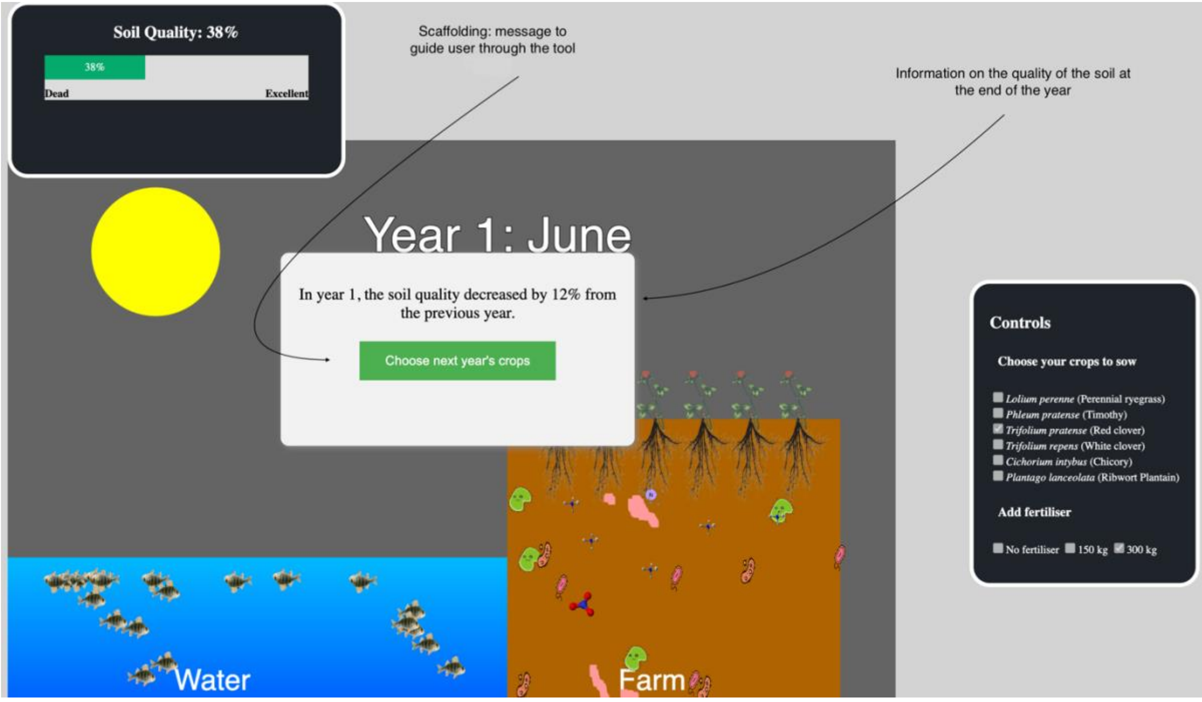


Figure 3.9: Challenge 1 (end of year 1)

Feedback is provided when a user attempts an action that is not permitted in the present scenario, such as starting the simulation without choosing the crops to sow (Figure 3.10).

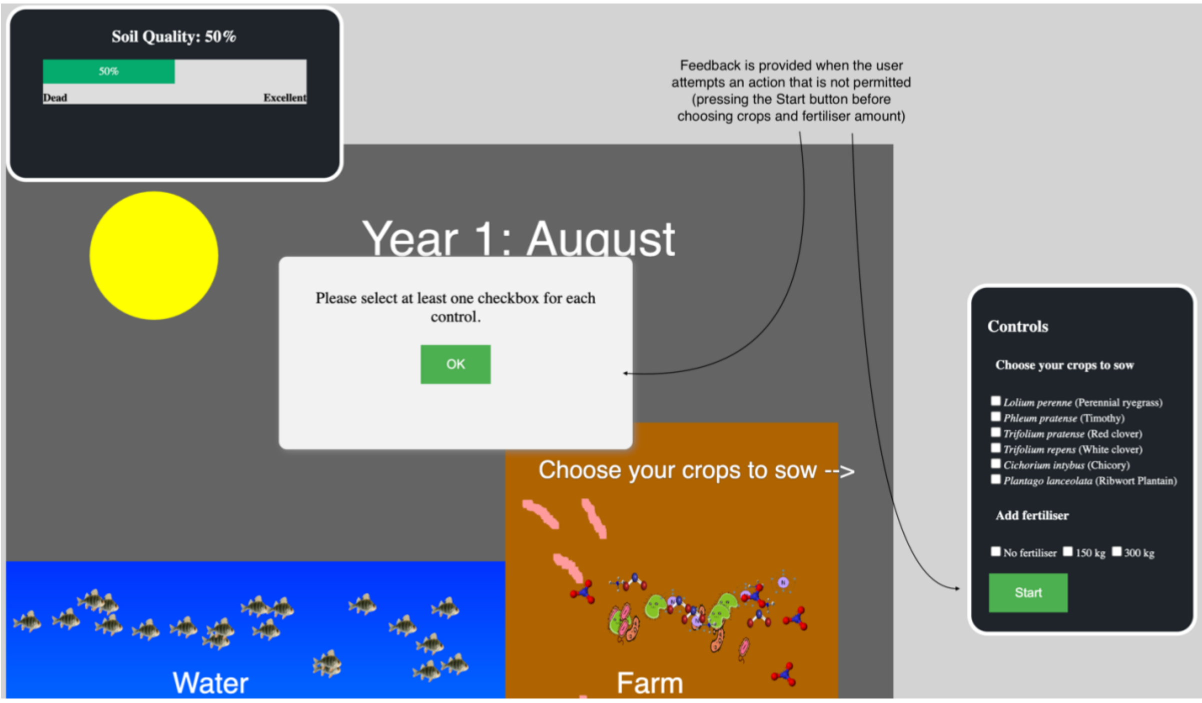
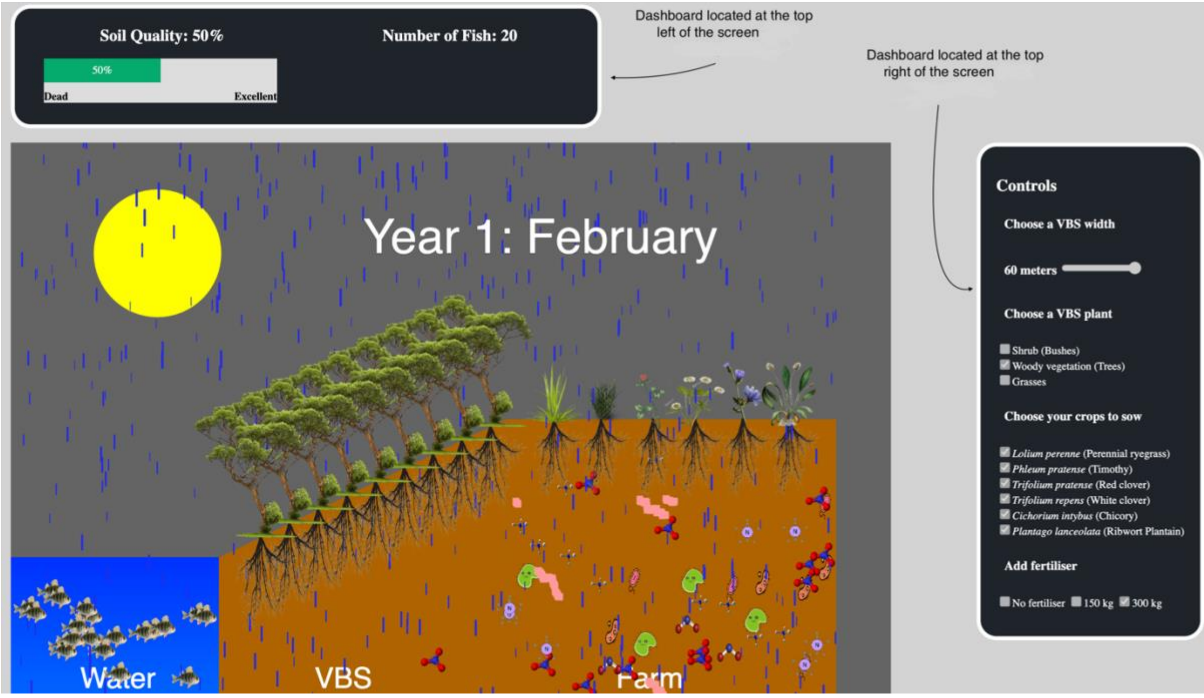


Figure 3.10: Challenge 1 (feedback when user attempts to start the simulation without choosing inputs)

Each challenge is laid out in the same way with consistent controls and dashboard placement. This consistency enables learners to transfer their knowledge from one challenge to another and quickly navigate the microworld and focus on the task at hand rather than spending time learning how to use the interface.



When designing the simulation, accessibility was a key consideration. Even with the most severe form of colour blindness, monochromacy/ achromatosia, the information in the simulation is still conveyed effectively and can be understood by the learner, as demonstrated in Figure 3.11. The creation of Figure 3.11 utilised the Colorblindly plugin, which is a Google extension that enables the simulation of different types of colour vision deficiencies to aid in the development of more inclusive designs.

