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MycroForest – Exploring the use of a microworld to teach about economic viability of climate aware forest management.

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Declaration

I, the undersigned, declare that this work has not previously been submitted as an exercise for a degree at this, or any other University, and that unless otherwise stated, is my own work.

The use made of AI tools in work described here, including the preparation of the document itself, is outlined in an appendix, as per the School guidelines. If relevant, use made of AI is also described in the body of the document.

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GAYATHRI GIRISH NAIR August 16, 2024

Acknowledgements

Abstract

Since industrialization, CO_2 levels in the atmosphere risen at an unnaturally fast pace due to anthropogenic activity. Today, forests absorb 30% of global annual emissions [1] and are integral to combating climate change. They are also, however, fragile. So, forest management education is important. This is especially true for 15 to 24 year-olds as they are decision makers of tomorrow who will inherit the planet and the challenge of rapid climate change. The Cities and Climate Change Project by the Intergovernmental Panel on Climate Change (IPCC) suggests that individuals in this age group have a strong sense of accountability, and are open to change [2]; thereby making climate change education very important for them

Several tools exist [3-7] to inform about ideas related to climate change/forests. Many are scientifically accurate decision-making aids aimed at experts or adults. Others are more abstract yet informative educational games. Few among these, target youth. Many, tackle several problems at once. While informative, this can be distracting or overwhelming. Effective education depends on learner engagement. Education technology tools based on microworlds have been successful at achieving this [8-11].

Thus, "MycroForest" as proposed here, is a web based microworld aimed at teaching young adults about the connection between forest management and CO_2 levels in the atmosphere. The tool enables learners to take on the role of a forest owner in a virtual world where they can create management plans involving planting trees or felling them for wood. Consequences of plans are reflected on the composition of the forest, atmospheric CO_2 levels, and virtual wealth. Using MycroForest, learners can be set challenges of increasing complexity like maximising income from the forest, maximizing carbon capture, or doing both. The tool is composed of a simulation, User Interface (UI) components, and input variables. The simulation is a simplified representation of tree growth and the carbon cycle using an object oriented approach. Designing a simulation that reflects patterns seen in nature, drafting a user friendly interface to best support possible effective learning scenarios, and developing the app using the NextJS framework were key design and implementation challenges faced as part of this project.

The proposed teaching tool was evaluated at a 2 hours session with 10 Transition Year students on the [TAP Bridge2College Programme]() at Trinity College Dublin. Feedback was also obtained from educators at the event. Overall, response to the app is largely positive with students finding it "informative", "fun", and "simple to use". The domain expert at the event was impressed with how students discovered for themselves, existing real-world forest management strategies like clear-felling and thinning using the tool with no prior knowledge about them or instructions from educators.

Overall, MycroForest is a web based teaching tool where students take on the role of a forest owner and put their own forest management plans to the test while striving to meet challenges set around learning scenarios and in the process, learn about the importance and difficulty of sustainable forest management in a constructivist fashion.

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1 Introduction

This section documents the motivation for this project and its goals. Referencing style adopted, and ethical compliance is also discussed here.

1.1 Motivation

Currently, we are amidst a climate emergency caused primarily due to heavy dependence on fossil fuels which show no signs of significant decline. There are multiple reasons for our global collective failure to reduce carbon emissions including economic, geo-political, psychological, and sociological factors. [12] Climate change negatively impacts almost all life on Earth given increasing temperatures, ocean acidification, desertification, and greater prevalence of extreme weather events, which in turn, would negatively impact society by leading to forced human migration, increased mortality, and possibly increased tension between societal factions at different stages of development and wealth [13]. Such environmental and socio-economic effects may also disrupt key industries, particularly agriculture [13], as productivity suffers. [12]

Since now considered an existential threat to humanity, it has been recognized that timely mitigation of rapid climate change demands global transformative reform at a fundamental level across technological, economic, and social factors that underpin direct drivers like fossil fuel usage. This was one of many messages put forth at the UN Climate Change Conference COP26 in Nov 2021. Such large scale drastic yet necessary changes however, are unlikely to happen via government efforts alone. It would require a shift in collective mindset and understanding between all stakeholders and key decision makers. [12] This is why, correct education targeted at key demographics like the youth is crucial to combating climate change.

In 2018, the Cities and Climate Change Project by the Intergovernmental Panel on Climate Change (IPCC) involved 99 youths (individuals aged 15 to 24) across diverse geographic and socio-economic backgrounds that collaborated with each other first digitally and then in person to produce the International Youth White Paper on Climate Change: Education and Cities. This project showed that the youth, to varying degrees, are aware of climate change, inequalities regarding responsibility or accountability of global warming and the importance of individual action. Feelings that they reported on the matter include fear, despair, guilt, shame, urgency, sadness, helplessness, and promisingly, hope and positive reappraisal. This suggests that young individuals who will soon comprise key decision makers tasked with solving the challenge of climate change, are indeed, eager to do something about it. [2] Thus, MycroForest aims to informing more members of this age bracket about the link between forest management and climate change.

So far, worldwide responses to government policies have been lukewarm at best despite several climate negotiations. There is a need to reinforce awareness about the urgency of the situation. It is important to realize that, given the difficult to model, non-linear and dynamic nature of Earth's climate, there exists a real risk of unexpected catastrophic changes catching us off guard despite best climate modelling efforts. Based on current trends and models, global average temperature is predicted to rise to between 2.1 °C and 3.9 °C by the end of the century which is expected to trigger several planetary tipping points from beyond which, restoration of natural systems become extremely difficult if not impossible. [12]

A *carbon sink* refers to any mechanism that absorbs more carbon than it releases to effectively remove it from the air so as not to contribute towards global warming. [14] Enhancing existing carbon sinks or creating new ones is among three suggested courses of action against climate change to avoid a dire future with the others being reduction of greenhouse gas (GHG) emissions and modification of Earth's energy balance. Efforts to lower GHG emissions have been historically inefficient and climate geo-engineering ideas like ocean iron fertilization, solar radiation management and marine cloud brightening have often proven infeasible or risky. [12] This means focussing on development and preservation of carbon sinks is a most practical option of the three.

Although Carbon Dioxide (CO2) is an important GHG that keeps Earth warm enough to support life, it's concentration in the atmosphere in excess is the primary driver of global warming and climate change. [13] Plants require CO2 for photosynthesis. Consequently, the almost 4 billion hectares of forests on earth absorb a large amount (around 30% of global emissions in 2022 [15]) of carbon from the air and store a portion of it as biomass. They are thus an important carbon sink [16, 17]. This carbon sink status of forests is however, fragile due to human activities. [17] Forests that are logged can turn into carbon sources. A carbon source refers to a system that releases more CO2 than it absorbs. This is because although forest regrowth is associated with fast absorption of carbon, deforestation leads to loss of a large amount of sequestered carbon due to heterotrophic activity and biological respiration as well as harvested biomass being burned for energy [15, 18]. Moreover, given that humans emit more CO2 than what new growth is estimated to be able to absorb, it is generally widely accepted that to fight climate change, in addition to planting more trees, active preservation of existing forests is necessary. [16]

This is supported by results of a detailed study by A. Daigneault et. al. in 2022 which modelled 81 future socioeconomic and climate policy scenarios across three common Forest Section Models to assess future forest climate mitigation pathways between years 2015 and 2105 [17]. In 95% of scenarios so modelled, projections point towards an increase in global forest carbon stocks under afforestation, shifting harvest patterns, and intensification of forest management. Further, with timber price expected to increase in the future and changes in forest carbon stocks found to be more positively correlated with changes in forest area and timber price than with wood harvests, the study by A. Daigneault et. al. also hints at it likely being possible to maintain economic viability of forests while promoting carbon sequestration through careful forest management strategies and alternate means of income generation.

Thus, teaching about the link between forest management and atmospheric CO_2 levels while also allowing learners to explore economic viability of forests through timber harvesting and other means of generating income from forests is a great way to promote awareness about the need to conserve forests, harvest responsibly, and discover new ways to sustainably earn from them. This also encourages learners to think about the financial motive, an indirect but fundamental influencer that underpins deforestation, which in turn, is a direct driver of climate change. The MycroForest teaching tool as presented in this work, strives to do this.

C. Karsgaard and D. Davidson, in their work about youth perspectives and Climate Change Education, point out some aspects of existing teaching approaches that may be strengthened. They stress the need to move away from the abstract “save the planet” idea to more concrete examples of how this might look like practically, to inspire action. [2] To this end, MycroForest presents sustainable forest management as one specific way to combat climate change.

Furthermore, while existing education concentrates on scientific reasons around the "what" and "how" of climate change; social, political, cultural, and economic reasons that define "why" is often overlooked. [2] By allowing learners to investigate the earning potential of a forest both in terms of timber sales and other resources or services, MycroForest garners attention onto the underlying economic “why” that motivates deforestation and by extension, climate change.

Increased engagement and attention w.r.t the subject matter has been linked to deeper understanding. Mindfulness that results from greater engagement often results in learners making a conscious effort to resolve conflict in their minds that stem from discrepancies between existing and new notions of an idea to eventually culminate in mental accommodation of novel concepts and improved assimilation of existing knowledge. [19] Further, teaching methods that promote problem-based, reflective, and inquiry-based learning have shown to strengthen persistence of learned ideas and enthusiasm towards learning [11].

A microworld is an interactive environment anchored on the theory of constructivism as first proposed by Jean Piaget [20] that facilitates such, long lasting and deep learning through “learning by doing or making” [21]. While microworlds may be digital or physical, the former makes for a more widely and easily accessible teaching tool [2]. Thus, MycroForest is a web-based teaching tool that incorporates a microworld comprising a simple conceptual model of a forest that learners can interact with through making their own forest management plans and decisions.

On the whole, the need to effectively educate the next generation about use of forests as carbon sinks being one practical part of the solution to the pressing issue of rapid climate change while encouraging them to think about economic viability of sustainable forest management, serves as prime motivation for this project.

1.2 Goal

The goal of this project is to build a microworld to inform 15 to 24 year old learners about the relationship between forest management decisions and atmospheric CO2 concentration, a key driver of climate change. In addition to the opportunity to earn income from timber sales, the tool shall also simulate effects of considering other streams of income from forests in an attempt to draw attention to the idea of conscientious commerce which is one of many principles encouraged as part of ensuring a sustainable future [22].

The result should be a user-friendly web application that comes with built-in help and support for gradual introduction of complexity. The tool should allow for features to be hidden and revealed at different stages in the learning activity so that learners may master simpler features first before gradually being introduced to the full complexity of the tool in stages, thereby ensuring a low entry threshold. [9]

The tool should incorporate a conceptual model of forest growth and the carbon cycle that reflects reality in sufficient detail. The simulated world should draw from observed natural phenomenon and be based on figures as measured on Earth. [4]

To promote self-regulated learning, the tool should be engaging and facilitate constructivist learning by allowing learners to draft their own forest management plans [19]. Learners should be able to take on the role of a private forest owner and make decisions regarding the number, frequency and type of trees chopped or planted over multiple years. They should also be able to pick between 3 options to earn income from the forest. Lastly, the app should allow users to increase or decrease amount of CO2 emissions due to fossil fuel usage and view effects of their decisions across time.

Hybridization of a microworld with elements of a simulation and gaming have been shown to produce particularly effective and engaging learning environments. Thus, to introduce gamification to improve motivation as well as further promote self-regulated learning, goal setting and ability to monitor own performance is key. The app should thus, enable learners to set targets such as atmospheric CO2 concentration and income goals such that graphical feedback presented informs about whether or not these targets have been met. [19]

Research shows that learners performed best when similar teaching tools provide graphical feedback supported by some instructional support. [23] Thus, MycroForest should favour graphics over text on the User Interface (UI) and reciprocate all user actions with graphical feedback. Built-in, easily accessible explanatory help is to be provided and land content should be indicated using informative icons that change over time. Adding or removing of forest management actions and income streams should be facilitated through a graphical user interface and consequence of CO_2 concentration in the air should be displayed on a scale with different colours coding expected quality of life for humans after considering effects of climate change at various value ranges.

Since exploratory learning is effective when guided by some structure. [9] MycroForest should be developed such that it is possible to formulate challenges using the app that increase the likelihood of specific learning outcomes. For example, it should be possible to set a challenge that encourages learners to maximize income from forests and another that allows them to strive towards minimizing CO_2 concentration so that the two may be combined in a third challenge to teach about the trade-off between these goals.

Finally, this project aims to evaluate MycroForest in terms of user experience, learning experience and changes in attitude towards climate change by having Transition Year students use the application as part of a 2 hour learning session and share feedback. Feedback should also be collected from tutors to assess perceived utility of this application as a teaching tool from the perspective of educators.

1.3 Referencing

This document adopts the Numerical style of referencing with EndNote to manage literature connected to Microsoft Word for inserting citations and the Bibliography.

1.4 Ethics

The tool was used by (N=20) TY students for a period of 1.5 hours as part of a two-day workshop, within the Bridge2College programme, exploring different aspects of climate change. Ethical approval for researching different aspects of the Bridge2College programme had been granted by the School of Computer Science & Statistics.

1.5 Document Structure

This document is organized such that this section 1 presents an overview and section 2 provides details regarding related areas of research and other similar tools. Section 3 explains design decisions, section 4 describes the implementation approach and Section 5 presents app evaluation methodology and results. Section 6 wraps up main content with a condensed review of the entire project.

2 Background

This section reviews other similar tools and describes existing work in areas like forest management, simulation design, education technology, and Human Computer Interaction (HCP) that guided key design decisions.

Please note that this section also mentions how ideas from existing work has been reflected in "MycroForest", the teaching tool that is the product of this work. Following section 3 shall describe the application in detail.

2.1 Forest Management

Forest management refers to actions comprising human interventions in forests driven by economic, social, or environmental principles to meet certain goals such as species/resource conservation/protection and maintenance/boosting of forest productivity. Common forest management actions include felling trees (deforestation), planting trees (afforestation), fertilization of degraded soil, building of infrastructure (roads to make the forest accessible, irrigation facilities, etc.), administering pesticides or weedicides for plant disease control, culling of invasive species, etc [24].

Ecosystem Services (ESs) refer to resources or services that a forest/ecosystem makes available. ESs may be categorized as (i) provisioning services (e.g. source of resources like wood/timber, food, water), (ii) regulatory services (e.g. climate regulation, water purification, pollination, etc.), (iii) cultural services (e.g. catering towards spiritual beliefs, provision of spaces for recreational activities, etc.), and (iv) supporting services (e.g. carbon sequestration, soil formation, nutrient cycling, etc. which comprise mechanisms that drive other natural systems crucial for life). Timber sales is the primary source of income from a forest [24]. Thus, given the economic viability and climate change premise of MycroForest, ESs that are of key interest include carbon sequestration and timber provisioning.

Planting and felling of trees are among most performed and important forest management actions because they are directly linked to timber production [24]. Thus, MycroForest incorporates these two actions (plant and fell) as possible forest management actions that learners may choose to perform in the microworld. In forestry, it is a common practice to create management plans per "rotation period". Here, a rotation period is the time between subsequent timber harvests, often on the scale of entire forest sub-plots/plantations. Clearing all trees in a plot at once is known as clear-felling and is often done at the beginning or end of a rotation period. This is one example of a very simple forest management strategy. Another approach may be to chop particular trees during intermittent years within a rotation period to encourage faster growth, sustained yield and so on. This is called thinning [25].