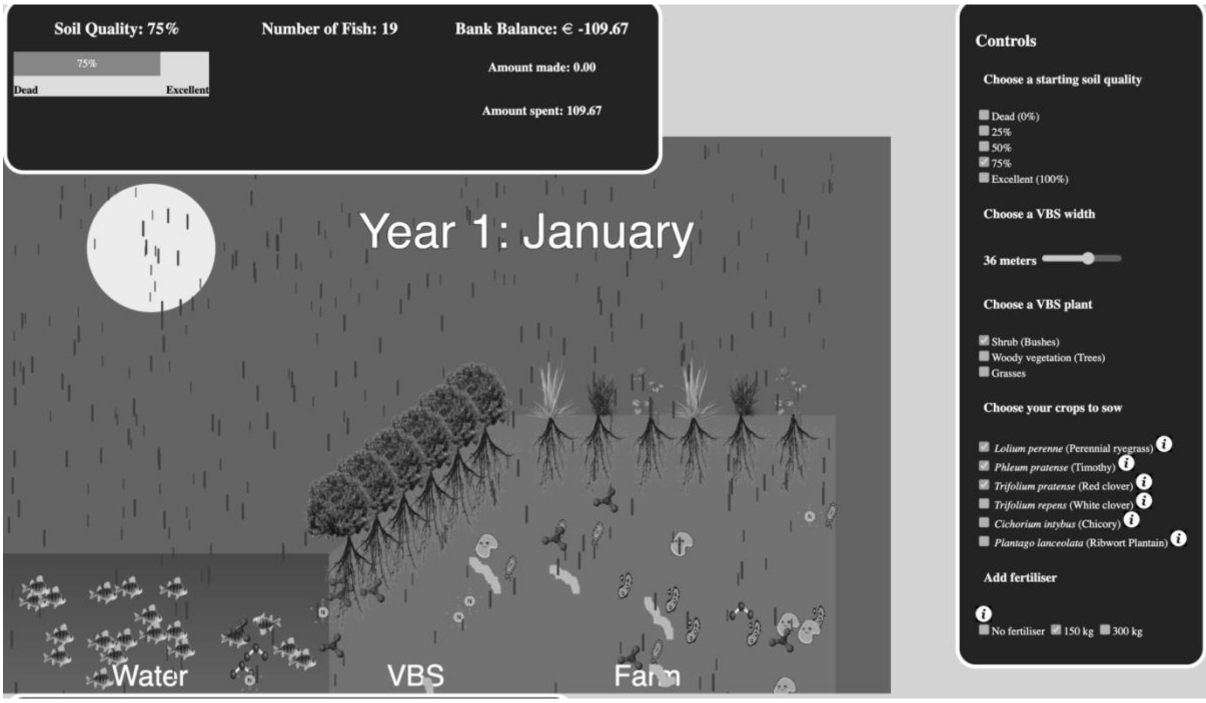


Figure 3.11: Challenge 3 (monochromacy/ achromatosia)

3.11 Summary

This chapter discussed the project specification, which is centred on creating a simulation tool that teaches key concepts of soil and water quality, supported by pedagogical theories. The simulator provides learners with the ability to configure input variables by changing the parameters, and visualises the resulting effects on soil and water quality, with output variables such as yield, profit, and fish health. Three challenges were developed to gradually increase the complexity of the simulator.

Universal design and HCI principles were used to model the simulation, with a focus on enhancing the flow of the application and allowing users to concentrate on discovery rather than learning about the interface. Functional and non-functional requirements were also considered, based on research carried out prior to the design phase. Throughout the design process, the feedback from the domain expert was consistently incorporated.

4 Implementation

Implementation of the microworld involved technical decisions about platform, languages, and system architecture. The different processes, including simulating the Nitrogen Cycle, the effects of artificial fertilisers on soil quality, the effects of runoff on local waterways including the ameliorating effects of VBS's and the relationships between optimising yield and environmental impact, were implemented. There was interaction with the domain expert throughout the implementation and changes were made based on the feedback. This chapter looks at how the microworld was developed, decisions that were made and challenges that had to be overcome.

4.1 Initial Technology Choices

The choice of platform was between a web application and an app; for reasons explained below a web application was chosen for this project. An app is suited to repeated use; however, this system is expected to be used only once or twice by each learner, thus this property is redundant. In addition, web applications facilitate rapid development and allow for updates to be easily pushed to users without requiring the user to download or install updates. Web applications are also accessible from multiple devices. Although a stable internet connection may present some challenges, the advantages web development offers are more significant.

4.1.1 HTML, CSS and JavaScript

The project requires unique visualisations therefore HTML and CSS were chosen. HTML defines the content of a web page and its structure, while CSS (Cascading Style Sheets) dictate the presentation of and style of the content. These two technologies, along with graphics and scripting, form the basis of web development. They are widely used by developers thus their popularity and longevity mean there are many resources available for learning and implementing these technologies, making them a reliable choice for this project. They allow for flexibility and customisation, resulting in seamless integration into the simulation.

JavaScript works in conjunction with HTML and CSS to allow developers to create interactive and dynamic elements on web pages, such as animation, form validation and other complex functionality. JavaScript is the most used programming language for web development, which means it has extensive support across many platforms. It has a vast array of frameworks and libraries available that can be used to enhance the functionality of the language and provide useful visualisation and interactive technologies.

Frameworks such as React and Angular are commonly used for building complex web applications. Although frameworks like React can ensure easier maintenance of larger codebases, for this project vanilla JavaScript was chosen as the project's codebase is relatively small and vanilla JavaScript has faster load times, greater control, and flexibility.

4.1.2 Cloud Hosting Platforms

Heroku was picked as the cloud hosting platform. It offers a number of advantages for hosting web applications built using HTML, CSS, and JS. Heroku has a straightforward deployment process, making it easy to get the application up and running quickly as well as an easy-to-use web-based interface for managing the application. Heroku is built on top of Amazon Web Services, which provides a robust and scalable infrastructure for hosting applications. This allows the application to easily scale as needed and manages performance and security issues. It has a large and active community, which means that there is plenty of documentation, support, and resources available for developers. Overall, Heroku is a reliable and efficient choice for hosting a microworld built using HTML, CSS, and JS.

4.1.3 Data Visualisation Technology Choices

Table 4A shows a comparative analysis of some JavaScript libraries available for visualisations. To meet the design requirements of including simulations and interactive visualisations, simulation visualisation was one of the criteria. It was also essential to choose a library that allowed for a broad range of customisations and animations to ensure that the visualisations aligned with the design's specific needs and requirements. Therefore, extensibility was also a critical factor. Given the importance of a good user experience, compatibility with different browsers and devices is important to ensure that visualisations work consistently across various platforms. In addition, considering the time constraint of the project, the ease of learning and using a library was a significant criterion. Moreover, the availability of documentation, tutorials, and resources is crucial in learning and using a library effectively.

Table 4-A: Table comparing a sample of JavaScript libraries

Library	Simulation Visualisations	Extensibility	Compatibility	Learning Curve	Documentation and Resources
D3.js	Lots of flexibility in designing and customising visualisations.	Highly extensible for manipulating data and custom visualisations.	Highly compatible across devices and browsers.	High	Extensive and well-maintained, with a large community offering support.
Chart.js	Some flexibility in customisation but is more limited compared to other libraries.	Extensible using plugins.	Highly compatible across devices and browsers.	Low.	Extensive and well-maintained, with a large community offering support.
P5.js	Lots of flexibility in designing and customising visualisations and animations. Has an intuitive and flexible interface for creating dynamic graphics, animation, and interactive applications.	Highly extensible, with a wide range of customisation options. Has the ability to create custom simulation visualisations and animations.	Highly compatible across devices and browsers.	Low.	Extensive, well-maintained, comprehensive and user-friendly, with numerous examples and tutorials available online.
HighCharts	Lots of flexibility in designing and customising visualisations.	Extensible for chart types.	Highly compatible across devices and browsers.	Low	Not open-source and requires a license for commercial use.

Plotly.js	Lots of flexibility in designing and customising visualisations, including 3D visualisations.	It is a relatively new library thus has less extensive features compared to other more established libraries.	Highly compatible across devices and browsers.	Low	Extensive and well-maintained, with a large community offering support.
Google Charts	It offers some flexibility in customisation but is more limited compared to other libraries.	Extensible library that can create custom charts and visualisation	Highly compatible across devices and browsers.	Low	Its documentation is extensive, and there is a large community offering support
Three.js	It offers excellent flexibility in designing and customising 3D visualisations.	Extensible library for creating 3D graphics and animations.	Highly compatible across devices and browsers.	High	Its documentation is less comprehensive compared to other libraries and there is a relatively small community offering support.

The analysis identified useful functionalities as well as drawbacks and limitations of existing libraries. P5.js library was chosen for this project because this design requires 2D animated simulations so a highly flexible library that provides complete control and customisation is needed. One of the unique features of p5.js is its minimal pre-set functionality, requiring developers to build visualisations from scratch. Although this requires additional effort, it enables the developer to design and implement simulation visualisations that align with their specific needs and requirements.

4.1.4 System Architecture

Table 4B shows a comparative analysis of different system architectures, based on a set of specific criteria similar to those used for comparing JavaScript libraries. The criteria used in this analysis were performance, development complexity, and user experience. Performance was assessed by comparing the loading times of different pages, while user experience was evaluated based on the interactivity and responsiveness of the system. Development complexity compares how simple or complex the system architecture is to implement.