Rotation length is an important choice in a forest management plan [26] because it significantly affects various ecosystem services, especially carbon sequestration and thereby, the overall sustainability of forest ecosystems. In 2023, E. Z. Baskent and J. Kaspar evaluated the long-term effects of varying rotation lengths on multiple ecosystem services (timber production, water provision, carbon sequestration, biodiversity conservation, soil protection, cultural values upkeep), in a multiple-use forest management setting in the Bürücek forest in Turkey, by comparing outcomes of simulating various management strategies using the Ecosystem Based Multiuse Forest Planning Model (ETÇAP DSS). They analysed differences observed when keeping all other management choices, the same except rotation period length for each scenario. It was found that generally, shorter rotation lengths increase the frequency of harvests, leading to higher immediate wood production and economic returns. But they also result in lower overall volume of trees in the long term meaning that the carbon sequestration ability of the forest declines. Greater carbon sequestration was almost always associated with longer rotation lengths. However, limited felling less frequently can also lead to increased net carbon storage due to Harvested Wood Products (HWPs) keeping a certain portion of the wood locked within as it is preserved for human use such that emissions of the consequent deforestation was minimal and could be compensated by new growth and CO2 uptake by the remaining forest area [27]. Furthermore, there is also the notion that keeping mortality in the forest from being too high by felling few trees at medium long to long rotations and using it largely for purposes other than burning for energy, could lead to lesser net GHG emissions into the atmosphere than if they were left to decay. Similar behaviour of how some rotation lengths led to better carbon sequestration than both shorter and longer period lengths, was observed by Baskent and Kaspar such that they expect there to "very well be, an optimal rotation length for carbon–neutral conditions as the forests get regulated" [25]. Rotation period length is a key learner input in MycroForest.

All too often, the purpose of forest management plans are to increase timber production [26] driven by the large economic returns from wood sales, and hence tends to lead to un-sustainable levels of tree removal (deforestation). Deforestation is among biggest drivers of climate change with it responsible for around a 5^{th} of all Green House Gas (GHG) emissions [28].

Wood from forests is used for 2 broad purposes. It may either be burned for energy or can be turned into generally long lasting wood products. Some research shows that replacing non-renewable energy sources like fossil fuels with wood, known as energy substitution, is climate friendly due to comparatively lower GHG emissions upon burning. Additionally product substitution wherein more energy intensive materials like concrete is swapped for wood is also generally considered climate friendly [27]. Others argue that loss of existing forests and their role as carbon sinks cannot be compensated for by material substitution and especially energy substitution [29]. Thus, given high demand for wood alongside the role of timber as a primary source of income from forests and the detrimental effects of deforestation on the ability of forests to store carbon and by extension on the climate, when it comes to creating forest management plans, there is a clear trade-off between objectives for forest production and objectives for carbon sequestration [24]. MycroForest tries to highlight this trade-off and educate learners about the growing need to compromise on profits and invest in truly climate friendly practices to avoid impossible living conditions due to climate change.

A large portion of forests are private or community owned with many of them being small to medium sized [24] such that owners rely on them for all or a portion of their income [23]. As long as funding for ecosystem services like carbon sequestration remains inadequate and unreliable as is largely the case [23, 30], it is unrealistic to expect forest owners to completely refrain from felling trees. But given the risk of irresponsible exploitation of such forests leading to significant aggravation of the climate crisis, it is crucial that these forests be managed sustainably. Thus, it is imperative that ideas like that of Climate Smart Forestry (CSF) that advocates reduction/removal of GHG emissions while maintaining/increasing productivity of forests and quality of their services, be adopted widely to slow down climate change.

Diversifying means of income from forests is one way to lower the motivation to fell trees for timber. Another popular way to earn from forests include selling of Non Timber Forest Products (NTFPs) like honey, fruit, mushrooms, medicinal herbs, etc [23]. Yet another way is to make forests available to the public for recreational use and charge for amenities or forest experiences [31]. MycroForest provides the option to activate these two other income streams to teach learners about the possibility of earning form forests in other ways and accompanying challenges. With the exception of few cases like sales of the Boletus edulis mushrooms in South Africa fetching more income than wood sales, other means of income from forests like NTFP sales, forest recreation, hunting/fishing, and carbon credits are often less dependable and profitable than timber due to greater fluctuations in /policies and other environmental conditions like weather, soil health, etc that availability of a resource may depend on [23, 24].

Ultimately however, several studies point to the fact that the best forest management strategy is likely “no management” or that of no interference at all. To truly maximize carbon sequestration, the generally agreed upon best approach is to stop viewing forests as an income source. In order to slow down dangerous rapid climate change, the best forest management strategy is to preserve existing natural old forests and stop all deforestation (legal and illegal) in addition to reforestation (turning land that once was a forest back into one) and appropriate afforestation (transforming land into healthy forest ecosystems native to the region that mimic natural vegetation age and species composition). William Moomaw, a distinguished physical chemist and environmental scientist, founder of the Center for International Environment and Resource Policy at Tufts University's Fletcher School, and lead author of five Intergovernmental (IPCC) reports, refers to this as “proforestation” [26, 28-30].

2.2 Education Technology

Education technology (EduTech) refers to software designed to facilitate learning. These include tools that are used to actively impart knowledge like e-books, mobile learning tools (e.g. Duolingo, Khan Academy), microworlds, serious educational games and ones that indirectly support it like assessment tools (e.g. Kahoot, Google Forms), learning management systems (e.g. Blackboard, Canvas, Moodle), text based tools (MS Word, Google Docs), knowledge organization tools (e.g. Evernote, Notion, Mendeley), synchronous collaboration tools(Zoom, MS Teams), etc. [32] Depending on design, EduTech tools can be empowering or constraining. [33] When they promote learner engagement, they have been shown to improve depth and persistence of learning. [11]

Many studies define engagement as active participation or positive interaction of the learner with the teaching tool or learning material as well as with peers and faculty. Others describe it based on the amount of time, effort, or energy invested in the learning activity. [32] Engagement improves learning because it invokes mindfulness in learners causing them to employ conscious effort and thought that results in development of personally meaningful knowledge. This is important because the likes of John Dewey, a pioneer in the "pragmatism" school of thought [34] and whose ideas inspired the much celebrated pedagogical paradigm of constructionism, subscribe to the notion that knowledge is only useful to someone when they find it personally meaningful. [19]

Constructionism is a learning theory rooted in "learning by making". It promotes self-regulated learning by encouraging students to build their own solutions. Constructionism is based on Constructivism, which is the idea that new understanding is built upon existing knowledge. [10] A microworld is a type of EduTech tool that is based on constructionism. It provides learners a digital, often simplified, model of some real-world system or idea that they can explore. Computational objects-to-think-with (OTTW) are central to the design of a microworld. [21] These are digital constructs in the microworld that learners can manipulate to elicit a response from the system as part of exploratory activities culminating in knowledge construction. [8, 10]

A child's sandbox is an example of a natural microworld where sand and tools like the bucket or shovel act as OTTW such that interacting with them through play leads to the child developing an intuitive understanding of density and volumes. [19] Logo, Boxer, and SimCalc are examples of some of the earliest digital microworlds used as a teaching tools, often to educate about mathematics or physics related principles. [35] Given advancements in technology (object oriented programming languages, improved graphics, web based applications) and the ability of microworlds to represent interdependent chains of cause and effect found abundantly in human and natural systems such as economics, the food web, disease progression, plant growth, and the effects of climate change on ecosystems, they are useful in multiple domains beyond mathematics and physics. [35-37]

At the heart of any microworld, is its ability to facilitate self-regulated learning (SRL) wherein the learner takes initiative in managing their own learning. According to Rieber from 1996, self-regulated learners are (i) intrinsically motivated (they find the activity rewarding or enjoyable), (ii) metacognitively active (they engage in planning an goal-setting), and (iii) behaviourally active (they tweak the environment to suit individual learning styles). [19] These characteristics closely parallel the 3 widely accepted components (affective/emotional, cognitive, behavioural) that comprise student engagement as described by Bond et. al. in their extensive statistical analysis of literature concerning EduTech and student engagement. [32] Thus, facilitating SRL promotes learner engagement in the activity. This reinforces the notion established through years of studies, that well-designed Microworlds make for particularly engaging teaching tools [8-10, 21, 35]. The Piagetian Learning Theory (PLT) by Jean Piaget whose ideas strongly inspired the proponent of microworlds Seymour Papert, and the Flow Theory of Optimal Experience (FTOE) by Mihaly Csikszentmihalyi are 2 popular theoretical frameworks that define necessary conditions for SRL. [19]

PLT accredits learning and knowledge building to resolution of mental **epistemic conflict**s between existing mental models and contradicting experiences or observations encountered in the learning environment. Such observations are made through the process of deliberately attempting to assess and understand, known as **self-reflection**. Conflicts are resolved either through *assimilation* when the learner is able to understand by placing experiences within existing mental models or through *accommodation* wherein learners tweak, rebuild, or expand existing mental models to accommodate new ideas in a process referred to as **self-regulation**. Thus, the 3 properties of epistemic conflict, self-reflection, and self-regulation summarize PLT. [19]

The flow state refers to the deepest level of engagement in an activity. This state is known to be beneficial for learning as it often results in psychological growth. The FTOE framework defines 8 components of an activity that may induce this state of heightened focus. They are (i) an optimized challenge level, (ii) ability to command the learner's complete attention, (iii) clear goals, (iv) clear feedback, (v) provides an absorbing enough experience to free the learner about other worries, (vi) provides the learner a sense of control, (vii) frees the learner of feelings of self-consciousness and (viii) distorts the learner's sense of time such that they feel it passing by quicker. Such a state is often reported by gamers. This indicates that gaming elements may be incorporated into microworlds to improve engagement. [19]

One way to introduce gamification into a microworld is to structure learning activities around challenges that learners strive to meet. The disadvantage with this strategy is that it is difficult to determine the right level of challenge difficulty such that learners are neither bored nor stressed. A common solution is to make multiple challenges available at varying levels of difficulty. [19]

Many a time, microworlds that try to teach about real world systems comprise a simulation model. This is especially the case if educational material is based on a natural system as is the case with MycroForest. To maintain learner engagement, it is necessary that simulation-as-microworld learning tools follow the “match the user principle” such that ideas presented “expand as the learner is ready” so as not to overwhelm. This is known as model progression. It is also necessary to ensure that such tools entail good UX to avoid learner frustration. [9, 19, 37]

Rieber in 2005, over several studies both directly (based on results of own work with colleagues) and indirectly (based on literature review) investigated how different representations of content influenced learning from simulations, games, and microworlds. [9] Table 1 summarizes key observations from this work.

<table>
<tr><td rowspan="5">Simulation</td><td>Graphical feedback accompanied by short, embedded multimedia explanations result in better understanding of ideas by students compared to when only graphical or textual feedback was provided instead.</td><td rowspan="2">Most students learn from microworlds only when exploration occurs within context of some carefully designed learning activity that provides structure.</td><td rowspan="2">Microworld</td></tr>
<tr><td>Providing short explanations intermittently boosts understanding as this makes it easier for learners to link thoughts to experiences. The alternative of a tutorial is less effective because it separates explanation from experience.</td></tr>
<tr><td>Learners consistently reported lesser frustration when feedback was graphical rather than textual.</td><td>Students who engaged in content related discussions demonstrated increased learning.</td><td rowspan="3">Game</td></tr>
<tr><td>Instructional support is best provided while students use the simulation as opposed to before, because the latter can lead to students forming early hypotheses that are generally hard to displace later even if evidence points against it.</td><td rowspan="2">Three game characteristics most favored by children in a study wherein student designed games were evaluated by other students were (i) storyline quality, (ii) competition, and (iii) appropriate challenge.</td></tr>
<tr><td>Students significantly benefit from simulations that build up complexity in stages (model progression) allowing enough time for developing a good grasp on easier tool mechanics and ideas before moving on to more complex ones.</td></tr>
</table>

Table 1. Observations regarding use of simulations, microworlds, and games as educational tools from Rieber's study in 2005. [9]

Although simulations, microworlds, and games, are all commonly adapted to be interactive educational tools, the best approach seems to be to combine relevant ideas from all 3 tool design approaches to optimize specific learning experiences. For instance, based on explored work, it may be concluded that although educational simulations present a great deal of information through visualization of dynamic complex systems, they also present the disadvantage that the mental model that learners develop is can be difficult to evaluate for correctness. This is why, in tools like MycroForest wherein an underlying simulation model is imperative to correct emergent behaviour of the system, a simulation-as-microworld approach can be beneficial as the constructionist nature of microworlds produce tangible external artifacts in the form of learner creations that are representative of the internal mental model of learners. [9]

Overall, there is significant evidence to suggest that hybridization of the constructivist concept of a microworld with elements of a simulation and gaming can results is a particularly effective and engaging learning environment. [9, 10, 19, 38]

2.3 Simulation Design

In order for forest management plans applied to the virtual forest within MycroForest to produce similar outcomes w.r.t amount of carbon in the environment as observed in the real world, it is necessary for the microworld to simulate tree growth and the carbon cycle sufficiently realistically.

A "model" here, refers to a representation of some primary system. When such a model can be updated over time based on simulated conditions to mimic true behaviour of a dynamic primary system, it is referred to as a "simulation". [39] Thus, at the heart of every simulation is a model of the system that it represents.

There exist several ways of modelling dynamic biological processes like forest growth, forest yield, forest succession, primary productivity, carbon storage, nutrient cycling, water balance, etc. This is because given their inherent high complexity, the large time periods over which ecological processes may play out, and their critical role in supporting life, simulating them is one of best ways to understand them better and conduct experiments without disturbing real-world systems. [40]

Of the many simulation paradigms, Agent Based Model Simulation Discrete Event Simulation are two popular ones.

2.3.1 Agent Based Simulation (ABS)

ABS is a type of simulation that leverages an Agent Based Model (ABM) as the underlying model. ABMs represent a system using independent agents with their own memory and rules that interact with each other and the environment. [41]

In the space of biological and ecosystem as well as climate modelling, ABMs are extremely popular. [41] This is because such systems are most often composed of discrete entities that independently interact with a shared environment or each other over time to accomplish their own separate goals such that composite behaviour patterns emerge as a consequence. This inspires natural progression towards modelling these entities as agents in an ABM. [41, 42] Also, ABMs impose no restrictions as to how many attributes or rules each agent can have, which makes it an attractive option for modelling complex systems like forests or entire ecosystems. [43] Furthermore, students who used education technology incorporating ABMs have been shown to outperform others on account of having understood cause and effect relationships more readily. Such students reported being able to “see” patterns better. This is thought to have been a consequence of the “agent perspective” and learners having found the idea of individual contribution within a shared environment resulting in emergent behaviour intuitive and straightforward. [38] Thus, MycroForest models tree growth and carbon capture as an ABM where trees are agents, and they interact with the environment composed of land and carbon reservoirs like air and soil.