Table 4-B: Comparing system architecture

Rendering Options	Performance	User Experience	Development Complexity
Client-side Rendering	Slow initial load times but subsequent page views can be fast.	More interactive and responsive user experience.	Simple to implement, flexible and easy to maintain.
Server-side Rendering	Fast initial load time but subsequent page views may be slow.	Less interactive and responsive experience.	Complex to implement and less flexible.
Hybrid Rendering	Fast load times and fast subsequent page views.	Responsive and interactive.	Complex to implement and difficult to maintain.

The analysis identified useful functionalities as well as drawbacks and limitations of different system architecture. It was decided that client-side rendering would be used for this design. While server-side rendering is better for larger applications that require a consistent user experience, this application is relatively small and demands a highly interactive user experience, which makes client-side rendering a more suitable option. While hybrid rendering can offer a balance between performance and flexibility, the added complexity and maintenance requirements do not justify its implementation due to the time constraints of the project.

4.2 Simulation

The p5.js library offers a powerful draw function which enables dynamic visualisations to be continuously rendered throughout the program by repeatedly calling draw() over and over, which calls several functions to render moving agents within the simulation in real-time so that the user can witness the impact of their decisions on the environment.

Initially, the framerate (the number of times draw() is called per second) was set to 60 frames per second. However, during the development process, it was discovered that the framerate is affected by the varying capabilities of different computers, leading to slower than intended simulation performance on certain computers. Therefore, the framerate was set to 25 frames per second. This adjustment enabled the simulation to run smoothly on both slower and faster computers, while still maintaining sufficient visual quality.

This microworld contained many components, and classes needed to be developed for each. The four Nitrogen molecules and the three bacteria involved in the Nitrogen Cycle were all in the NitrogenCycleComponent (NCC) class. The Earthworm Class was modelled on the Snake in the popular Snake game (Angelos, 2021). Classes were also developed for Plants, Rain, and a Fish class was created to represent aquatic life.

4.2.1 Simulating the Nitrogen Cycle

As described in Chapter 2 the Nitrogen Cycle is a multi-step process in which different bacteria convert Nitrogen from the air into forms that can be absorbed by the plant roots.

The movement behaviour of the NCC (the bacteria and Nitrogen components) in the simulation is handled by the move() method, which uses conditional statements to determine the NCC’s behaviour based on their current state and location. In order to simulate the chemical reactions between the different bacteria and the Nitrogen compounds that result in Nitrogen-fixing , a function called checkContact() was created, which loops through all the NCC’s and checks their location against every other NCC. If the specific bacteria and Nitrogen compound are in close contact, the bacteria converts that form of Nitrogen into a more absorbable form according to the following equation:

Nitrogen gas (*rhizobia*)→ ammonia (*nitrosomonas*)→ nitrite (*nitrobacter*)→ nitrate

To simulate plant absorption of nutrients whenever NH_4, NO_4 or NO_3 is located within the region where plant roots are present the NCC’s y value will decrease, creating the effect of the crop root absorbing the nutrient.

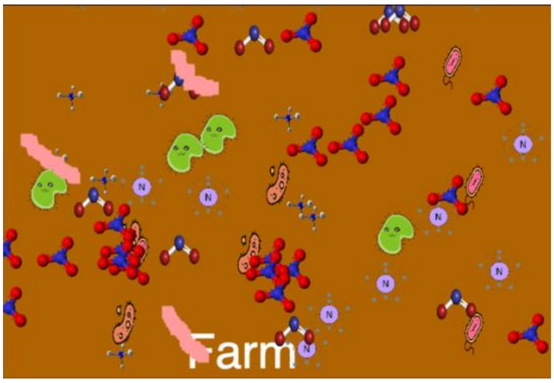


Figure 4.1: Nitrogen Cycle components moving around the soil

A challenge encountered when creating the move() method was checking if the NCC had collided with the slanted side of the VBS region, which is trapezoidal in shape. Unlike rectangular regions, checking if the NCC is within the boundary of a trapezoidal region is more complicated. To overcome this challenge, the trapezoidal region was split into a rectangular region and a right angle triangle region. The rectangular region was treated in the same way as the other rectangular regions by checking if the x and y values of the NCC are within the x and y values of the corners of the rectangle. For the right angle triangle, the code checks if the NCC is within the outside triangle that is formed by joining the right angle triangle with an outside triangle to create a rectangle see Figure 4.2. If the NCC is within this outside triangle, the x and y values of the NCC are multiplied by -1 to create the bouncing effect off the slanted side of the trapezoidal region.

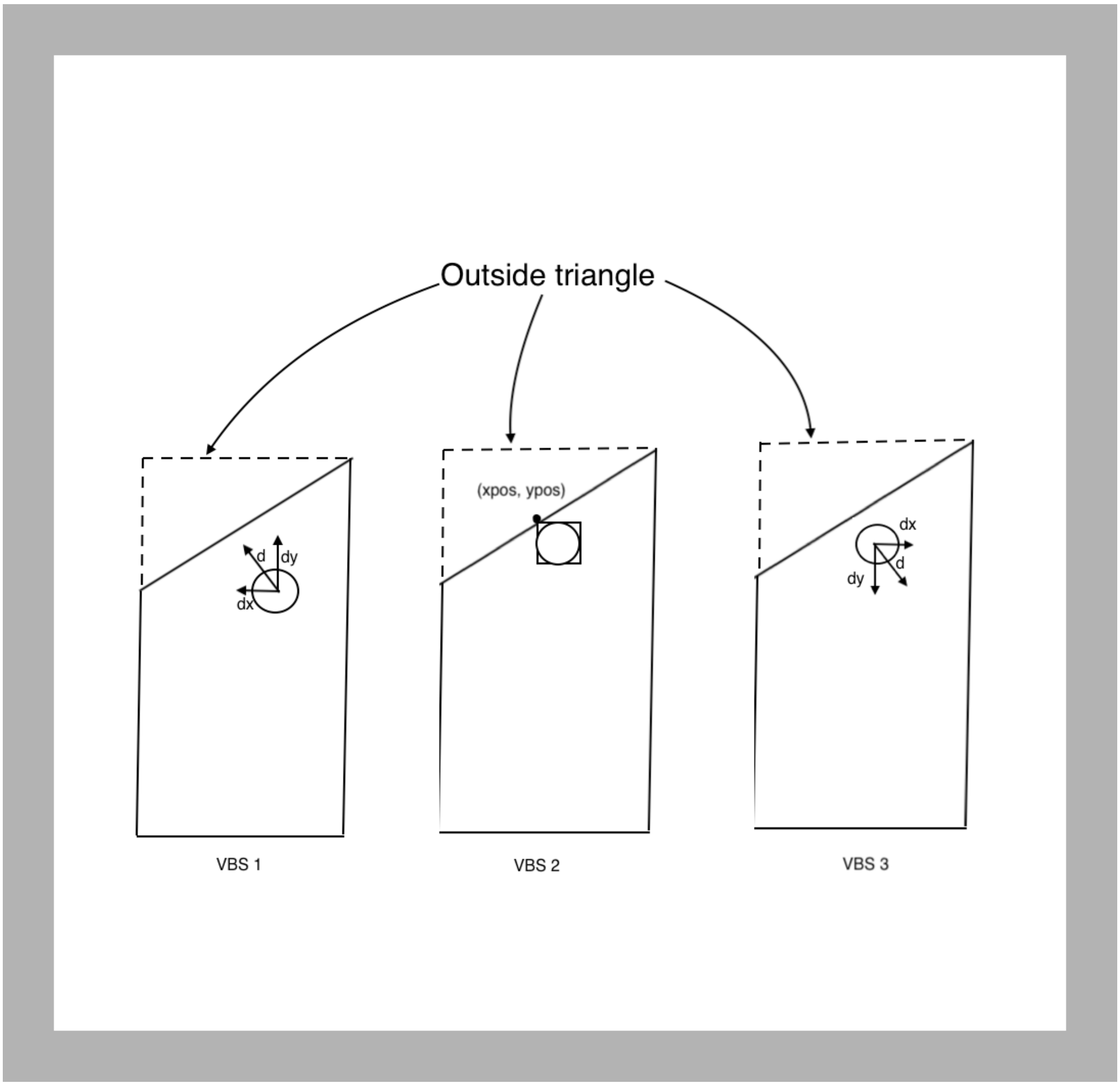


Figure 4.2: Diagram of a collision between a compound in the soil and the slanted sile of the VBS.

4.2.2 Simulating Earthworm

The Earthworm was modelled on the Snake in the popular Snake game. Both move on a 2D grid and turn as they move. However instead of the user's keyboard determining the direction of the snake the Earthworm needs to be programmed to move around the simulation independently. To navigate and change the direction of the worm, the changeDir() method is called. This method randomly determines which direction the EarthWorm should move next, based on its current direction and sets the xspeed and yspeed properties accordingly. The update() method then updates the position of the EarthWorm instance and its tail.

4.2.3 Simulating Plant Life

The Plant class has a render() function that displays an image of the plant and its roots at a given position. The translate() function is used to space out the plants on the farm, while the image() function is responsible for showing the images on the screen. When a plant absorbable nutrient (NH_4, NO_2 or NO_3) comes into contact with the roots of a plant, the size attribute of the plant is increased. The VbsPlant class extends the Plant class to display plants on the slanted side of the VBS.

Figure 4.3: Plants in the plant class

4.2.4 Simulating Rainfall

In the Raindrop class the fall() method updates the raindrop's position based on its speed and gravity, while the show() method displays the raindrop. By animating multiple raindrop objects using the update() and show() methods within the draw loop, the simulation creates the effect of rain.

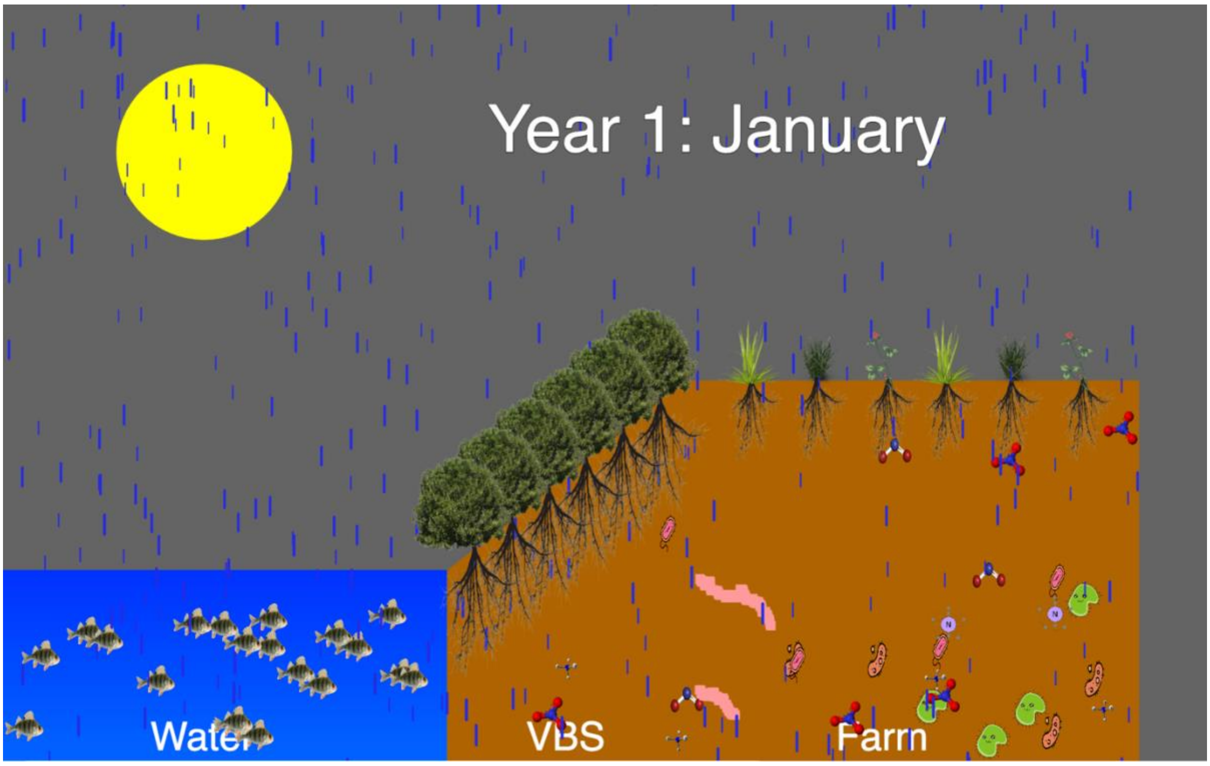


Figure 4.4: Example of the rain

4.3 Summary

This chapter discussed the implementation of the microworld, including the decisions that were made and challenges that had to be overcome. Technical decisions for the design outlined in Chapter 3 were made regarding the application's platform, library, and system architecture. The microworld was implemented as a web application using HTML, CSS, JavaScript, and P5.js. It is deployed on the cloud hosting platform Heroku. In addition to these technical decisions, implementation involved simulating the Nitrogen Cycle, the effects of artificial fertilisers on soil quality, the effects of runoff on local waterways including the ameliorating effects of VBS's and the relationships between optimising yield and environmental impact. There was interaction with the domain expert throughout the implementation and changes were made based on the feedback.

5 Testing and Evaluation

This chapter presents the testing and evaluation conducted to evaluate the tool's usability and educational value. To provide triangulation the microworld was tested by multiple audiences including a Botany academic (the project domain expert), Ph.D. Botany students, and non-Botany undergraduates.

5.1 Planned Lecture and Evaluation Session

For the testing and evaluation of the microworld, an interactive lecture and evaluation session was planned for the domain expert's Botany students. The session was to commence with an informative introduction to the topic using lecture slides, followed by the students' interaction with the microworld, enabling them to delve into different methods of managing water and soil sustainability while observing the outcomes of their decisions. Upon completion, participants would be requested to fill out a post-session questionnaire, providing insights into their experience of the microworld. A select group of participants would then be invited to take part in semi-structured focus group interviews that would last between 10 – 20 minutes, allowing for a deeper qualitative analysis of the questionnaire results.

Although this testing was scheduled to take place at the end of March, difficulties with timetables and project deadlines led to its cancellation. It was decided that the activity would be moved online. The domain expert would create a 5-10 minute video as an introduction to the topic, after which the students interact with the microworld and complete the accompanying questionnaire. This online activity was granted the necessary ethics approval.

Unfortunately, due to circumstances outside author's control the domain expert was unable to share the video and link with her class. Instead an opportunistic approach was taken and it was decided that the microworld would be tested on a sample of the author's peers, including Botany students and zoology students within the author's university. This approach aimed to leverage the diverse backgrounds and knowledge of the participants while also testing the microworld's effectiveness in a broader setting. This testing consisted of the participants interacting with the microworld remotely and then answering a questionnaire comprised of two sections (usability test and educational questions).

5.2 Usability Testing

Usability testing is a crucial aspect of evaluating the user experience of applications, and there are several methods available for assessing and comparing interfaces in terms of their usability and other desirable attributes. Two commonly used and respected methods are the System Usability Scale (SUS) and the Post-Study Usability Questionnaire (PSSUQ).

5.2.1 System Usability Scale (SUS)

The System Usability Scale (SUS) is a well-established questionnaire-based method for assessing the perceived usability of an interface. It consist of ten statements that are rated on a five-point Likert scale ranging from "strongly disagree" to "strongly agree". The SUS is designed to balance positive and negative statements, which helps to mitigate response bias.

1. I think that I would like to use this system frequently.
2. I found the system unnecessarily complex.
3. I thought the system was easy to use.
4. I think that I would need the support of a technical person to be able to use this system.
5. I found the various functions in this system were well integrated.
6. I thought there was too much inconsistency in this system.
7. I would imagine that most people would learn to use this system very quickly.
8. I found the system very cumbersome to use.
9. I felt very confident using the system.
10. I needed to learn a lot of things before I could get going with this system.

Figure 5.1: SUS questions

https://www.usability.gov/how-to-and-tools/methods/system-usability-scale.html

SUS scores are calculated by subtracting 1 from each odd-numbered statement rating and subtracting the participant's response from 5 for each even-numbered statement, and multiplying the sum by 2.5 to obtain a score between 0 and 100. The primary use of the SUS is in quantitative usability testing, as it provides a standardised score that can be compared across different interfaces and studies. Due to its widespread use since its introduction in 1986, the SUS has accumulated a large dataset of responses, allowing for more meaningful comparisons and benchmarking. (Peres, et al., 2013)

5.2.2 Post-Study Usability Questionnaire (PSSUQ)

PSSUQ is a method similar to SUS, measuring the user's perceived satisfaction through a series of statements that users agree or disagree with using a Likert scale. However, PSSUQ was designed specifically for scenario-based usability studies, so its questions are more targeted, such as "I believe I could become productive quickly using this system".

1. Overall, I am satisfied with how easy it is to use this system.
2. It was simple to use this system.
3. I was able to complete the tasks and scenarios quickly using this system.
4. I felt comfortable using this system.
5. It was easy to learn to use this system.
6. I believe I could become productive quickly using this system.
7. The system gave error messages that clearly told me how to fix problems.
8. Whenever I made a mistake using the system, I could recover easily and quickly.
9. The information (such as online help, on-screen messages, and other documentation) provided with this system was clear.
10. It was easy to find the information I needed.
11. The information was effective in helping me complete the tasks and scenarios.
12. The organization of information on the system screens was clear.
13. The interface of this system was pleasant.
14. I liked using the interface of this system.
15. This system has all the functions and capabilities I expect it to have.
16. Overall, I am satisfied with this system.

Figure 5.2: PSSUQ questions h

ttps://uiuxtrend.com/pssuq-post-study-system-usability-questionnaire/#:~:text=The%20PSSUQ%20(Post%2DStudy%20System,System%20Usability%20Metrics)%20in%201988.