ABMs support varying levels of abstraction. This may be readily observed in context of plant growth modelling. In population level ABMs, an agent refers to an individual plant. This facilitates capture of emerging forest level behaviours. On the other hand, individual level ABMs take this a step further and are more nuanced with agents now referring to specific modules within a single plant. This could be structural components like leaves, roots, and so on, or more abstract constituents like pools of carbonates. [43] Since MycroForest aims to teach about forest level changes under the influence of a learner’s management plan as opposed to plant physiology or the growth mechanism, the ABM within MycroForest is a population level one with a forest comprising a population of trees.

Underlying assumptions that influence key mechanisms like increase in tree volume or reproduction pattern, can also vary in terms of both approach and level of detail. [43] The following 2 examples of slightly different plant growth ABMs built on empirical and mechanistic approaches respectively, demonstrate this difference. [43]

<u>Example 1</u>: JABOWA [43, 44]

- Consider the JABOWA model. It simulates new growth in forests in response to changes in canopy cover. This was among the first uses of ABM in plant ecology. Here, underlying sub-routines that drive key processes like increase in tree volume is based on simple equations that capture observed phenomenon or relationships on a high level. For example, annual growth rate is modelled as follows.

$$\delta(D^2H) = R \times LA \times \left(1 - \frac{DH}{D_{max} \times H_{max}}\right)$$

  This equation incorporates attributes of the tree agent, namely $D =$ Diameter at Breast Height (DBH), $H =$ tree height, $D_{max} =$ maximum DBH, $H_{max} =$ maximum height and $LA =$ leaf area, with R being an added constant and δ suggesting “change” in volume D^2H. Tree height is computed as $H = 137 + b_2D - b_3D^2$ with b_2 and b_3 being species specific constants, based on the ratio gleaned from available data on real tree diameters and heights. This equation also captures known phenomenon such as growth being directly proportional to amount of sunlight received using the term $R \times LA$ and it also being inversely proportional to energy required to maintain living tissue as captured using the term $1 - \frac{DH}{D_{max} \times H_{max}}$. Notice that volume of the tree is computed as D^2H. This is derived from the formula for the volume of a cylinder $= \pi r^2 h$ and therefore, stems from an assumption of the volume of a tree being akin to that of a cylinder. Another assumption here, is that other growth conditions are optimal. These assumptions simplify the model and makes computation faster.

- Thus, the aforementioned growth mechanism simplified via assumptions like that of optimal growing conditions, models growth rate of the tree using an empirical formula that incorporates agent attributes like diameter and height based on rules influenced by statistical insights gained from data.
- The JABOWA ABM built upon empirical equations that modelled just 9 tree characteristics (species, age, size, spatial location, growth rate, mortality, shade tolerance, reproduction, competitive ability) and 7 environmental characteristics (canopy gaps, light availability, spatial location, environmental stress, aging, altitude) was able to simulate real ecosystem behaviours such as competition, secondary succession and change in vegetation at different elevations. This goes to show that complex systems can be simulated in useful detail even when some of that complexity is abstracted away through simplifying assumptions.

<u>Example 2</u>: PLATHO [43, 45]

- Consider the PLATHO model which simulates plant growth to understand resource allocation patterns. It accomplishes this through sub-models that each capture a different plant process. Phenological development, photosynthesis, water and nitrogen uptake by roots, biomass growth, respiration, and senescence are the 6 mechanisms so modelled. This is also a population level ABM wherein each plant is an agent.
- Within a plant, assimilates, structural biomass, carbon-based secondary compounds, and reserves comprise 4 key biochemical pools that PLATHO takes into consideration. The simulation is a result of repeatedly computing resource fluxes between these pools and generating, storing, as well as transferring resources accordingly. The whole system, therefore, revolves around executing functions that update the state of certain plant and environment variables to meet the demand for resources like nitrogen, carbon, water and so on, at various plant organs.
- This type of modelling also incorporates some assumptions like “potential allocation to defensive compounds is inversely correlated to maximal plant growth rate” and simplifications such as representing volume of a tree as that of a cylinder. Since there may be multiple actions that can be executed in response to certain program states, there is a need for prioritization. This is facilitated by assumptions or rules based on existing knowledge such as “photosynthesis is less affected by nitrogen deficiency than growth”.
- Although often not necessary for simpler systems, with complex primary systems, the mechanistic modelling approach can represent parts of the model using mathematical equations. Given below, is one expression that is a part of the PLATHO

model. It calculates total potential carbohydrate demand as needed for structural growth and synthesis of defensive compounds.

$$D_{pot} = r_{max} \times W_1 \times \Delta t \times f_T \times f_{Ph}$$

Here, r_{max} is the maximum growth rate, W_1 is the amount of living structural biomass, Δt represents the time step, f_T is a factor in the range 0 to 1 that is a function of air temperature, and f_{Ph} is a factor in the range 0 to 1 that is a function of the phenological stage of the plant based on its seasonal growth cycle.

- Overall, the PLATHO model facilitated testing of several hypothesis and revealed likelihood of responses to different conditions. It successfully reproduced several observed results like the effect of nitrogen fertilization on rate of biomass gain validated upon comparison of simulated and measured values of apple trees which largely matched. Even when simulated results differed from observed truths such as when the model overestimated the effect of CO2 on the concentration of defence-related compounds in spruce needles, this triggered further investigate and revealed the importance of effects such as acclimatisation of plants to increased levels of CO2 over time, thereby contributing to increased understanding.

<u>Example 1 and 2</u>: Contrasting or Complementary

Literature often presents empirical and mechanistic methods as contrasting ways of modelling. Often, this distinction is clear. Mechanistic modelling involves formulating a conceptual representation of some primary system based entirely on knowledge of its underlying structural elements and functional mechanisms. Such models may or may not represent processes or parts thereof using mathematical expressions. Algorithms or functions based on informed assumptions are the key drivers of simulation. On the other hand, empirical modelling is rooted in entire systems being represented using a high level mathematical function based solely on statistical relationships uncovered from measured data. This is useful when outputs or attribute values of a primary system is available as data, but knowledge about its underlying structure/working is limited. [39]

The primary difference between JABOWA and PLATHO lies in the level of mechanistic detail that the model captures. JABOWA captures plant growth at a much higher level with representations incorporating tree attributes like height, diameter, and leaf area, but not explicitly modelling detailed processes like photosynthesis, respiration, and water uptake. Thus, it swaps sub-models as in PLATHO for parameters in an equation whose values are informed from real tree attribute data. This is what makes JABOWA more empirical a model than PLATHO. PLATHO is more mechanistic because sub-models are built to represent underlying biochemical processes. This models plant growth more realistically in greater detail.

That said, when the primary system modelled is very complex, as is botany or ecology, there is a need to intentionally limit the level of detail modelled for computational feasibility or to reflect the specific purpose of simulation. Also, knowledge about the underlying system is likely partially available, but still incomplete and fragmented. Thus, in such situations, it can be argued that the distinction between the two modelling approaches is often blurred.

Although more so than JABOWA, PLATHO is still not entirely mechanistic. It has embedded empirical modelling elements such as use of mathematical expressions to simplify sub-model processes formulated based on observed data in addition to knowledge about the primary system's underlying mechanics. Similarly, JABOWA also makes a few mechanistic assumptions to make decisions regarding what attributes are to be included in an expression and what characteristics are to be considered for modelling so as to promote emergence of appropriately realistic behaviour.

Biology, ecology and climate change are thus, examples of domains wherein simulation of primary systems may call for an ABM which is built on hybrid modelling approaches that combine mechanistic and empirical elements to better suit unique requirements. [39] Thus, the ABM within MycroForest models key processes like tree growth and reproduction using high-level mathematical expressions based on certain mechanistic, informed assumptions or rules about underlying mechanisms and structure of the system like the relationship between height and diameter of trees, coniferous trees generally being more long lived than deciduous ones, and so on. This results in a model that mimics real-world phenomenon but is still fast enough to be computationally feasible and provide smooth user experience.

2.3.2 Discrete Event Simulation (DES)

A Discrete Event Simulation (DES) is simulation paradigm that models the primary system using a Discrete Event Model (DEM). This is among most popular simulation paradigms and is particularly suited to modelling process flow. [46] It breaks down system behaviour into an ordered sequence of events or processes that can but need not occur at regular time intervals. [41]

This event or process oriented worldview that underpins DES allows for some real-world time to be abstracted away as time between events is not simulated. Modelling evolution of the system from event to event instead of from moment to moment makes it possible to simulate slow systems in a shorter time frame. Time periods between events when there is minimal change is not simulated and thus, does not contribute to duration of the simulation. Also, events can be structured such that state changes over long time periods in the real world is executed within a single event to make the simulation faster. [47] Time scales over which forests grow and change significantly is generally long. This is one reason why real-world trial and error based assessment of forest management strategies is often infeasible. Thus, the ability to hasten slow, real-world processes in simulation that comes with DES is deemed very beneficial in the forestry sector. [46]

At the broadest level, all DEMs comprise entities and a priority queue that manages events. [47] Running a DEM usually involves the following 3 steps that get iteratively executed until a stopping condition is met. [48]

1. Execute events as per the calendar.
   The "calendar" is just an ordered set of events. Across literatures, it is also referred to as a "schedule", "plan", or "priority queue".
2. Execute "activities" or "processes" that constitute each event.
   It is permitted under the DES paradigm for these processes to include stochastic elements or have a probabilistic execution duration rather than a deterministic one. Uncertainty is often modelled using suitable probability distributions and can entail use of a random number generator.
3. Update entity attributes, system states, and statistics in response to executed processes.

A use case wherein DES is most popular, is decision making or when there is a need to compare strategies because human decisions can easily be incorporated as separate events added to the simulation queue. This is the prime reason for incorporating DES into MycroForest where it manages timely execution of forest management actions added by the user. In forestry, DES is frequently used to compare different forest management or harvesting strategies in addition to assessing effects of different facility layout or equipment configurations, comparing resource logistics management strategies, and performing cost assessments. [46] The work of K. Westlund, L. E. Sundström and L. Eliasson [49] is a most recent example of this. They present an optimization-simulation framework to assess performance delivery of wood supply chains under varying weather conditions which affect road accessibility and by extension the ability to transport resources. Their framework has 2 parts. An optimization model produces a good wood harvest schedule based on demand and supply capabilities. This feasible harvest schedule along with weather scenarios, customer order details, and forest road segment data are provided as input to a DEM which simulates events in the schedule to facilitate comparison of delivery performance under varying weather conditions as input by the human user. [49]

The idea of entities that generate events comprising a set of instructions to be executed at planned times is one that is very practical to implement in software. DES is very compatible with Object Oriented programming because model entities can readily be implemented as objects with their properties being entity attributes and their methods defining events or event processes. [47]

Simulations in general are used for one of two purposes being either to analyse some phenomenon or system, or to provide a training environment to teach about it. There is evidence of DES being beneficial when incorporated into teaching tools as its structure makes it easy to incorporate learner decisions into the existing event schedule. [46, 50]

MycroForest is implemented in an Object Oriented manner as this allows for better separation of concerns and keeps code flexible and resistant to breaking. This teaching tool aims to allow learners to create and explore effects of different forest management strategies over 300 years on a virtual forest that they own. This presents an ideal use case for DES w.r.t scheduling and execution of management actions as events.

2.3.3 Hybrid Simulation

Briefly put, DES is apt for modelling discrete decisions/actions over time and ABS is apt for capturing individual agent interactions with the environment that results in emergent behaviour. When it comes to simulating plant growth and carbon capture that gives rise to forest-level patterns from independent tree interactions with the environment, ABS is appropriate. DMS is more appropriate for simulation of discrete user generated actions that gets executed as and when planned. Therefore, a hybrid approach that incorporates both these methods of simulation is likely most beneficial. Thus, MycroForest adopts ABS to model tree growth with each tree object being an agent and adopts DES to manage a planner that shall contain forest management actions created by learners which get executes as and when planned.

Such a hybrid approach to simulation incorporating elements of more than one simulation paradigm is not uncommon. It is frequently observed in the health care, supply chain management, manufacturing, and construction domains. In fact, the combination of ABS + DES is considered to be most effective in “any situation which includes resources that must perform activities as well as human interactions where individual behaviours alter how these activities proceed” [51]. This once again points towards the decision to incorporate this combination within MycroForest being sound.

HS is often adopted as an attempt to manage complexity of particular primary systems. It allows for complex problems to be broken down into smaller parts such that the simulation paradigm most suited to each part may be employed. Moreover, HS accommodates abstraction of parts of the system thereby helping strike an accuracy or complexity and performance trade-off balance. [52, 53]

A key challenge with HS is compatibility of integration of the two simulation paradigms adopted. Ensuring interoperability between elements from different simulation methodologies can be difficult. [52, 53] In addition to these two simulation paradigms, MycroForest also leverages a more general Object Oriented (OO) design as shall be discussed in the following section, to simulate the remainder of system mechanisms. This OO design ties DES and ABS together because it is compatible with DES as previously discussed, as well as with ABS as agents may be objects and agent types, classes. [51]

2.3.4 Object Oriented Design

Object Oriented (OO) here, refers to the general software design pattern of viewing a system as a sum of several objects or entities with their own data and functions that interact with each other. Object Oriented Simulation (OOS) is when the idea of the world being composed of "objects" is incorporated into the design of the simulation. An important reason for popularity of this notion is that it is the most natural way to represent many real-world systems. For example, a single cell may be modelled as being composed of objects representing its various functional units like cell membrane, nucleus, mitochondria, cytoplasm, etc. Even abstract or non-physical elements of a system, like say the force of gravity in a physics simulation, can be modelled as an object if some unique attributes and functions can be associated with it. [54]

Given below are 4 ideas that are referred to as the 4 pillars of OO design. [55, 56]

1. **Abstraction**: This principle dictates that only most relevant attributes and functions be implemented. Further, this entails that functions be implemented at a high enough level for callers to be able to leverage it for desired results without being concerned about the intricacies of how it works. For instance, it can be made possible to call a function drive(A, B) that takes the caller from point A to B without having to call functions like startEngine(), shiftGears(), or pressAccelerator(). The main advantage of following this principle is that it helps manage complexity and minimize use of computational resources while making code more reusable and maintainable. In MycroForest for example, the main aim is to have trees absorb and release carbon such that their presence or absence results in changes in CO_2 in the atmosphere as is observed in the real world. Thus, it is only necessary to keep track of how much carbon is stored in a tree. Details about where this is stored and the mechanism of carbon allocation between different plant organs is irrelevant. Thus, the volume of the tree may be simplified to that of a cylinder and amount of carbon in a tree can be abstracted to x% of the mass of that tree such that x = average value of the proportion of carbon in real trees based on real world data.
2. **Encapsulation**: This principle urges that each object be self-contained with clear responsibilities and specialized attributes as well as functions to perform its unique role within the system such that only those properties or methods that other objects or functions need to be able to access is exposed publicly whilst all others remain private. The main advantage that this presents is modularization or separation of concerns which in turn ensures that code is flexible and can be updated with minimal breakage. For example, in the implementation of MycroForest, there exists a function called computeBiodiversityScore() within the Land class. A "class" is the term used to refer to the type or definition of an object. Consider a Shirt class with an attribute colour. Then, Shirt("blue") and Shirt("red") would both be objects of the Shirt class. This computeBiodiversityScore() function contains the algorithm that computes biodiversity of the land based on composition of the forest. This is a private function that no objects outside the Land class can directly call. Thus, code

elements outside the Land class object cannot compute biodiversity score themselves, but they may still access its value via a public attribute of Land that stores it after computation. At one point during development, there was a need to rectify an older way of computing biodiversity score wherein a forest with the most no. of old trees was assigned highest score to another approach where a certain ratio of young to old trees as observed in natural forests was to be scored highest. Since encapsulation of the functionality of biodiversity score was implemented, this was easy to do with there being the need to update only a single function.