Compared to SUS, PSSUQ is longer with 16 questions in total, and the answering scale ranges from 1 to 7 instead of 1 to 5, allowing for more nuanced responses. PSSUQ scores are calculated by summing up the responses to each question, subtracting 1 from each response, and multiplying the sum by 25/16 to obtain a score between 0 and 100, reflecting overall user satisfaction based on the respondent's experience. PSSUQ also has 3 sub-scores, derived from subsets of the 16 questions. The three sub-scores can identify specific areas where improvements can be made in system usefulness, information quality, and interface quality (Klaassen, et al., 2016)

5.2.3 Usability Questionnaire Criticism

Questionnaires are widely used in usability testing to assess user's perceived satisfaction and the system's perceived usability. However, despite their popularity, questionnaires have several drawbacks that should be considered when using them as a means of measuring usability. One of the main criticisms of questionnaires is their subjective nature. The results obtained from questionnaires are based on participant's subjective opinions, which are influenced by a variety of factors such as mood, context, and personal biases. As a result, the data collected from questionnaires may not accurately reflect the actual (objective) usability of the system being tested. (Orn, 2013) Another criticism of questionnaires is their limited scope, as questionnaires may not capture subtle nuances of user experience that are not easily quantifiable (Orn, 2013).

Nielson (2021) explains that usability questionnaires such as SUS do not provide a complete picture of the user experience. Therefore, it is important to spend time observing the participants as they use the system to identify what comes easily, what's challenging, and how they perform their tasks. For example, while it is common for questionnaires to ask about the visual design's appeal, a better assessment can be obtained by noting users' comments as they use the system.

Despite questionnaires only measuring the participant's version of interaction, which can be positively biased or brutally honest, this is their opinion of the system, which is important. Questionnaires are a valuable tool, that provide a standardised and systematic way of measuring user satisfaction and can be useful in identifying areas where improvements can be made. However, it is important to recognise the limitations of questionnaires and to use them in conjunction with other methods, such as user observation to obtain a more complete understanding of the usability of the system.

5.3 Creating the Questionnaire

The questionnaire was created to gather feedback from peers to evaluate the tool's educational value and usability (Appendix 3).

5.3.1 Choosing the Educational Questions.

The project aimed to create an educational tool that help learners achieve specific learning outcomes. To evaluate its effectiveness, a survey was conducted, which included questions to determine if the learning outcomes were met. Participants were asked to describe three things they learned from the session, their opinion on the simulation's ability to raise awareness about environmental issues, and their likelihood of using or recommending the tool in an educational setting.

5.3.2 Choosing a Usability Questionnaire

The System Usability Scale (SUS) was selected as the questionnaire to evaluate the perceived usability of the microworld. When deciding between SUS and PSSUQ tester fatigue was considered. "PSSUQ is a longer more complex survey, and therefore puts greater cognitive stress on testers. If the test is already complex it is better to use SUS. " (Rotolo, 2017)

Additionally SUS, unlike PSSUQ, is specifically designed to balance positive and negative statements, which helps to mitigate response bias. The primary objective of the questionnaire is to determine the perceived usability of an application. (Sauro, 2011) Both SUS and PSSUQ are well-established methods for accomplishing this, but SUS was chosen due to it having fewer questions while still including the relevant features necessary for a sufficient evaluation.

5.4 Peer Feedback

This section discusses the results obtained from the questionnaire filled out by 11 participants. The results from the educational questions are discussed first, followed by the results from the usability questions.

5.4.1 Educational Question Results

In order to evaluate the effectiveness of the application, feedback was gathered from the author's peers, including students in Botany, and Zoology. Overall, the feedback received indicated that the application was successful in meeting the learning objectives, as evidenced by the responses to the question "Describe three things you learned from today's session." For challenge 1, the learning objective was to teach users about the Nitrogen Cycle and the benefits of Nitrogen-fixingplants. Responses such as "Nitrogen fixers are important" and "Nitrogen-fixingplants like beans, peas and clover are good" indicate that users were able to understand and retained the information presented in this challenge. Challenge 2 aimed to teach users about

VBSs, and the feedback suggests that this learning objective was met. Only two respondents did not mention VBSs in their list of three thing they learned from the microworld. Responses such as “VBS are important to prevent runoff” and “You don’t need VBS if you don’t use fertiliser” demonstrate that users were able to understand and retained the information presented in this challenge.

The third challenge required utilising the knowledge gained from the previous challenges to optimise profits. Through the use of multispecies cultures, it was possible to increase yield without a corresponding increase in fertiliser usage, thereby keeping costs low and yields high. While there were fewer responses specifically related to this learning objective, one user did mention “Mixing crops are beneficial.” It is possible that the lack of a mediated learning environment for this challenge made it more difficult for users to fully understand and apply the concept of multi-species cultures, leading to fewer specific responses related to this objective. However, overall, the feedback suggests that the microworld successfully met its learning objectives and provided a valuable learning experience for users.

	C
1	Describe three things you learned from today's session
2	nitrogen fixers are important, VBS are important to prevent leaching nitrogen fixing bacteria live on roots of legumes
3	1. Clover is good for soil. 2. Vegetative buffer strips help protect water biodiversity. 3. Mixing crops are beneficial.
4	Nitrogen fixers are good for soil. Different vegetation affect the effectiveness of VBSs. Trees are the most effective at absorbing runoff.
5	I learnt about the bacteria involved in the nitrogen cycle such as Rhizobia and Nitrobacter. A 12 meter VBS with grass is not very effective (all the fish die :( ). Fixers are good for soil.
6	1. more fertiliser dose not necessary mean more profit. 2. crops need nitrogen cycle to grow 3. N2 is not plant absorbable.
7	i) I learnt about what Vegetative buffer strips are and how they can be used to protect the fish. More worms is an indication of a healthy soil.
8	1. Nitrogen fixing plants like beans, peas and clover are good. 2. Fertilisers are bad for soil. 3. Vegetative buffer strips (I didn't know what they were)
9	Clover is a nitrogen fixing plant. Clover is better for soil than grass. To much fertiliser is bad for soil.
10	I learnt about VBSs and how they absorb runoff.
11	Fish die from too much fertiliser. You don't need a VBS if you don't use fertiliser. Woody vegetation works best as a VBS.

Figure 5.3: Results for the question "Describe three things you learned from today's session"

One interesting way to assess the effectiveness of the simulation was by examining the participants’ response to questions about whether they believed the microworld could raise awareness about environmental issues, and if they would recommend the microworld in an appropriate educational setting.

The tables below demonstrate that the majority of participants believed that this microworld could help raise awareness about environmental issues, with 91% of respondents answering yes and 9% responding maybe. Additionally, the results showed that the majority of participants would recommend the tool in an appropriate educational setting.

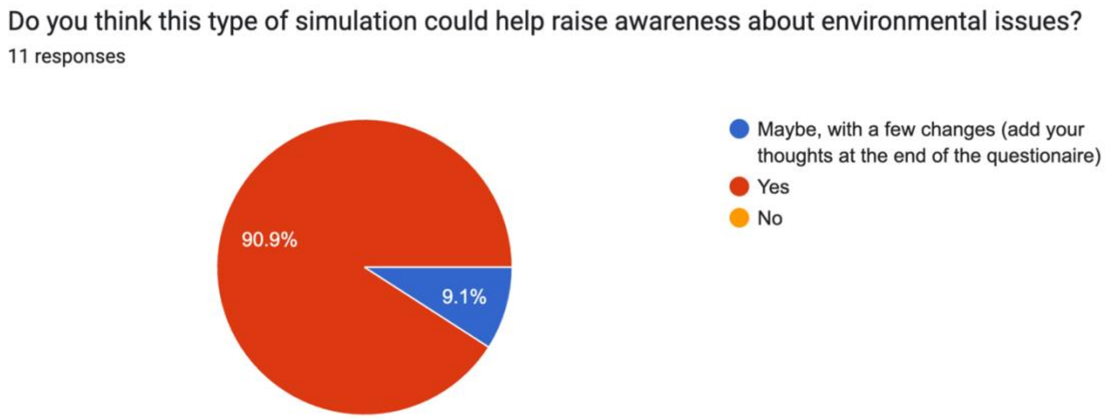


Figure 5.4: Result for question about raising awareness about environmental issues (pie chart)

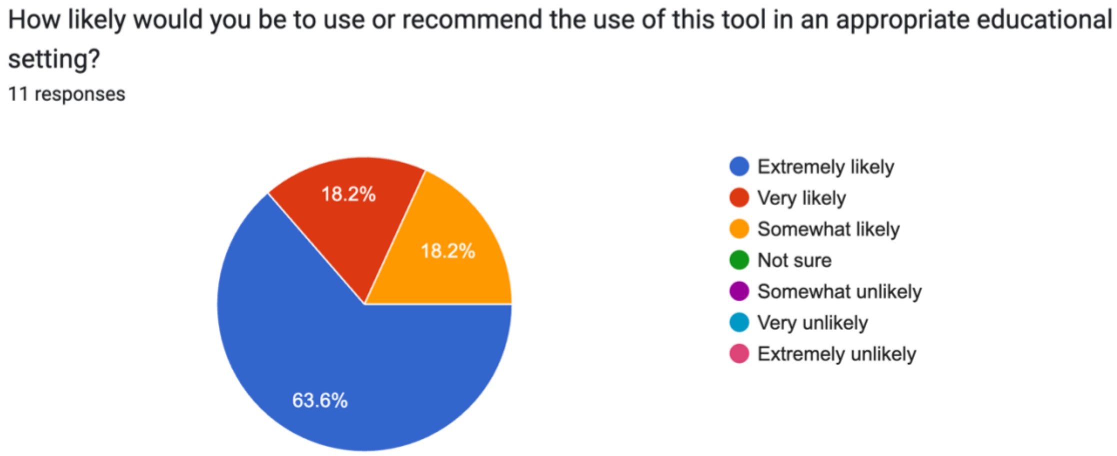


Figure 5.5: Results for question about recommending the tool (pie chart)

5.4.2 Usability Results

The peer questionnaire included the completion of the SUS by 11 participants. While the sample size in this study was small it is not untypical and SUS results still provide a good indication of the perceived usability of the microworld.

SUS uses percentile ranks to indicate how the SUS score compares to other interfaces tested using SUS, with the average score at the 50th percentile being 68, any score above 68 is above average while a score below 68 is below average. As the score for this project was 78, it is above average and in the 88th percentile. This suggests that the interface is perceived as user-friendly and intuitive, and users perceive it to be easy to navigate and interact with the application.

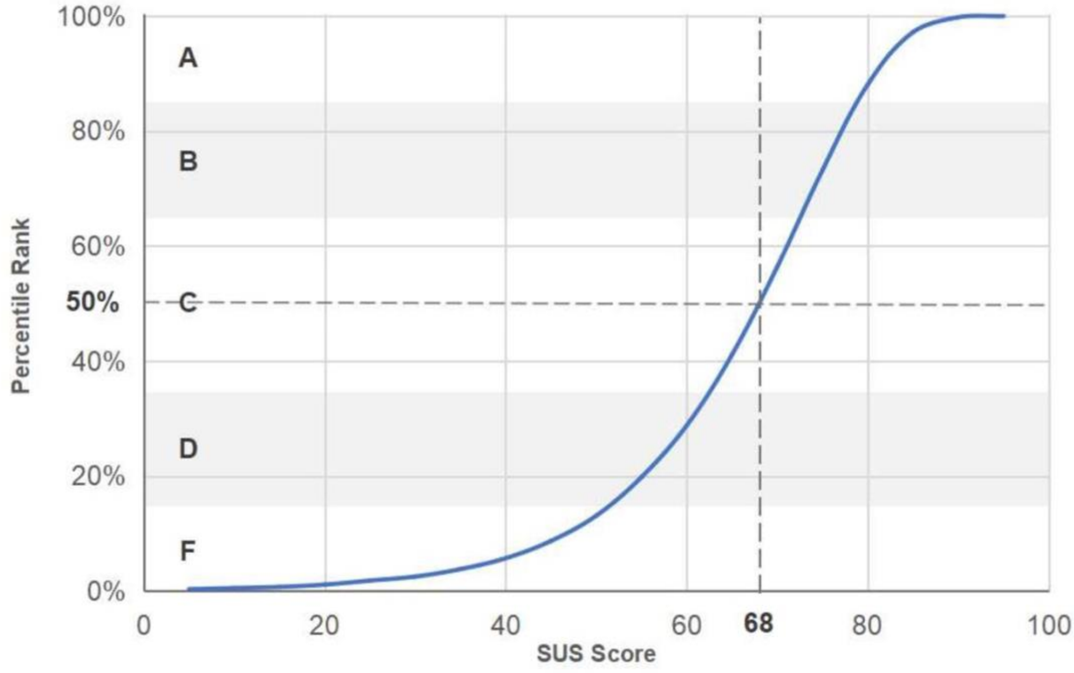


Figure 5.6: SUS on a curve with percentile ranks and grades.

https://measuringu.com/interpret-sus-score/#:~:text=Percentiles&text=Percentile%20ranks%20tell%20you%20how,below%2068%20is%20below%20average.

While most of the SUS questions received positive responses, the question "I think that I would like to use this system frequently" elicited mixed reactions from participants, with some strongly disagreeing and other strongly agreeing. This finding may suggest that users do not see a need to use the application beyond once or twice. However, it is important to note that the project's goal was to create a microworld where users can learn about a topic, understand it, and move on, rather than an application that is meant to be used frequently. Therefore, this result is not surprising, however brings the overall SUS score down.

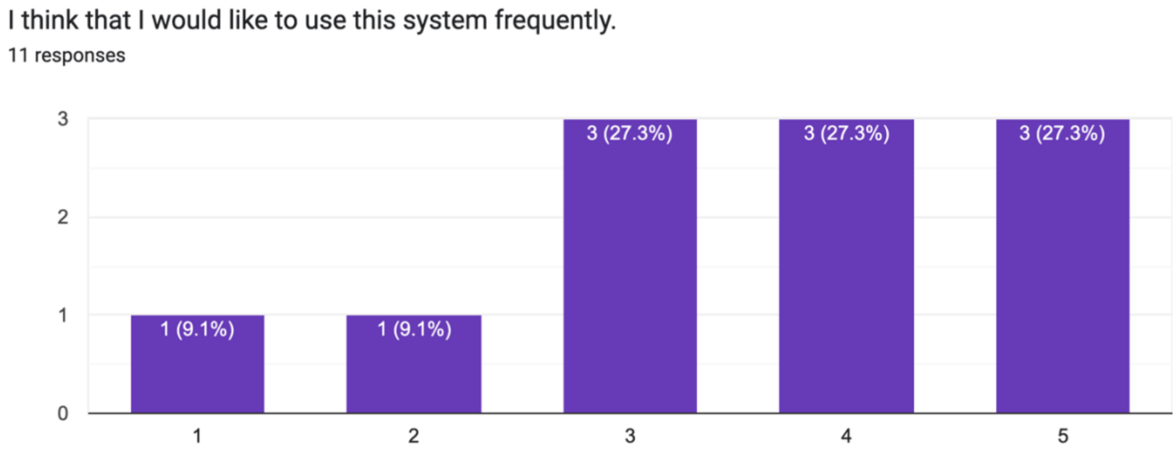


Figure 5.7: Result for SUS question about using the system frequently (column-chart)

The question "I need to learn a lot of things before I could get going with this system" also received mixed feedback from participants. Upon analysing the qualitative feedback, it appears that the low scores may be attributed to the absence of a mediated learning environment for the application, as some participants suggested including more explanatory material. Therefore, a user's response indicating the need to learn a lot beforehand is related to the Botany topic rather that the application's usability. It is important to note that this question is part of the SUS questionnaire, which aims to assess the ease of use and intuitiveness of the application, rather than the user's prior knowledge of soil and water quality. Participants should have been provided with clarification on this question. Moreover, as the application is designed for Botany students, it's expected that the challenges are difficult and users need to have an in-depth knowledge of the topic before using the system. Nevertheless, future iterations could improve the clarity of the questionnaire and include more material on the Botany topic.

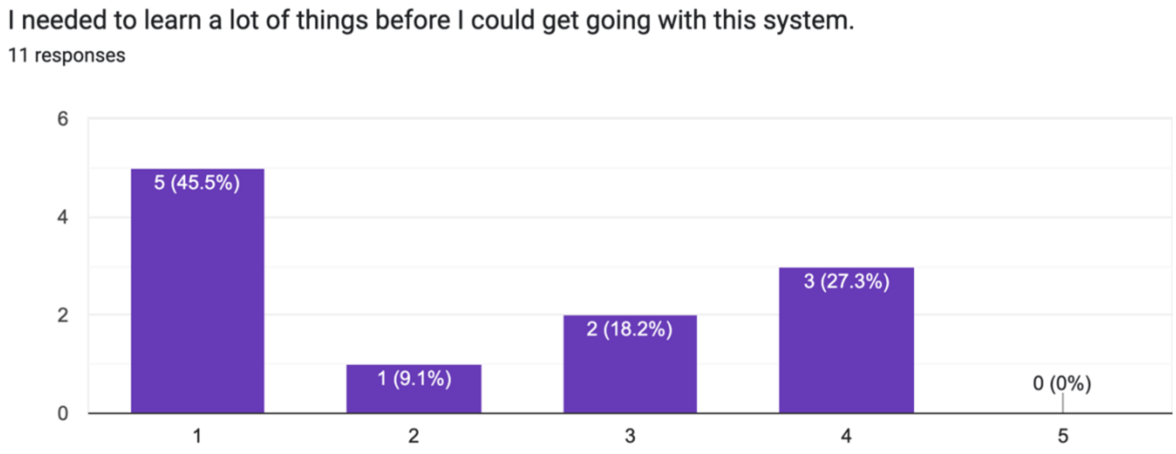


Figure 5.8: Results for SUS question about learning before using the system (column chart)

While some questions received mixed responses, the overall results suggest that the application is usable and accessible. This provides a solid foundation for future iterations with ongoing testing and evaluation.

5.5 Domain Expert Feedback

The domain expert, was involved in the entire development of the microworld to ensure its accuracy. Her feedback was taken into account each week, resulting in changes to the microworld. The domain expert confirmed that the microworld met expectations, and expressed satisfaction with the simulation.

As mentioned previously, while questionnaires are a valuable tool, it's important to recognise their limitations and supplement them with other methods like user observation to gain a better understanding of the system's usability. During the testing of the application, four PhD students were observed using the system with the author present but providing no instructions on how to use it. The feedback received was overwhelmingly positive, with participants being able to complete tasks and expressing appreciation for the simulation design. This was determined through observations of their reactions and comments such as "It's raining, that's cool," "I like the worms," and "My fish are dying, oh no."