3. **Inheritance**: OO design allows for there to be a class hierarchy where classes lower in the hierarchy known as "children" or "child" classes of those above known as "parent" classes received attributes or functions of the parent class. Thus, child classes inherit properties of their parents. The reason for creation of such child classes is often to personalize or extend functionalities of the parent in several unique ways. For example, if Vehicle() is the parent class, then Car(), MotorBike(), and Truck() may be children who all inherit properties like colour and functions like drive() from Vehicle() but may also have other features unique to each child. This can aid in reducing code duplication. For example, in MycroForest, classes Timber, NTFP, and Recreation are all children of the IncomeSource class. This serves to say that there are 3 ways of earning from the forest. Income may be generated by selling timber, non-timber forest products (NTFPs) or by selling permits that allow the public to use the forest for recreational activities. Because Timber, NTFP, and Recreation inherit from IncomeStream, the sell() function need only be defined once within the parent class IncomeStream. All children, also inherit this functionality.
4. **Polymorphism**: This idea states that the same attribute or function may be defined again with a different value. A common use case is where children inherit a function from the parent and then redefine or extend it. For example, consider a Mammal() class with a speak() method. Child classes Dog and Cat may inherit the speak() method and then modify it to facilitate barking and meowing respectively. This allows for behaviour sharing with minimal resource overhead.

MycroForest adopts an OO design because it provides a natural way to map the real-world hierarchical structure to code components while keeping code modular, concise, reusable, and flexible. MycroForest defines an Environment class that contains a Land object which in turn can contain several Tree objects, mimicking natural world structure.

Furthermore, OOS has the advantage that communication between objects is simple to implement with the standard practice being via function calls and variable fetching. This is much less resource intensive than other methods of communication such as message passing, or event based ones that could require continuous listening for events or the need to store state of all objects at each timestep to facilitate replayability. This simplicity that does not demand strict enforcement of more paradigm related principles, also makes it easier to integrate both other paradigms with the remainder of the simulation. [54]

All simulations require some form of simulation time synchronization. This can be challenging when HS is adopted. [54] MycroForest overcomes this challenge by implementing a Simulation class that coordinates processes of all other simulation objects. It does this by taking the first step that triggers a time step update. This motion to update time is propagated to nested objects and soon leads to all simulated objects moving forwards in time. The tree agents that are a part of the growth ABS execute their independent behaviours within their respective time update functions. The Simulation object also contains a Planner object comprising an ordered sequence of learner defined forest management events which get executed at planned years.

2.3.5 Time Advance

The time advance mechanism is a key component of every simulation. A time advance mechanism refers to how progress of time is modelled within the simulation. There are generally 2 ways to implement this. [51]

1. **Time Step:** This method of time advance involves selecting a certain period of time as step size such that all simulated times are multiples of this time step Δt. Thus, when the simulation runs, each timestep shall involve incrementing the simulation clock by Δt and then updating all system variables to emulated changes that take place within this time step. This type of time advance is the norm for ABS implementations.
2. **Next Event:** This method of time advance is rooted in the event worldview of DES. Here, all stage changes are triggered by execution of events that may be scheduled at irregular intervals of time. Time between events is not simulated. Unsurprisingly, most DES implementations adopt this method of time advance.

MycroForest implements time advance using the Time Step method such that $\Delta t = 1$ year. MycroForest aims to allow users to scrub forwards or backwards through a timeline GUI and move to any simulated year to view the state of the world at that point in time. This adds replayability to the simulation which improves understanding of the cause – effect relationship w.r.t the learner's created management plans and corresponding changes in the microworld. It is easier for the learner to measure impact of their decisions and determine when to execute management actions if the model progresses predictably in fixed time steps. Moreover, forest management activities such as felling trees and planting them in the real world, is generally planned such that unit of time is years. This is because trees, depending on their species, generally have long lifespans ranging from anywhere between 50 to 3000 years with the oldest known living tree, the Great Basin Bristlecone Pine, estimated to be at least 5000 years old. [57]

The major disadvantage with the time step method is that the rate at which the simulation can progress gets strictly limited to $\frac{1}{\Delta t}$. It is impossible to step through faster than this. Typical implications of such a rate limit include it being impossible to imagine different scenarios where decisions made may be faster or slower and vast variations in model behaviour under different time step sizes. Of these two common concerns, it is the second one that applied to MycroForest because plant growth is continuous with the rate of growth being significantly different across seasons for most deciduous trees. This makes it difficult to pick a value for Δt as behaviour of the model could be significantly different depending on whether $\Delta t = 1$ month, $\Delta t = 1$ season, $\Delta t = 1$ year, or $\Delta t = 1$ decade.

A common approach to minimizing the influence of Δt on model behaviour is to set it to be very small so that changes are almost smooth. This is, however, not feasible in case of MycroForest because of the long lifespan of trees. If $\Delta t = 1$ day, the simulation would simply take too long to run, given that the aim is to allow learners to view changes over 300 years. It is necessary to simulate between 200 to 300 years. The more time that can be simulated, the more visible long term effects of forest management plans become. This is because significant changes in carbon levels on Earth occur over centuries. Also, real world forest management actions are often planned in rotations to allow trees enough time to mature between timber harvests. A rotation period, i.e. time between subsequent timber harvests, range from 5 to 150 years with common values being 20 or 40 years [25]. Thus, while both 1 month and 1 season were initially considered to be Δt, this was later abandoned for 1 year because annual update is compliant with real world forest management planning time frames, is large enough to visualize significant changes in tree growth over their long lifespans and allows the simulation to cover a long enough timeframe so as to be able to see effects of changing carbon levels, all while keeping the time taken to animate through it reasonably short.

2.4 Human Computer Interaction

Human Computer Interaction (HCI) is the discipline concerning design and implementation of interfaces between human users and computer systems that ensure realization of user goals through appropriate system responses with good usability - functionality balance to maximize effectiveness of human - machine communication where usability is a measure of a system's capability to enable efficient and appropriate task fulfilment. [58, 59]

Interfaces are determined by the amount and variety of inputs and outputs they are to handle. Based on this, human – computer interfaces get categorized as Uni – Model wherein user input is received via a single channel (a.k.a. modality) or Multi – Model when more than one input channel like facial/body movement detection (vision based), voice recognition (audio based) or keyboards/mouse interaction (sensor based) methods of communication is involved in the interaction. While Multi – Modal interfaces are more likely to grant a more immersive or wholesome user experience, it has 2 notable disadvantages. [59] Vision or audio based HCI often requires special technology (e.g. infrared cameras, speech recognition software, haptic devices, etc.) which can reduce accessibility and affordability of the associated system. Also, multiple communication modalities with a computer system can be distracting, especially for young learners using a teaching tool. Hence, MycroForest provides a simple Uni – Modal means of HCI wherein learners interact with the tool via familiar mouse and keyboard sensor based interactions.

Another common HCI grouping is that of active and passive HCI. Active HCI involves direct and deliberate interaction between users and systems in a command – action event flow wherein systems respond only upon user initiated action. For example, a typical email send action requires that the user click on the send button first. MycroForest presents an active HCI. This allows for experiential learning and increased user control, both of which contribute towards a good learning experience. [60] Passive HCI on the other hand involve systems that detect the user and pick up on non-physical or indirect environmental queues to which they then respond. Voice commands like "Hey Siri" is an example of this. [61]

Furthermore, current technological advancements like Augmented Reality (AR), Artificial Intelligence (AI), the Internet of Things (IoT) and improved computational capability in general, drives HCI further, to realization of Intelligent HCI and Ambient HCI. Voice recognition, face/gaze detection, naturalistic textual and verbal conversations, etc. are indicative of Intelligent HCI. Ambient HCI is when devices embedded in the environment enable humans to interface with machines without any apparent physical barriers like the need for a keyboard/mouse. [61] Future technologies like Human Brain Interfaces may take this further still and completely blur the line between human and synthetic senses.

The HCI discipline is, however, fragmented with no single universally acknowledged set of principles to guide HCI theory application. Instead, there are several good perspectives with some like Norman's model from 1988 being more practical than others such as Nemirovsky's Audience Participation Model from 2003. [58]

Its intuitiveness makes Norman's Model a particularly popular choice. This model splits the HCI experience into 7 iterative steps: (i) Goal establishment. (ii) Intention formation. (iii) Action sequence specification. (iv) Action execution. (v) System state perception. (vi) System state interpretation. (vii) System state evaluation. These are organized such that steps (i) to (iv) comprise an "execution" component and steps (v) to (vii) comprise the other "evaluation" component. Further, undesirable HCI is defined as a consequence of the "gulf of execution" and the "gulf of evaluation" which may be thought of as misalignment between "task language" (user's conceptual understanding and the actions they can take to achieve their goals) and "core language" (system's internal processes, responses, etc., and how it represents information to the user). Other researchers like Abowd and Beale in 1991 extended Norman's ideas by defining the User Interface (UI) as a bridge connecting the languages. They state 4 key mappings between task and core languages that the UI must ensure is strong. These are (i)

Articulation (user maps their goals to actions), (ii) Performance (system interprets user actions correctly and makes appropriate state changes in response), (iii) Presentation (system presents updated state), and (iv) Observation (users updates mental model/understanding based on presented changes). [62]

One challenge with Norman's Model even with Abowd and Beale's explicit UI extension is that is that it can still seem abstract from a developer or UI designer's perspective. Thus, it may be advantageous when aiming to design applications in accordance with Norman's Model to also try to adhere to more practical guidelines like Jacob Nielsen's usability heuristics which is a set of 10 rules to avoid common interface design problems. These are (i) Use simple language with no irrelevant information. (ii) Speak the user's language such that information is presented in a familiar fashion. (iii) Minimize memory load such that the user need not remember all information between dialogues. (iv) Maintain consistency. Words or actions must mean the same thing throughout. (v) Provide timely and apt feedback. (vi) Clearly mark exits to allow users to undo mistakes or revert state to a previous version. (vii) Incorporate few shortcuts for the benefit of expert users. (viii) Display good error messages. (ix) Design to prevent errors. (x) Ensure help is readily available. [58]

To address the lack of consensus on a single set of best principles in the field, V. Hinze-Hoare in 2007 conducted a survey of HCI literature and assigned scores to key principles within them weighted based on proportion of overall citations the corresponding authors received. This analysis suggests 8 fundamental principles of HCI in decreasing order of weightage being (i) Recoverability (ii) Familiarity (iii) Consistency (iv) Substitutivity (v) Task Migratability (vi) Synthesisability (vii) Predictability (viii) Perceptual Ergonomics. [58]. The first three were most significant and is inherent within Nielsen's 10 principles.

Thus, the UI of MycroForest strives to facilitate Norman's interaction experience while trying to follow Jacob Nielsen's usability heuristics to strengthen the mapping between the user's understanding of the system and the system's responses to the user.

2.5 Related Work

There exist multiple low and high tech interactive tools [3-7, 63-67] that model forests or forest growth, often in the context of climate change and/or forest management. A common purpose of such tools is to serve as decision making aids for experts in the field like working foresters. Another popular use is as educational tools. This section shall explore 5 such tools in detail.

<u>**Tool 1 – SimForest**</u> (Educational Simulation)

[65]

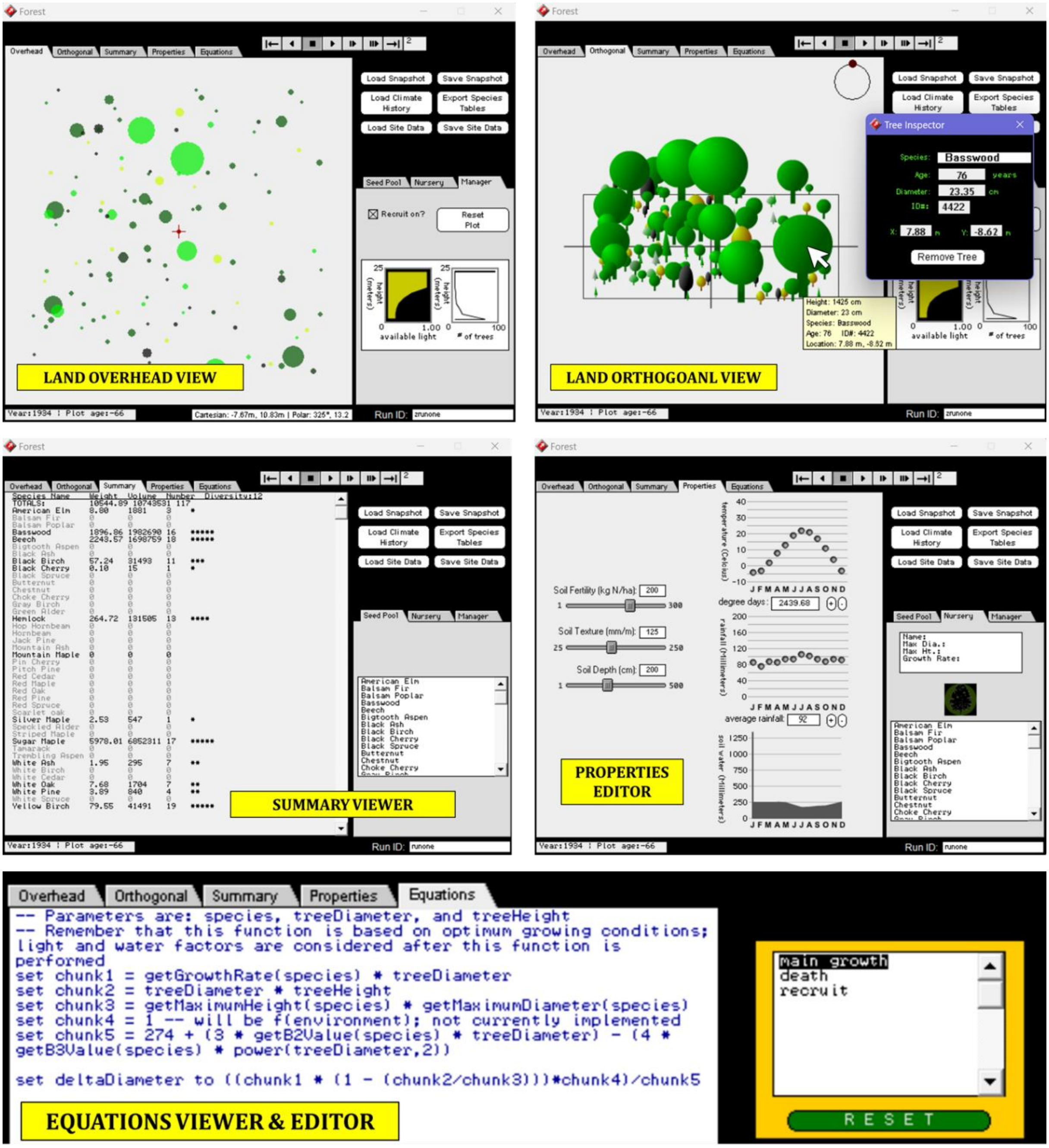


Figure 1. SimForest UI.