During the testing, it was observed that none of the users accessed the How it Works page. All four participants proceeded directly to Challenge 1 and began interacting with the system, acquiring knowledge as they progressed. This observation was interesting and reenforced the idea that users prefer to learn by doing rather than reading instructions. Moreover, it indicates that the How it Works page is not an effective way to introduce these users to the system. Consequently, the system should be designed to be intuitive, with clear instructions integrated into the interface. Based on this observation, the How it Works page was removed.

Some feedback suggested changes to the VBS and dashboard. The feedback suggested that the VBS should be subtracted from the farmland instead of the waterway as this would be a more realistic representation. However due to time constraints it was not possible to make this change. Another suggestion was that the Dashboard should have less information on soil and water quality and more information on the cost of crops and fertilisers. The necessary changes were made to improve the Dashboard.

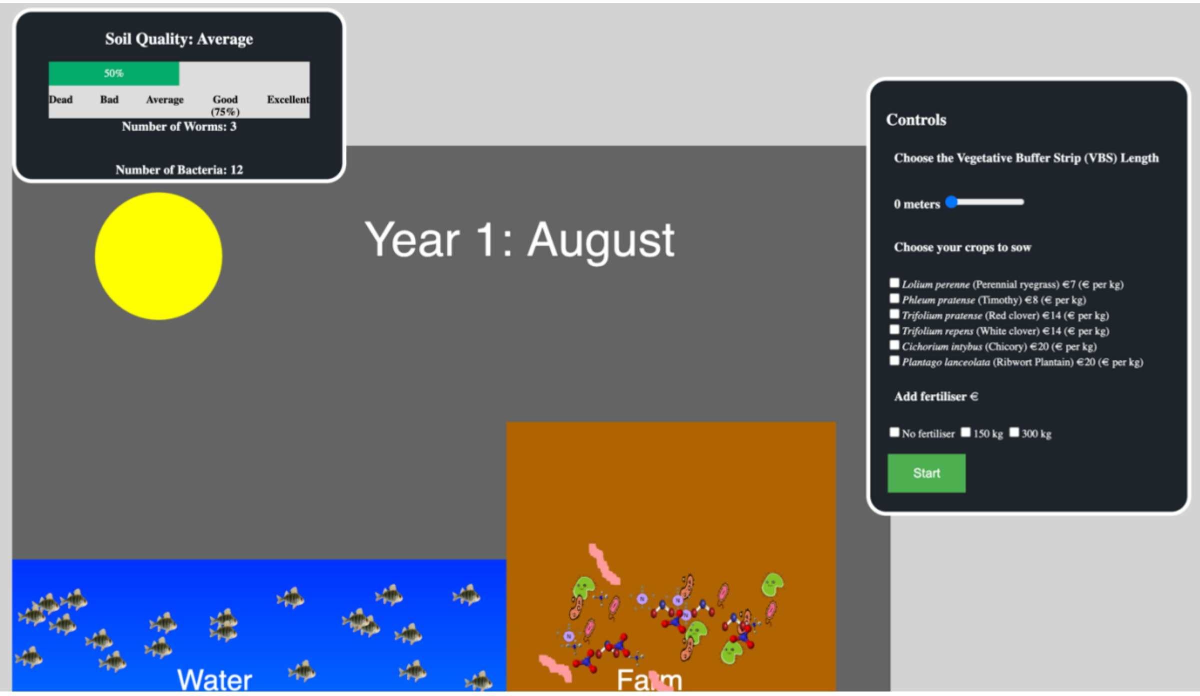


Figure 5.9: Challenge 1 before the changes were made.

The resulting changes can be seen in the Figure 5.10, with a clearer dashboard displaying only the relevant information.

Figure 5.10: Challenge 1 after the changes were made.

5.6 Summary

This chapter discussed the testing and evaluation of the microworld. To provide triangulation the microworld was tested by multiple audiences who evaluated the tool's usability and educational value. Those involved in the testing were a Botany academic (the project domain expert), Ph.D. students in Botany, and non-Botany undergraduates. Both the quantitative and qualitative data was collected. (Plans to test the tool with Botany undergraduates did not come in fruition of reasons outside the author's control). From a HCI perspective data from the System Usability Scale indicated that respondents were satisfied with the overall usability of the tool, with all respondents (N=11) stating they would recommend using the tool in an educational setting. Analysis of other data showed the tool helped learners to understand the topic and raised awareness of environmental issues.

6 Conclusions

The aim of this project was to develop a microworld to aid in teaching undergraduate Botany students the effects of farming on soil and water quality. Throughout the development process, the domain expert actively contributed valuable insights and expertise.

Extensive research was conducted including meeting with researchers and reviewing the literature on topics related to soil and water health, including the Nitrogen Cycle, the effects of fertilisers, plant diversity, crop yield, and multispecies culture. In addition, different modelling tools that could be used in the simulation were analysed, and ultimately agent-based modelling was chosen. Research was conducted into visualisation techniques to display soil and water quality as well as microworlds and related pedagogical theories. Microworlds espouse the idea of creating powerful thinking tools, while visualisations are essential to creating the cognitive loop that makes the application become part of the thinking process. Research was conducted on HCI principles to facilitate the development of a user-friendly and effective computer system. A sample of similar applications were also compared to inspire the design process and gain insights into the strengths and shortcoming of existing applications.

The goal was to design a low fidelity microworld that focuses on teaching key concepts instead of precise modelling, supported by pedagogical theories. The tool was designed to provide learners with the ability to change input variables, and observe the effects of their decisions on soil and water quality. Three challenges were developed to gradually increase the complexity and engage learners. Universal design and HCI principles were used to model the simulation, with a focus on enhancing the flow of the application and allowing users to concentrate on discovery rather than learning about the interface. Throughout the design process, the feedback from the domain expert was consistently incorporated.

The microworld was implemented as a web application using HTML, CSS, JavaScript, and P5.js. The technologies chosen proved to be advantageous, in particular the P5.js library's minimal pre built functionality and innate flexibility encouraged a level of creative freedom that was essential to this project. In addition, P5.js's extensive customisations options allowed for the simulation and animation of the following: the Nitrogen Cycle, the effects of artificial fertilisers on soil quality, the effects of runoff on local waterways including the ameliorating effects of VBS's and the relationships between optimising yield and environmental impact.

For testing and evaluation to provide triangulation the microworld was tested by multiple audiences who evaluated the tool's usability and educational value. Those involved in the testing were a Botany academic (the project domain expert), Ph.D. students in Botany, and non-Botany undergraduates. Both the quantitative and qualitative data was collected. Based on the evaluations in Chapter 6, it is evident it has the potential to positively impact individuals' understanding of the topic. While the evidence suggests the application incorporates the hallmarks of an effective microworld, and has the ability to positively affect learning outcomes, further evaluation is need including testing with Botany students in a mediated form to more accurately examine its effectiveness.

6.1 Future Work

This section offers possible extensions to the presented work.

6.1.1 Testing and Evaluation with Botany Undergraduates

Testing the effectiveness of the application as originally intended would be a priority in any future work. This would provide a more comprehensive qualitative and quantitative insight into the effectiveness of the tool.

6.1.2 Change the VBS

Following on from the suggestion from the Ph.D. students, to change the VBS so that it is subtracted from the farmland instead of the waterway, would be priority in any future work. This would be a more realistic representation and has the potential to enhance engagement with the simulator and enable learners to critically access the situation.

6.1.3 Modelling of Real Data and Scenarios

From interacting directly with Grange, et al. and having seen the research being done with Teagasc into sustainable farming, the author would be interested in following their research and expanding the microworld to reflect their future findings. This could allow for increased complexity and more interesting simulations that could extend the cognitive engagement of the learners. This could also help raise awareness about advances in sustainable farming practices.

6.2 Author's Reflection

Reflecting on the project as a whole, I found it very challenging but also an extremely rewarding experience. It was the first time that something I crated was being used by real people, which made me nervous, but it was also the most satisfying part. Witnessing people derive benefit and enjoyment from using my application was a tremendous source of satisfaction. Unlike group projects that I have worked on in the past, this project required me to plan, design, build, and evaluate an application at a much more in-depth and complex level. To successfully complete all of the elements of the project, I had to draw upon a wide range of software skills I had learned over my four years in college, from basic programming concepts in my first year to developing server architecture. As the sole developer of the application, I could not rely on playing to my strengths or avoiding aspects of development that were not my strong suit, as is often possible in group projects. Instead, I had to put in the time and effort to develop my weaker skills to ensure that they did not negatively impact the project. While managing the workload of this project during my busy Final Year was sometimes challenging, I am grateful for the experience, as it has made me a more well-rounded and capable coder.

Completing this project required more than just coding skills, as I also had to research and plan. Moreover I had no experience of formal writing. This was a major challenge for me, given that I am dyslexic and initially chose Computer Science to avoid writing lengthy essays. However, through this experience, I realised that academic writing is not just about presenting information, but also about constructing a compelling argument and using the research to support it. This newfound understanding changed my perception of formal writing and instead of simply summarising information, I focused on developing a logical argument. While this was difficult, I learned a great deal and proved to myself that I am capable of more than I thought possible. It still amazes me that I accomplished it.