SimForest is a software built using Java (information about any other technologies that may have been used to refine the application and make it ready for deployment is not available) for inquiry-based interactive learning that simulates forest growth under various environmental settings (soil fertility, soil texture, soil depth, soil water, temperature, rainfall). The forest can grow (reproduce) on its own or learners may also plant trees from the nursery containing 30 species to choose from. The tool allows learners to play and pause the simulation as well as move forwards or backwards at different speeds to view the forest change over time. Two possible views of trees in the forest are provided (overhead and orthogonal). Clicking on a tree reveals its properties (species, age, diameter, ID, position) and the option to remove it from land. Learners can edit some tree properties (diameter, age, position, species) and all environmental conditions. A summary tab reveals weight, volume, and no. of trees of each species currently on land and another equations tab can be used to view and edit key mechanisms like plant growth, death, and recruit (reproduction) at a lower level.

The tool is available in two flavours depending on level of control that the learner has over underlying variables of the simulation model. The black box model is the one displayed above. The also exists a glass box model where almost all model parameters and equations are accessible to the learner and are editable. This glass box model also allows for trees to be cut down and for core samples of trees to be extracted and analysed using a core sampler window. Lastly, the tool also allows climate history, site data, and world snapshot to be saved and re-loaded later.

SimForest	
Pros	**Cons**
Rich set of manipulatable controls.	No big cons.
General forest growth simulation around which multiple learning scenarios may be developed.	Does not consider atmospheric CO2 levels.
Can be adapted to teach a range of age groups and expertise levels (school grade 4 all the way up to university graduate students and forestry professionals).	
Facilitates inquiry-based constructivist learning comprising multiple iterative inquiry cycles with steps (i) ask question or form hypothesis, (ii) plan to answer or test hypothesis (iii) note observations, (iv) analyze data gathered, (v) communicate learnings.	Only available on PC and requires download and possibly some set up (OS, Java, or Swing related compatibility issues possible).
Clean user-friendly UI.	
Allows moving through times at various speeds.	Does not consider economic value of forests.
Good data visualization.	
Allows multi-level control (high-level or black box, as well as low-level or glass box).	

Table 2. SimForest - Pros and cons.

The underlying simulation model in SimForest is very detailed and based on allometric equations. MycroForest assumes most growing conditions simulated by SimForest to be ideal in the underlying model as availability of carbon needed for growth is the primary concern. In SimForest, forest management is not the focus. The focus is to observe results of tweaking tree or environment parameters. This is unlike MycroForest, where only realistic manipulation of land content is made possible (learners can construct management plans involving chopping and planting trees but cannot change the species of a full grown tree or change how old or tall it is).

Like SimForest, MycroForest also allows system state and management plans to be saved and reloaded as this would make it easy to share system settings and reproduce past results despite inherent randomness in models that might lead to different starting forests each time state is refreshed/reset. Also, MycroForest provides timeline controls similar to the one in SimForest (move forwards or backwards in time, play/pause simulation).

__Tool 2 – Foster Forest__ (Decision Support Simulation)

[3]

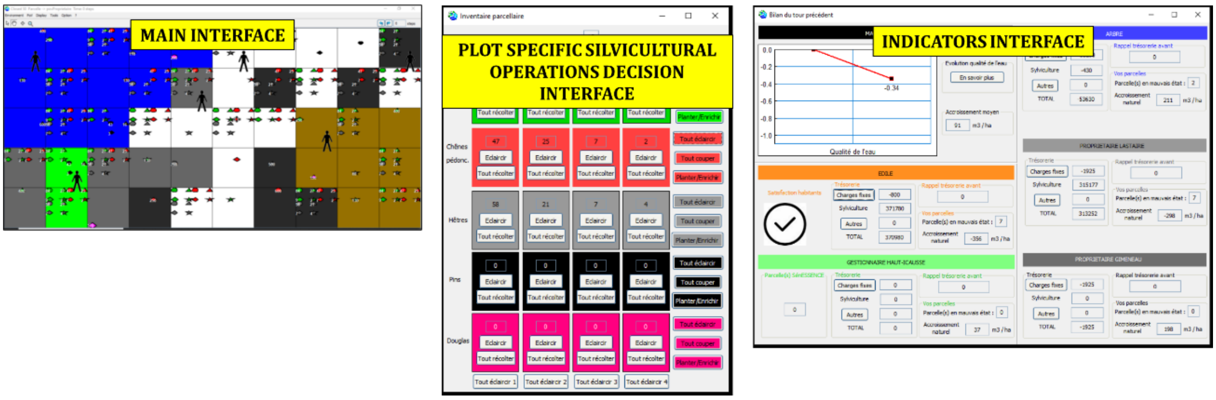


Table 3. Foster Forest UI – The main interface displays the 50 land plots simulated. Different views (owner view, eligibility for conservation plan view, etc.) can be selected to be overlayed on these plots. The above main interface image shows the ownership view coded per participant. The indicators interface displays overall and participant specific ecological and land parameters.

Foster forest, embracing the companion modelling (ComMod) approach, is a participatory simulation adapted to be a Role Playing Game (RPG) catered towards domain experts like real-life forest managers, members of community forest federations, etc., wherein 5 participants assume the role of a mayor who's responsible for a communal forest, a public forester, a protected area manager, and 2 private landowners. Together, they make decisions regarding social, economic, and ecological processes to manage availability of forest ecosystem services. In addition to the 5 participants, this RPG experience requires a facilitator who is a FosterForest application expert. This person computerises decisions of participants and can adapt source code to implement more creative strategies.

All participant roles must manage their budget and avoid negative impacts of ecological factors like overgrazing. Some roles have more exclusive objectives. For example, the mayor maintains water quality and upholds aesthetic value of forests, the public forester focuses on timber harvests and the protected area manager promotes conservation of old growth forests and shares information about carbon storage.

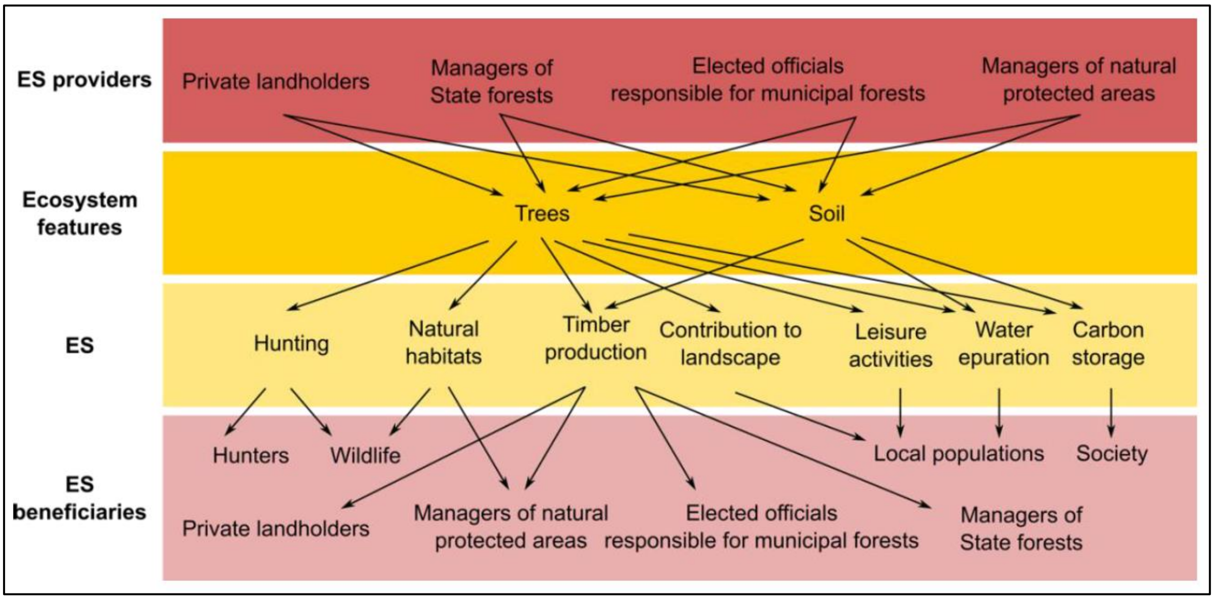


Figure 2. Foster Forest conceptual model summary (ES stands for Ecosystem Service).

The simulation is built upon an Agent Based Model (ABM) composed of spatial entities (land plots owned by participants), semi-autonomous entities (participant roles), and physical entities (trees) using the renewable resource management ABM platform, CORMAS. The participatory experience comprises 5 steps starting with all players filling in a pre-simulation questionnaire that tries to understand existing views on climate change, followed by a detailed briefing session that informs participants about how to use the application. Then, the main activity composed of multiple simulation rounds is conducted. The session ends with a post-simulation questionnaire and a collective debriefing session.

The simulation progresses in 10 year timesteps with each step being a round composed of an action period and a computerized update period. The action period involves the facilitator sharing information about climate projections for the decade as well as expected timber and carbon prices. The players then discuss and present their forest management strategy comprised of actions related to planting or removing trees, hunting, trading plots, and engaging in sustainable forest management programs like protecting old growth forests. The computerized update phase begins with the facilitator assimilating player decisions into the tool which responds by computing successive stages of ABM entities. Thus, income and expenses related to silviculture activities like timber harvesting as well as social and ecological parameters (plot carbon storage, plot soil fertility, plot soil compaction, etc.) get updated and tree growth is simulated. This phase ends with the facilitator giving an overview of latest parameter values and resulting climate changes.

Pros	Cons
Tool is very **flexible** and supports a rich variety of	Participants must be familiar with the domain. Not for the lay man.

scenarios. Participants can come up with creative strategies not severely limited by tool capabilities.	Participants found the UI too mathematical and hard to relate to.
	Participants cannot interact with the tool directly. They must rely on the facilitator.
Tool is **realistic** with well a designed ABM.	Tool requires extensive introductory training and user guides.
Participants appreciated being able to test strategies in a risk-free environment.	Tool use instructional material (2 usage videos, 6 booklets one for each role + facilitator) provided was overwhelming for some participants. Thus, learning curve is very high.
Participants enjoyed the ComMod wherein decisions followed group discussions.	This tool requires an elaborate set up with 2 projectors and a facilitator. It was built using software that needs to be downloaded and installed along with associated user guide materials. This makes this tool less accessible.

Table 4. Foster Forest – Pros and cons.

Following are some design decisions within MycroForest inspired from Foster Forest.

- MycroForest adopts an ABM approach to modelling forest growth and carbon flow.
- Carbon reservoirs mirror plot carbon storage parameters in Foster Forest.
- Like Foster Forest, MycroForest also keeps track of participant income and expenses w.r.t cost and returns of forest management actions.
- The land contains more than one species of trees each with slightly different properties. In MycroForest, much like in Foster Forest, tree species have differing growth rates and wood price.
- Sensitivity to environmental factors is greater among younger trees than mature ones.
- Only mature trees may reproduce, and natural regeneration requires presence of a mature tree nearby.
- Learning activity associated with MycroForest borrows the idea of tool use sessions interleaved by debriefing sessions from the participatory simulation event flow as this also happens to compliment good pedagogy.
- Inspired from success of the ComMod approach, learning activities around MycroForest was conducted with students in groups who designed management plans collaboratively.

The ABM within MycroForest is simpler than the one in MycroForest as modelling details like soil fertility, soil compaction, tree density, competition among trees, impact of grazing on seedlings, etc. is beyond the scope of this project primarily in terms of the timeline. Moreover, the simpler model captures the link between forest management practices and atmospheric CO2 levels well. This is sufficient for educational purposes w.r.t getting young learners to think about the important role forests play in mitigating rapid climate change.

Also, unlike Foster Forest, MycroForest is a web application. This makes it more widely and easily accessible with minimal set up. The UI design has been curated carefully to be very user friendly and aesthetically pleasing. Furthermore, user guidance in MycroForest is incorporated into the app in easily accessible bite sized chunks that are not overwhelming. Last but not the least, MycroForest is a microworld that non-expert and young audiences can directly interact with. It requires no special hardware and software set up beyond a standard browser on a desktop or laptop computer and a stable internet connection.

<u>**Tool 3 – MineSet**</u> (Educational Game)

[4, 64]

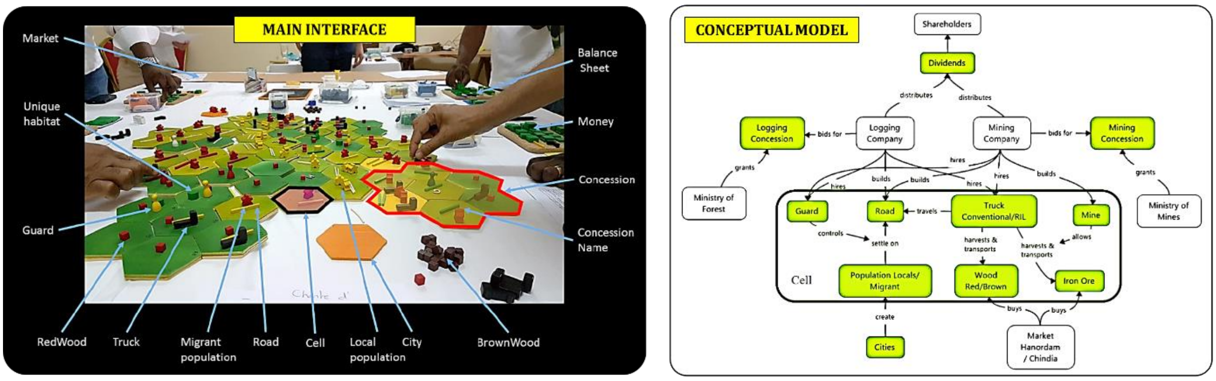


Figure 3. MineSet interface (left) and conceptual model (right). [4]

MineSet is a role-playing board game aimed at a broad audience including various forest stakeholders such as local communities, NGOs, protected area managers, companies, and governments. Players act as CEOs of logging or mining companies and interact with markets, the government, and NGOs to develop strategies which alter land use as measured in terms of forest cover, biodiversity, and volumes traded. The underlying model captures all main drivers of land use change in central African forests (demographics, economical, governance, technological, cultural) via simple rules. [4]

In 2023, P. O. Waeber et. al. tried this game with Forestry graduate students online via a zoom call. They confirm good engagement, a great learning experience, and emergence of realistic strategies. Participants expressed a need for a fully digital version of this game and/or similar ones for use as widely accessible, effective, transformative learning tools. [64]

Mine Set	
Pros	**Cons**
ComMod.	Allegorical model is less scientifically accurate.
Engaging and immersive.	
Models a rich variety of land use change drivers.	Significant set up required.
Incorporates model progression to gradually reveal game complexity.	No explicit mention of climate change.