Regular meetings with my project supervisor and the domain expert were invaluable in providing guidance and a roadmap for tackling such a complex project. Not only did I learn about soil, VBS, etc. through these meetings, but they also provided an enjoyable and effective way of learning. The domain expert answered my questions and corrected any misunderstandings I had. Additionally, the group meetings provided an opportunity to connect with other students who were also building microworlds for their projects. The feedback and support from these meeting deepened my friendships and allowed me to make new friends. I am grateful that my supervisor organised these meetings as they made the entire process much more enjoyable.

As someone with varied interests, including sports, art and sustainability, this project was an eye-opener, showing me that my computer science skills are valuable across many fields. It was a reminder that I don’t necessarily have to work for a tech company, and that my degree offers me a wide range of opportunities. This project has left me feeling excited about my future and the possibilities it holds.

Overall, this project was a challenging yet immensely rewarding experience that taught me a lot about myself and my capabilities. I take pride in creating something that I am proud to show off and will carry the confidence gained from this experience into my future career.

Appendix 1

When a species is planted as monoculture with a proportion of 1, there are no interactions and the yield is the expected yield for a monoculture of that species. In a four species equi-proportion mix of the two grasses and two legumes, the predicted yield (y) is 11.918, calculated as y = (9.25x0.25)+ (10.7x0.25)+(10x0.25)+(10x0.25)+(1.4x0.25x0.25)+(2.9x0.25x0.25)+ (6.4x(0.25+0.25) (0.25+0.25)) =11.918. This is an instance of transgressive overyielding where the yield from the mix (11.9) surpasses the yield from the highest performing mono-culture (10.7).

Appendix 2

A working version of the simulator can be found at:
https://fyp2023.herokuapp.com/

The survey given to the students for the evaluation can be found at:
https://forms.gle/z96o6k4iK7TTEqrb9

The source code of the application can be found at:
https://github.com/emer289/FinalYearProject2023

Appendix 3

Microworld to Teach About Soil and Water Quality

In the following questionnaire, researchers from Trinity College would like to collect information on your experiences from the "Microworld to Teach About Soil and Water Quality" session which you have just completed. Before you continue we would like to remind you again of the Participant Information Sheet for this research.

Participant Information Sheet

You have agreed to participate in the "Microworld to Teach About Soil and Water Quality" research project. This project is being undertaken as a Bachelor's Final Year Project as part of the B.A. Computer Science degree in the School of Computer Science & Statistics, Trinity College Dublin. The undergraduate student undertaking this research project is Emer Murphy, supervised by Dr. Brendan Tangney and Carla Harper.

Limiting pollution in water systems and in soil is essential for protecting the environment, preserving water quality, and addressing the challenges of climate change. It is important that students are educated on the topic however unfortunately these topics can be difficult to understand.

To Address this issue, a Microworld is developed based on an aspect of farming, you can attempt to maximise profits by selecting certain inputs, for example particular crops and fertilisers, over a given time period. The Microworld will model the effects of your choices on the local environment i.e. the soil and water systems. Choosing a more sustainable farming approach might initially reduce profits, but should ultimately result in healthier, more resilient soil, leading to increased crop yields and greater profits in the long run.

On completion of the simulation, you will be asked to complete a questionnaire. You may also be invited, individually or with a sample group of students to participate in an interview which will last 20-30 minutes and will be audio recorded for qualitative analysis. All questions are optional and you are free to omit a response to any questions; however the researcher would be grateful if all questions are responded to.

The experiment is expected to take approximately 2 hours to complete.

Your participation is entirely voluntary and at any stage of the process, you may change your mind and withdraw from the project. In this case, we will not use any information already collected on you. You may withdraw by verbally asking the researcher or by email.

All information collected by the researchers will be anonymised (all names and personal identifiable information) will be removed and will be stored in accordance with the General Data Protection Regulation at Trinity College, Dublin. Following a period of 5 years of the submission of the report, electronic copies of the data will be deleted from all storage sites, and paper copies will be shredded. In the unlikely event that information about illegal activities should emerge during the study, the research will have to inform the relevant authorities. There may be dissertations, conference presentations, lectures, and peer-reviewed journal articles written as a result of this project but you will not be identified.

A version of the produced report will be available to all participants. This report may include direct quotations from interviews. You may reach out to research to verify the validity of these quotes.

If you have any questions, feel free to contact Emer Murphy, murphe65@tcd.ie, and she will be happy to answer questions about the project.

Information of Data Controllers (GDPR)

Data Controllers: Trinity College Dublin

Data Protection Officer: Data Protection Officer, Secretary's Office, Trinity College Dublin, Dublin 2

dataprotection@tcd.ie

Yours sincerely,

Emer Murphy

B.A. Student, Integrated Computer Science

Project Leader

murphe65@tcd.ie

Dr. Brendan Tangney

Professor in Computer Science

Supervisor

Lloyd Building,

Trinity College Dublin, Dublin 2
tangney@tcd.ie

Please re-indicate your consent to continue. By selecting 'Yes' you will begin the questionnaire or by selecting 'No' you will be automatically exited from the questionnaire. *

• I have read, or had read to me, a document providing information about this research and this consent form. I have had the opportunity to ask questions and all my questions have been answered to my satisfaction and understand the description of the research that is being provided to me.

• I am aware that my participation in this research may involve filling in questionnaires and participating in individual or group interviews, which will need to be audio recorded for later qualitative analysis.

• I understand that all information that is collected by the researchers will be anonymised and stored in accordance with the General Data Protection Regulation at Trinity College, Dublin.

• I agree that my data is used for scientific purposes and I have no objection that my data is published in scientific publications in a way that does not reveal my identity.

• I understand that data that has been fully anonymised may also be shared with external researchers and project evaluators.

• I understand that if I make illicit activities known, these will be reported to appropriate authorities.

• I understand that I may refuse to answer any question and that I may withdraw at any time without penalty.

• I understand that if the results of the research have been published, or my data has been fully anonymised so that it can no longer be attributed to me, then it will no longer be possible to withdraw.

• I understand that I may stop electronic recordings at any time, and that I may at any time, even subsequent to my participation request to have such recordings destroyed (except in situations such as above).

• I understand that, subject to the constraints above, no recordings will be replayed in any public forum or made available to any audience other than the current researchers/research team.

• I freely and voluntarily agree to be part of this research study, though without prejudice to my legal and ethical rights.

• I understand that if I or anyone in my family has a history of epilepsy then I am proceeding at my own risk.

• I have received a copy of this agreement.

- [x] Yes
- [ ] No

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Next

Clear form

Microworld to Teach About Soil and Water Quality

murphe65@tcd.ie Switch accounts

Not shared

Each question is optional. Feel free to omit a response to any question; however the researcher would be grateful if all questions are responded to.

Describe three things you learned from today's session

Your answer

Do you think this type of simulation could help raise awareness about environmental issues?

- Maybe, with a few changes (add your thoughts at the end of the questionaire)
- Yes
- No

As a result of today's session, which of the following statements accurately reflects your interest in sustainability?

- Much more interested
- More interested
- No change
- Less interested

How likely would you be to use or recommend the use of this tool in an appropriate educational setting?

- Extremely likely
- Very likely
- Somewhat likely
- Not sure
- Somewhat unlikely
- Very unlikely
- Extremely unlikely

In your opinion, how likely would learners be to engage with this tool over existing teaching materials?

- Extremely likely
- Very likely
- Somewhat likely
- Not sure
- Somewhat unlikely
- Very unlikely
- Extremely unlikely

If you have any specific feedback regarding your experience using the tool, please share here

Your answer

System Usability Scale (SUS)

Each question is optional. Feel free to omit a response to any question; however the researcher would be grateful if all questions are responded to.

I think that I would like to use this system frequently.

Strongly disagree

1 ○

2 ○

3 ○

4 ○

5 ○

Strongly agree

I found the system unnecessarily complex.

Strongly disagree

1 ○

2 ○

3 ○

4 ○

5 ○

Strongly agree

I though the system was easy to use.

Strongly disagree

1 ○

2 ○

3 ○

4 ○

5 ○

Strongly agree

I think that I would need the support of a technical person to be able to use this system.

Strongly disagree

1 ○

2 ○

3 ○

4 ○

5 ○

Strongly agree

I found the various functions in this system were well integrated.

Strongly disagree

1 ○

2 ○

3 ○

4 ○

5 ○

Strongly agree

I thought there was too much inconsistency in this system.

Strongly disagree

1 ○

2 ○

3 ○

4 ○

5 ○

Strongly agree

I would imagine that most people would learn to use this system very quickly.

Strongly disagree

1 ○

2 ○

3 ○

4 ○

5 ○

Strongly agree

I found the system very cumbersome to use.

Strongly disagree

1 ○

2 ○

3 ○

4 ○

5 ○

Strongly agree

I felt very confident using the system.

Strongly disagree

1 ○

2 ○

3 ○

4 ○

5 ○

Strongly agree

I needed to learn a lot of things before I could get going with this system.

Strongly disagree

1 ○

2 ○

3 ○

4 ○

5 ○

Strongly agree

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