Caters to a wide audience, particularly forest stakeholders. However, non-expert audiences can also enjoy and learn from it.	The physical nature of the game requires in-person attendance. This makes it less widely accessible unless online collaborative tools (like zoom, google meet, etc.) are incorporated and a third-party coordinate and communicates all player moves. This is tedious.
The physical mine set board game is a more holistic visceral experience that is more likely to be remembered given close in-person interaction with peers and physical interaction with game pieces.	

Table 5. Mine Set – Pros and cons.

Similar to Mine Set, MycroForest focuses more on the model correctly capturing causal links between system components than it producing accurate real-life outcomes. This approach is appropriate for learning tools where the focus is on management activities and their consequence on the environment as opposed to the science of plant growth or carbon transformations from one form to another. This is also more practical as it allows models to be simpler thereby making the learning tool faster and more user friendly.

In MineSet, landscape composition, land type patch size, perimeter length of forest fragments, and species diversity comprise important indicators of change. Land composition change over time and biodiversity score in MycroForest mirror this. MineSet adopts an approach of setting maximum values to limit figures within ranges that can be categorized into few, more mentally trackable categories of change. For instance, maximum Forest Cover associated with each game board cell in Mine Set, limits Forest Cover figures to the 1 to 10 range. This range is then divided into colour coded "Open Forest" (score = 0 to 4), "Low Density" (score = 5 to 8) and "High Density" (score = 9 to 10) forest cover areas. MycroForest adopts a similar range limiting and colour coded categorization strategy to make the atmospheric CO2 level indicator more impactful. Also, biodiversity score is mapped to land classes in MycroForest that make it easier to judge the health of the forest.

"Learning begins when the game is over." This a powerful idea and central to teaching tools like MycroForest and Mine Set where the primary focus is to encourage discussion around sustainable resource management. Upon having played a game of Mine Set, participants reported learning about (i) the system, (ii) themselves, and (iii) peers, thanks I large part due to frequent group discussions. This further justifies the decision to have students use MycroForest in groups and interleaves challenges with debriefing sessions.

Tool 4 – About That Forest (Educational Game)

[5]

About That Forest is a multi-player RPG where learners play as forest dwellers who draft and vote on policies to decide on harvesting trees or selling non-timber forest products to make money. Players can also plant new trees and monitor others. The environment reciprocates poor health of the forest via floods that lead to loss for all community members. This game is available on mobile devices, the browser, and the PC.

<table>
<tr><th colspan="2">About That Forest</th></tr>
<tr><th>Pros</th><th>Cons</th></tr>
<tr><td>Underlying code allows for easily modifiable settings.</td><td>No big cons.</td></tr>
<tr><td>ComMod.</td><td rowspan="3">Underlying model and research not openly available.</td></tr>
<tr><td>Engaging.</td></tr>
<tr><td>Competition in addition to cooperation.</td></tr>
<tr><td>Multiple economic drivers of exploitation.</td><td rowspan="3">Atmospheric CO2 levels is not a modelled indicator.</td></tr>
<tr><td>Widely accessible.</td></tr>
<tr><td>Appeals to a wide age group and range of starting knowledge levels.</td></tr>
</table>

Table 6. About That Forest – Pros and cons.

About That Forest draws explicit attention to economic motivators underlying forest exploitation and draws attention towards the underlying “tragedy of commons” scenario wherein the best decisions for economic profit leads to overuse of forest resources leading to collapse of key ecosystem services and by extension the community. MycroForest also focuses on economic viability of forest management. Both tools consider non timber forest products as a secondary source of revenue from the forest.

MycroForest’s click-through introduction on the landing page is inspired from About That Forest’s text based introduction that places the game in a fantasy setting effectively through a few short dialogues.

About That Forest presents land as a grid such that each cell may contain a tree whose icon changes to reflect it growing over time. This makes for a simple and informative visualization of land composition change over time. MycroForest thus, also adopts this approach of land presentation.

Both About That Forest and MycroForest have one main indicator of climate change. This is less distracting. Unlike About That Forest wherein this indicator is “floods”, in MycroForest, this is atmospheric CO2 levels since this is more suited to drawing attention to the role of forests as carbon sinks.

<u>**Tool 5 – Forest Kids**</u> (Educational Game)

[6]

Figure 4. Forest Kids UI elements.

Forest Kids is a mobile (Android, iOS) or web based educational game built on Unity 3D exclusively for young children where they can visit 4 different types of forests (boreal, tropical, temperate, arid) along with a team of exploring children and an alien space explorer to learn about the various flora/fauna on Earth as well as services that forests offer. It contains fun timed mini games (picture matching memory game, match at least 3 in a row game, spot a plant or animal game) that earn learner points (stars). Spotted species get added to the learner's collection. Trying to complete the collection could be good motivation to keep exploring. The tool also provides short fun facts and teaches about the water cycle, greenhouse effect, days, and seasons. The primary mode of interaction is point and click or drag. There is no element of planning or constructionist learning. However, children have lots of content to unlock on a map and check off on their list. Overall, this application leans more towards being an interactive explanatory learning tool than one that grants experiential learning through making.

<table>
<tr><th>Pros</th><th>Cons</th></tr>
<tr><td>Age appropriate for children.</td><td>No learning through making.</td></tr>
<tr><td>Visually very attractive.</td><td rowspan="2">Facts presented during matching and memory games are random and lack connection. This can make them hard to learn.</td></tr>
<tr><td>Great user experience with smooth interactions.</td></tr>
<tr><td>Motivating mini games.</td><td rowspan="4">Games are very engaging. The timing element adds a sense of urgency. As pointed out in [9] , games that are very competitive or engaging, often with a scoring mechanism, especially in the absence of constructionist mechanisms, can significantly affect learning negatively. Users tend to enter a "twitch" mode where they are hyper focused on improving score and learning suffers. This is a real threat in this game. Personally, when trying the memory game, I soon found myself ignoring</td></tr>
<tr><td>Very informative and covers different topics related to forest biodiversity and Earth's climate.</td></tr>
<tr><td>In-app help is well placed and provided in small, easy to absorb chunks.</td></tr>
<tr><td>Text in the game is supported by audio readouts to make it easier to absorb for children.</td></tr>
</table>

Facts are repeated from time to time but not too frequently. This may promote information persistence in memory.	the facts as I focused more on memorizing tile symbols to get the matches right before the timer runs out to score maximum points.

Table 7. Forest Kids – Pros and cons.

A key lesson to take away from this tool is that games in educational tools must not distract learners such that learning suffers. Unlike Forest Kids, MycroForest therefore, has no score or point system. Competition is introduced through having students work in teams and later compare their strategies and lowest CO2 target or highest income target they could set and meet as part of challenges. Meeting targets requires drafting optimal forest management plans that requires much thinking and hence ties the activity, although competitive, back to the premise of forest management thereby lessening the changes of learners entering the gamer's "twitch" mode.

Like Forest Kids, MycroForest also tries to be age appropriate for young adults and boasts custom artwork that tries to add to aesthetic appeal that can be a motivating factor and/or improve UX.

Discussion

One key aspect that most above tools have in common is that they provide a low-risk environment within which to experiment with management strategies. This is the primary reason why simulation, microworlds, and games are apt for forest management exercises. Learning through trial and error in the real world is not practical as key ecosystem services may be negatively affected by such exercises. Another driver for the prevalence of simulated experiences in forestry is the accompanying speed up of natural and ecological processes which makes it possible to appreciate the true gravity of the consequences of decisions made over time. This is also an attractive quality for educational tools to possess.

There is merit in presenting educational games or teaching tools like microworlds with gamified elements as just "games" because this encourages participation. [4] Moreover, given the make-belief setting and the notion of games generally being "fun", prompts learners to interact and discuss freely which breeds creativity. Due to engagement that stems from a motivating setting, learners often end up taking the game seriously as they progress and leave the experience reporting it to have been immersive and educational. However, given the academic context and young learner group within which MycroForest was evaluated, it was presented as a teaching tool to encourage students to take the learning activity seriously and respect fellow peers as well as faculty members.

All tools related to forest or resource management (Foster Forest, Mine Set, About That Forest) include timber harvesting as a primary means of revenue from the forest. Timber is the default income stream within MycroForest.

Another common lesson learned from all tools (Foster Forest v/s others) is that good UX and a clean aesthetically pleasing interface is crucial to keeping users engaged. This is especially important for teaching tools where learner engagement is paramount. Thus, MycroForest strives to stick to HCI best practices.

Table 8 compares all aforementioned tools (table columns) against each other w.r.t certain qualities (table rows) that, at the beginning of the project, were deemed desirable for the tool developed as part of this work to have. MycroForest, the result of this project, has been added to this table to analyse whether it possesses all qualities as originally intended. In this table, 🟢 stands for completely satisfies, 🔴 stands for fails to satisfy, and 🟡 stands for satisfies with some caveats.

Following points briefly define what each quality entails.

- **Realistic:** The application most model the real world sufficiently realistically such that environment responses to forest management actions mirrors that in the real world.
- **Engaging:** Users must find the application engaging.
- **Easily Accessible:** The application should be widely accessible with minimal set up required.
- **For Youth:** Young adults should be able to understand and use the application with ease and find it informative.
- **Team:** The application should allow for decision making that is rewarding to formulate as a group.
- **Solo:** The application must provide a rewarding experience for individual learners.
- **Focused Aim:** The tool should not try to do too many things at once. It should focus on few specific key ideas (e.g. forest management actions and atmospheric CO2 levels, forest management actions and economic gains/losses).
- **Forest Management:** The tool allows learners to make forest management decisions.
- **Forest As Carbon Sink:** The tool must highlight the role of forests as important carbon sinks.
- **Financial Motive:** The tool must draw attention to the underlying financial motivation that drives forest exploitation.
- **Low Entry Threshold:** It must be fairly easy to begin using the tool such that the learner is not overwhelmed.
- **Easy To Use UI:** The tool must provide a good UX. It should boast a simple UI that is easy to navigate without getting frustrated.
- **Sufficient Built-In Help:** The tool must contain a user-friendly, comprehensive, built-in user guide.

INFORMATIVE **TOOL →** **QUALITY ↓**	*FOSTER FOREST*	*MINE SET*	*ABOUT THAT FOREST*	*FOREST KIDS*	*SIMFOREST*	*MYCROFOREST*
REALISTIC	🟢	🟡	🟡	🟢	🟡	🟡

ENGAGING	🟢	🟢	🟢	🟢	🟢	🟢
EASILY ACCESSIBLE	🔴	🔴	🟢	🟢	🔴	🟢
FOR YOUTH	🔴	🟢	🟢	🔴	🟢	🟢
TEAM	🟢	🟢	🟢	🟢	🟡	🟡
SOLO	🔴	🔴	🔴	🟢	🟢	🟢
FOCUSED AIM	🔴	🔴	🟢	🟢	🔴	🟢
FOREST MANAGEMENT	🟢	🟢	🟢	🔴	🔴	🟢
FOREST AS CARBON SINK	🟢	🔴	🔴	🔴	🔴	🟢
FINANCIAL MOTIVE	🟢	🟢	🟢	🔴	🔴	🟢
LOW ENTRY THRESHOLD	🔴	🔴	🟢	🟢	🟢	🟢
EASY TO USE UI	🔴	🟢	🟢	🟢	🟢	🟢
SUFFICIENT BUILT IN HELP	🔴	🔴	🟢	🟢	🔴	🟢

Table 8. Comparison of closely revied tools against each other and MycroForest in context of desirable qualities. (🟢= completely satisfies, 🔴= fails to satisfy, 🟡=satisfies with some caveats)

Many apps are very scientifically accurate or realistic w.r.t the underlying plant growth model. This is true for decision-making aids like foster forest aimed at experts or adults, and very simple explanatory tools like Forest Kids that displays accurate facts. Mycroforest is not as realistic as these tools because the underlying conceptual model for teaching about forest management makes multiple simplifying assumptions (e.g., all plant growing conditions other than CO2 considered ideal, all plant species abstracted to just 2 general tree types – coniferous or deciduous). This is acceptable as MycroForest need not capture plant growth and the carbon cycle in extreme detail given that its purpose is to teach about causal links between forest management actions and atmospheric carbon levels, which the simple model captures well. Other tools like Mine Set, About That Forest, and SimForest are also only deemed partially realistic because they too abstract away many details of plant growth biochemistry to focus on broader behaviours or interactions. Of these, simplified tools, SimForest is likely most detailed as underlying model equations consider more plant growth and environmental factors like (temperature, light availability, soil depth, soil water capacity, etc.) compared to others.

MycroForeset and SimForest do not have a built-in multiplayer support (no sign-up/log-in, no multi-player mode). However, learning activities can be structured such that groups of students make decisions using these tools thereby making ComMod possible.

FosterForest requires added hardware and a facilitator along with special software that needs to be downloaded. Mine Set is a physical board game needed set up of game components. Physical proximity is needed to may Mine Set as intended (playing online over web conferencing is possible, but tedious to coordinate and not as interactive). SimForest requires downloading and installing of the application that can cause compatibility issues on different operating systems. Thus, compared to web-based and/or mobile applications like About That Forest and MycroForest, tools like FosterForest, Mine Set, and SimForest are not considered easily and widely accessible.

Overall, Mycroforest meets all intended criteria w.r.t this project. It is a sufficiently realistic, engaging, and easily accessible web-based application aimed at the youth. Although the app itself is not multiplayer, it allows for team learning activities in addition to individual ones. Unlike many existing tools that try to do multiple things at once, Mycroforest focuses exclusively on forest management, it's effect on atmospheric CO_2 levels, and impact of financial motives. This app is built to be easy to get into and use with lots of built-in help.

2.6 Summary

TO DO.

3 Design

This section describes the scope of this project, the pedagogical approach adopted, current user interface along with how HCI best practices were applied, the system architecture and technical development related details.

3.1 Scope

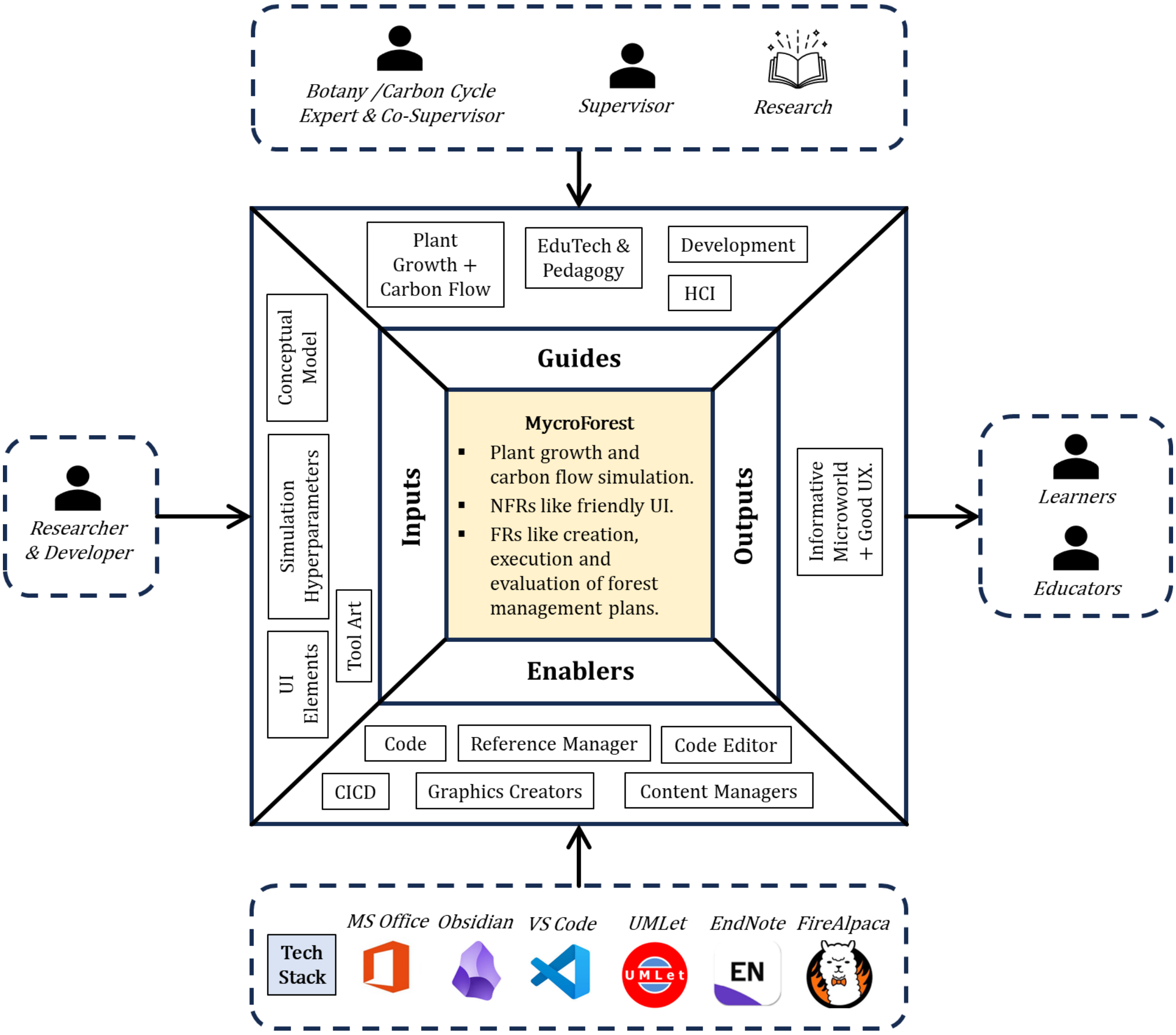


Figure 5. Scope diagram with core focus in the middle in yellow. [68]

[69]

<u>**Deliverable Name**</u>

MycroForest.

<u>**Project Justification**</u>

Objectives of this project are as follows.

- Research the field of education technology, simulations/microworlds, forest management, and climate change, to develop a user friendly, easily accessible, teaching tool that prompts young adults to think about the role of forests in sequestering carbon from the atmosphere and underlying economical motivators that lead to exploitation of forest resources through self-regulated learning.
- Evaluate the tool w.r.t educational value, learner engagement, and usability based on feedback from students who try it as part of the Bridge to College program at TCD.

<u>Scope Statement</u>

MycroForest is a microworld within which users learn about economically viable climate aware forest management by creating and executing their own forest management plans as well as analysing its effects on a simulated virtual forest. The tool is designed to be user friendly and informative for young adults. It is not expected to model bio-chemical processes like photosynthesis accurately. Sufficient level of detail that results in realistic cause-effect relationships between management actions and carbon levels in the environment, is acceptable. It also does not expose plant growth or environmental model hyperparameters to the user other than those related to frequency and number of trees to plant/fell as part of management actions.

- **In Scope:** MycroForest shall present learners with their own personal virtual forest such that they can watch it grow and change over time, driven by an underlying hybrid simulation model. The tool allows learners to construct, execute, and analyse effects of forest management plans wherein they decide the number, frequency, and type of trees to plant or fell and sell for timber. Learners may also opt to activate other means of income from the forest such as selling non-timber forest products (honey, mushrooms, berries) or visitor permits upon conditioning the forest for public recreational use. The tool's UI shall adhere to HCI and data visualization best practices.
- **Out of Scope:** Given limited time and the interdisciplinary nature of this project, the underlying forest growth model and carbon flow models are not expected to be detailed and bio-chemically accurate. Only variables directly influencing the simplified carbon cycle in the world is modelled into plant process equations with all other conditions assumed to be ideal and parameterized using high-level average figures observed in the real-world. Thus, simplifying assumptions and abstractions have been made. For example, plant volume gained during growth is based on maximum height of the tree, real-world tree height to diameter ratio, and carbon availability in the atmosphere. Effects of factors like sunlight availability, ambient temperature, soil water, humidity, soil nutrients, role of mycorrhizal fungal networks, competition among plants, etc. that influence underlying processes like photosynthesis and respiration, have not been modelled explicitly. Further, since the primary focus is forest management, the only way in which learners can alter the underlying model is through creation of management plans. Thus, they cannot

choose to alter maximum heights of trees, percentage of carbon the soil releases per year, mass of air in the microworld, etc. These hyperparameter values are pre-defined based on research and opinions of domain expert, Dr. Silvia Caldararu.

FRs & NFRs

Following tables outline functional and non-functional requirements prioritised using the MoSCoW scale (priority in decreasing order of importance: Must > Should > Could > Would) [70].

#	*FUNCTIONAL REQUIREMENT (FR)*	*PRIORITY*
1	System shall allow users to create, edit, and delete actions comprising a forest management plan.	MUST
1.1	System shall enable users to make following decisions regarding each forest management action: * Action type = Plant / Fell. * Type of tree affected = Age & Species. * No. of trees affected. * The time when this action shall be executed. * Whether this action is to repeat or not.	MUST
1.2	As the simulation steps through each timestep, system shall try to execute every planned action for that step.	MUST
1.3	System shall allow users to define the harvest rotation period (1 rotation = ? no. of years)	SHOULD
1.4	System shall provide feedback on execution status of actions (fully/partially successful, failed).	SHOULD
1.5	System shall allow saving and reloading of a forest management plan along with system state.	SHOULD
2	System shall allow the user to navigate through time using a timeline.	MUST
2.1	System shall facilitate a play/pause button that allows the user to view the state of the forest at each point in time as an animation.	MUST
2.2	User may skip to any point in the timeline.	SHOULD
2.3	User may move through time one step at a time.	COULD
3	System shall display concentration of CO_2 in air in a color-coded manner where colors stand for expected quality of human life at that CO_2 level.	MUST

4	System shall allow users to earn income from the forest.	SHOULD
4.1	Successful execution of fell actions result in gaining income via the timber income stream.	MUST
4.2	Users may activate the non-timber forest products income stream.	SHOULD
4.3	Users may activate the Forest Recreation income stream.	SHOULD
5	Forest management actions and/or maintaining other income streams shall cost the user some virtual money.	MUST
6	System shall display in-world wealth of the user.	MUST
6.1	System shall display overall income and expenses.	MUST
6.2	System shall display per year income and expenses.	SHOULD
6.3	System shall display income per rotation and expenses.	SHOULD
6.4	System shall allow users to view breakup of their income and expenses between different income streams.	COULD
7	System shall include built-in help.	MUST
7.1	System shall present short extracts of component relevant help.	MUST
7.2	System shall have a help page with all user guide materials on it.	SHOULD
8	System shall display land content.	MUST
8.1	System shall display presence/absence of trees on land.	MUST
8.2	System shall display biodiversity score and class related to the land.	SHOULD
8.3	System shall allow users to hover over a tree on land and view its species and age.	WOULD
9	System shall allow users to edit amount of Carbon emitted due to burning of fossil fuels.	MUST
10	System shall allow users to set CO2 and income targets.	SHOULD
10	System shall allow users to set target CO2 concentration and display whether this target is met (CO2 level <= CO2 target) throughout the simulation.	SHOULD
10	System shall allow users to set target per rotation income and display whether this target is met (income this rotation >= per rotation income target) throughout the simulation.	SHOULD

11	System shall allow users to sign-up and log-in to persist information.	WOULD

Table 9. MycroForest - Functional Requirements (FRs)

#	NON FUNCTIONAL REQUIREMENT (NFR)	PRIORITY
1	The tool shall be valuable to both individual and groups of learners.	MUST
2	The tool shall provide good UX.	MUST
2.1	The tool shall be easy to use.	MUST
2.2	The tool shall respond quickly enough and present information effectively enough to minimize learner frustration.	SHOULD
2.3	The tool shall adhere to good HCI and data visualization practices (e.g. Norman's model, etc.).	MUST
3	Learners shall find learning activities using the tool valuable.	MUST
4	The tool shall be widely accessible with minimal set up required. Hence it is a web application. It should work well, at least on Firefox, Chrome, Edge, Brave, and Opera browsers on any modern PC or laptop.	MUST
5	The tool shall subject all user inputs to sanitization checks prior to performing internal parameter updates to avoid erroneous or malicious input corrupting data.	MUST
6	The tool shall be suitable for youth (15 - 25 year old individuals).	MUST
7	The tool shall highlight the role of forests as important carbon sinks as well as draw attention to the underlying financial motives that drive exploitation of forests.	MUST
8	The tool shall not overwhelm learners and instead present user guide related information as short extracts with supporting images. Features of the tool shall also be introduced few at a time, gradually over multiple challenges.	SHOULD
9	The tool shall make available, sufficient amounts of easily findable built-in help.	SHOULD
10	Learners shall find the learning experience using the tool enjoyable.	COULD
11	The tool shall try to provide an optimal level of challenge for learners by allowing multiple challenges of varying difficulty levels to be formulated using the tool.	COULD

12	Gamification elements in the tool and associated learning activities shall motivate learners without distracting them.	WOULD

Key People & Technologies

The researcher and developer (author), the project supervisor who is a Computer Science professor and expert at Education Technology, along with the project co-supervisor who is also a Botany, Climate Change, and Carbon Cycle expert, comprise key people who have contributed to this project. Web development tools comprising the tech stack (explained in section 3.5.1) and other software such as MS Word, MS Excel, MS PowerPoint, Obsidian, FireAlpaca, VS Code, UMLet, and EndNote were instrumental in the successful completion of this project. MS Word was used to prepare this writeup. MS Excel was used to organize information in tables and spreadsheets. MS PowerPoint was used to create images. Obsidian is a file organization tool used to manage interlinked personal file networks. UMLet was ysed to create UML diagrams like the class diagram. FireAlpaca is a simple graphics design tool that was used to create all artwork within MycroForest. EndNote is a reference manager that helped keep track of material reviewed during research. Lastly, Visual Studio (VS) Code was the code editor used.

Working With Domain Experts

Throughout the course of this project, the author has worked in close association with two domain experts, Dr. Brendan Tangney (supervisor) and Dr. Silvia Caldararu (co-supervisor).

Dr. Tangney is an expert in Education Technology. He has carefully reviewed UI and learning activity challenge designs to ensure that they cater to a good learning experience, present the appropriate level of complexity for young adults, and serve to educate as well as engage without confusing the learner. Periodic meetings with him provided the perfect space wherein to discuss project artifacts as part of the analysis phase of the agile methodology. Prof. Tangney is skilled at identifying when research or development seems to be off-course or too broad. He would then remind the author of priorities w.r.t the project and advice refocussing on certain areas. Following are some concrete examples of valuable suggestions/observations made by Dr. Tangney.

- Initially, it was not possible to add management actions in the years within a rotation period as the author assumed this may add too much complexity or confuse the learner even though management practices like thinning in the real world is known to involve sometimes infrequent chopping of trees or parts of it in intermediate years within a rotation period. Dr. Tangey was the first to point out that it is likely both more interesting and intuitive for learners to be given the option to schedule management actions for years in between rotation periods in addition to just the start of a rotation period. Upon closer thought, this suggestion was deemed very valuable, and the feature was included in the application. This feature enabled students to discover a management strategy like thinning, for themselves.

- He identified an instance of inconsistency in an early version of the application in which both total bank balance as well as the money related target had the same label that read "funds". Given that this does go against Jacob Nielson's Usability Heuristics rule (iv) and was therefore likely to lead to learner confusion, the UI design was slightly amended by renaming the income target and bank balance using distinct, more meaningful terms.
- During the Bridge2College learning session post-activity discussion periods, Dr. Tangney put forth critical questions like "Do you think forestry is good?" which encouraged learners to think more deeply about the subject and reflect on learnings from the tool better.
- Dr. Tangney suggested designing challenges such that learners can leverage the target setting features of the tool to compete in groups. This inspired the idea to have teams of students try to set and achieve a higher income target or lower CO2 level than the other team as part of the learning activity that did seem to make the activity more enjoyable for students based on healthy levels of enthusiasm observed during post activity discissions.

Dr. Caldararu is an expert in plant growth and how both plants/forests affect the climate as well as how the climate affects them. She played a critical role in reviewing the plant growth and carbon flow simulation model to ensure that it is a sound, albeit simple reflection of reality. She also reviewed the UI and provided valuable feedback on the same. Following are few specific examples of her contribution.

- Preliminary idea pitches of the carbon flow model did not consider soil carbon (only considered reservoirs were air, vegetation, and fossil fuels). Dr. Caldararu advised further investigation of the role of soil/land in the carbon cycle and its inclusion in the model. She informed the author about the critical role our soils play in regulating and stabilising atmospheric carbon levels.
- Dr. Caldararu also advised investigating the different ways in which harvested wood is used which could lead to significantly different amounts of carbon released into the environment. This led to the author incorporating use of wood for energy production v/s as lumber which here stands for any use of wood that sees its preservation. Associated research led to the discovery of the important role Harvested Wood Products can play in locking away carbon and possibly increasing net carbon sequestration provided new growth has replaced felled trees.
- Initially, hunting and fishing was considered as an alternate means of income from forests. Dr. Caldararu advised that this might take away from the learning outcome of sustainable forest management. She pointed out how often, the income stream of hunting/fishing is abused to the point of significant loss of biodiversity in a forest which in turn adversely effects forest resilience (e.g. due to lack of pollinators/seed

dispersal agents). Thus, it was deemed best not to draw special attention to this as a climate friendly income source from forests.

- Dr. Caldararu suggested incorporation of a “developer mode” within the application that tracked key variables like “carbon absorbed”, “life stage of the tree”, etc. throughout the simulation such that it can be downloaded and visualized to facilitate easier diagnosis of model inadequacies. Heeding to this advice, a dev mode was implemented wherein state of individual trees (stress, carbon absorbed, life stage) and the environment (amount of carbon in each reservoir, atmospheric CO2 concentration) was recorded such that it can be saved as a csv file. A python notebook was leveraged to visualize recorded data. Python libraries pandas, numpy, and matplotlib was used. This aided in diagnosing code errors faster. Figure 6. Dev mode.Figure 6 illustrates screenshots of aspects of this developer mode (Dev Mode activation in utils.js file, the UI button to save data, data saved in an excel sheet, data in csv file visualized as line plots using Python programming language).

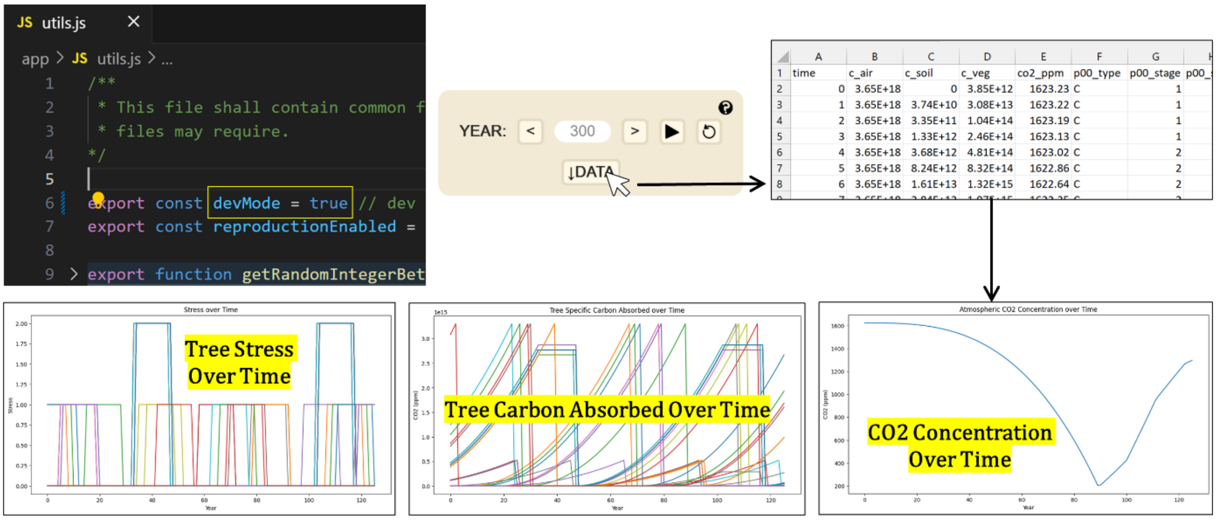


Figure 6. Dev mode.

3.2 Pedagogical Approach

As previously discussed in section 2.2, appropriate hybridization of microworlds, simulations, and game theory in education technology has been shown to improve learning. Tastefully visualized simulations provide an informative representation of a real-world system or idea that learners can readily relate to. Microworlds present users with multiple avenues to manipulate characteristics of the underlying model and thus interact with it. Exploration of a microworld that provides timely and appropriate types of feedback can command and keep attention of learners, thereby owing for an absorbing experience. Ability to build custom virtual constructs in the microworld invokes a sense of control in learners. Gamification of this experience through incorporation of challenges into the simulation-as-microworld with the option for model progression and varying challenge intensities, can grant users a challenge at an appropriate difficulty level so as not to overwhelm or bore, such that they find trying to overcome it stimulating and enjoyable. Finally, a narrative can be built into the teaching tool to add an element of fantasy or role-play and present a storyline within which learners may be mentally freed of other worries and can opt to imagine themselves operating in, free of self-consciousness. Thus, combining elements from simulations, microworlds, and games can result in a learning environment that aligns with principles from frameworks like FTOE and therefore, likely better caters towards SRL than does any of these approaches alone.

MycroForest is a microworld that incorporates a simulation to model forest growth and the carbon cycle. It also adopts gaming like ideas such as target setting. All microworlds contain interactive OTTW that encourages learning either by providing a way for users to manipulate system variables or by allowing users to explore outcomes of previous inputs. By this definition, every panel on the world and planner page of MycroForest is an OTTW. Most OTTW that allow manipulation of system variables through forest management plan construction and income stream settings is found on the planner page. Other modes of user input being target setting, simulation time navigation, and carbon emission due to fossil fuels setting is facilitated by the target setter, timeline, and fossil fuel usage panels respectively in the world page. All other panels on the world page are OTTW due to their significant role in graphically reflecting internal system state changes across simulation time.

Table 10 below, summarizes main ideas from background section 2.2 regarding education technology. Following paragraphs explain how design elements within MycroForest and the intended learning activity strives to adhere to identified pedagogy best practices w.r.t a simulation-as-microworld with game theory elements.

Piagetian Learning Theory (PLT)	**Good Practices (GP)**
(i) Epistemic conflict.	(i) Structure learning activities around challenges to introduce gamification.
(ii) Self-reflection.	(ii) Multiple challenges at varying difficulties improve likelihood of learners finding a difficulty level, optimal.
(iii) Self-regulation.	(iii) Model progression is beneficial.
Flow Theory (FTOE)	(iv) Good UX is key to avoiding learner frustration.
(i) Optimized challenge level.	(v) Graphical feedback accompanied by short, embedded multimedia explanations boosts understanding and reduces frustration.
(ii) Holds attention.	
(iii) Clear goals.	(vi) Guidance during interaction with the tool improves learning.
(iv) Clear feedback.	(vii) Learners should explore the microworld within context of a structured activity to ensure learning.
(v) Absorbing experience.	
(vi) Sense of control.	(viii) Topic related discussions boost understanding.
(vii) Frees learner of self-consciousness.	(ix) Students find a storyline, an important motivator and construct using which to mentally relate to the tool.
(viii) Hastened sense of time.	

Table 10. Pedagogy best practices.

Content icons in the land plot is updated after every timestep as the simulation runs, with a delay of 100 milliseconds reflect simulation model changes in response to both time updates as well as any forest management actions planned by the user. Execution status of planned actions appear colour coded in both the plan viewer and the planner. Virtual money earned and spent get updated in the money panel over time. Both colours and a number that get updated over time reflect changes in atmospheric CO_2 concentration. Achieved or failed status of targets are made clear using green or red colour in the targets panel. Finally, invalid text box entries are displayed in red to indicate erroneous input. Although MycroForest provides output that is a blend of graphical as well as textual elements, it is primarily graphical in nature. Additionally, MycroForest presents both a dedicated help page as well as short multimedia (text + image) user guides upon clicking easily accessible “ ? ” symbols associated with each panel in the world and planner page. This caters towards GP (v), PLT (ii), and FTOE (ii, iv, vi).

Good User Experience (UX) is key to avoiding frustration (GP (iv)) that can significantly hinder learning. Thus, research was conducted to determine best HCI practices. Care has been taken while designing the UI of MycroForest to apply identified HCI principles (Norman’s Model, Task – Core Language Mapping, Jacob Nielsen's Usability Heuristics) and data visualization knowledge to maximise UI usability. Further, informed simplifying assumptions made w.r.t the underlying simulation model ensures that UX is adequately fast and smooth.

This teaching tool is to be used by students in the presence of a qualified facilitator as mid-activity guidance hastens correct learning. Also, it is intended for the learning activity to be split into multiple short parts, with each part having a slightly different goal/theme such that group discussions are held in-between where learners can share their experience and observations with tutors and each other. This serves as an opportunity for tutors to ensure learners have built the right mental model. This learning activity structure aligns with GP (vii, viii), PLT (ii, iii), and FTOE (ii, iv, v). Furthermore, learners may be split into teams such that different teams arrive what their notion of best forest management strategy to meet specific set goals. The facilitator may then review each team’s strategy along with all students to discuss pros and cons and foster a healthy competitive spirit among learners. This can be motivating and enjoyable thereby lending itself to GP (i) and FTOE (ii, v, viii).

MycroForest has a built in feature that allows learners to set maximum atmospheric CO_2 concentration and minimum income per rotation targets. The tool indicates using colour (green or red) if these targets are met or not. This ability to set targets and evaluate own performance aligns with FTOE (i, iii, iv, vi) and PLT (ii).

Structure is needed to ensure learning from microworlds. One way to establish such structure is to present learners with challenges revolving around certain goals. In addition to guiding thought process, this also adds an element of gamification that can keep users motivated. Given below are the 5 challenges that are built into MycroForest currently. The level of difficulty of challenges increases from challenge 1 to 5. Only panels, controls, and help associated with UI elements essential for each challenge is displayed on the screen. Other panels are hidden. This serves to aid in model progression and gradually familiarize learners with all capabilities of MycroForest such that it is never overwhelming. This is also in agreement with GP (i, ii, iii, vii), FTOE (i, ii), and PLT (i).

Table 11 summarizes the 5 implemented challenges. To switch between these challenges, facilitators are to press Ctrl + Alt + 1, 2, 3, 4, or 5 on the keyboard.

	Goal	Active Features	Possible Learnings	Expected Learner Activity
Challenge 1	Maximize income from the forest.	Timeline Land Money Viewer Plan Viewer Planner Timber Income Stream	# Timber is profitable resource. This motivates deforestation. # Generally, forest management activities are performed in rounds.	# Create management plans that chop as many trees as possible. # Note down income. # Edit plan. Try changing rotation period. # Coniferous trees are more profitable. Try planting only coniferous trees.
Challenge 2	Keep atmospheric CO2 concentration at as desirable a value as possible.	Challenge 1 Features + CO2 Target Setter + CO2 Scale - Money Viewer	# Forests are crucial to keeping CO2 levels in check as they sequester CO2. # Mature and older trees are needed to keep atmospheric CO2 levels low. # Mature trees absorb more carbon as they grow. But older trees store more CO2. # Chopping an older tree releases more CO2 at once than chopping a mature tree. # Clear felling is the worst strategy. # Thinning is a better idea. # No management is the best strategy.	# Activate CO2 target. # Try best plan from challenge 1. Note highest CO2 concentration figure across 300 years. # Set a slightly lower concentration value as target. # Tweak management plan. # Try to hit lower CO2 target. # Repeat last 3 steps.
Challenge 3	Maximize income while trying to keep CO2 concentration ideal.	Challenge 2 Features + Money Viewer	# It is impossible to keep CO2 levels in a safe range without lowering profit margins.	# Set both CO2 target and income target. # Tweak plan and see if targets are achieved. # Report lowest CO2 + highest Income target combination achieved.

Challenge 4	How long before fossil fuel usage leads to critical CO2 levels (red) or complete forest death in the microworld? How to increase this time?	Challenge 3 Features + Fossil Fuel Usage Panel + Carbon Distribution Panel + Biodiversity Score & Land Class	# Only way to improve CO2 concentration in the air is to significantly cut down fossil fuel emissions. No silver bullets. # There is more carbon trapped within earth as fossil fuels than there is in the air and vegetation.	# Set fossil fuel usage emission to current global level of 10 GtC and observe how many years pass before CO2 levels reach critical levels and the entire forest dies out. # Tweak plans to see if some management strategy can keep carbon levels in check. # Realize that this is not possible. Only way to reduce atmospheric CO2 concentration is to reduce emissions.
Challenge 5	How helpful is diversifying income from forests?	Challenge 4 Features + NTFP Income Stream + Recreation Income Stream	# Other income streams are not very profitable. Neither are they as reliable as timber. # There is a need to research more ways of earning from a forest that does not involve chopping down trees. # Means of earning from forests such as forest recreation that involves building infrastructure requires large upfront investment.	# Activate other income streams. # Compare per year, per rotation, and overall income and expenses of these other streams with that of the default timber stream.

Table 11. Learning activity challenges implemented in MycroForest.

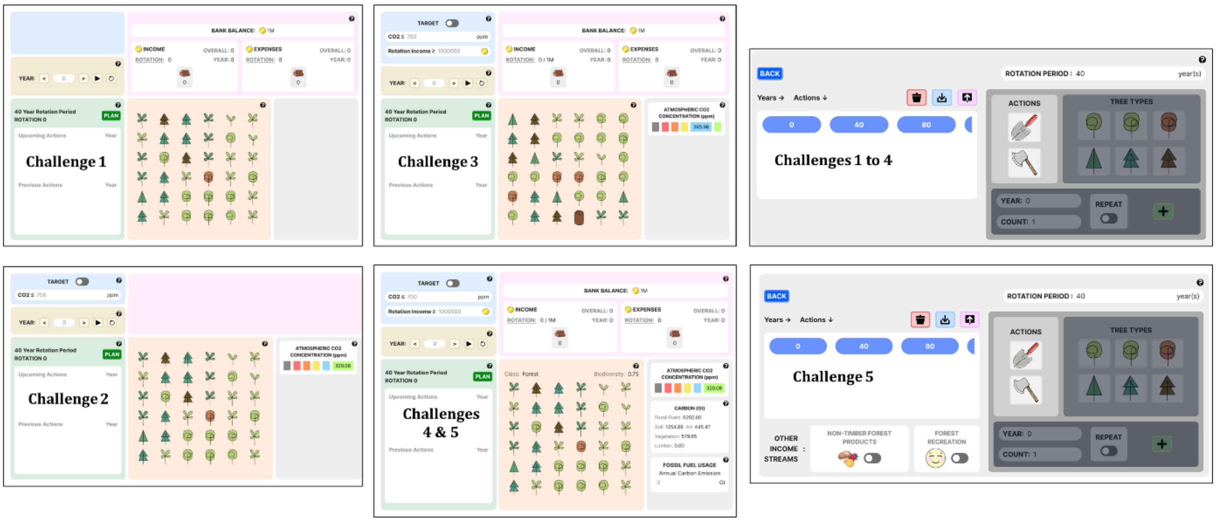


Figure 7. UI gradual feature reveal over 5 challenges.

Effective implementation of (i) problem-based learning, (ii) reflective learning and (iii) inquiry-based learning approaches through appropriate class climate, peer relationships, teacher-learner, and learner-learner interactions improve the likelihood of young learners retaining taught values and information into adulthood. [11] MycroForest facilitates all these 3 learning conditions through target setting facilities, appropriate immediate feedback, and challenges interlaced by discussion opportunities.

Lastly, a good story line, make belief setting, or premise for the learning activity is shown to be much appreciated by young learners (GP (ix), FTOE (vii)). This is why the landing page incorporates a fun interactive exercise to spark interest followed by a quick click-through introduction that provides a narrative that welcomes the learner and sets the scene for activities to follow (please find details about this landing page in the following section 58).

The challenges themselves derive inspiration from the Hero's Journey storytelling framework. This framework takes the audience (learners in this case) through a journey from the ordinary world (real world) to another one (fantasy world – here, the microworld) and back. In literature, cinema, and storytelling in general, this is often done by means of a leading character and their journey that the audience relates to. The advantage with games and interactive tools like MycroForest is that they make it possible for the audience to experience this for themselves. The Hero's Journey formula with 11 stages was proposed by Joseph Campbell in his work "The Hero with a Thousand Faces" which reviews the standard path that multiple global mythological stories take. Briefly put, the journey begins with the hero of the story being compelled to go on an adventure. There is usually a wise figure or some friend who assists the hero and together they depart from their familiar day to day world to a different special world mentally, circumstantially, or literally, where trials await. The hero approaches the trials and tries to overcome them. At this point, there is often a crisis that leaves the hero at their lowest point wherein they discover something extremely valuable (treasure) that can be used to confront the crisis. Upon battling the crisis, literally or figuratively, the hero reaps the result of their success (or failure) before returning to their ordinary world again. The adventure however changes the hero's life as lessons learned, and circumstances experienced leave them with new resolutions and a fresh outlook on life.

Figure 8 displays the attempt to map the learner's UX to the Hero's Journey framework while developing challenges in MycroForest. Here, the learner is the hero and MycroForest is the special world. The landing page and click-through introduction is the call to adventure as it sets the stage for the learning activity. Teaching faculty and other peers in the group assist learners as they explore the tool. Challenges 1 through 3 are smaller trials. Challenges 4 and 5 present a crisis as the learner at his point, is confronted with all features of the app including the option to emulate anthropogenic carbon emissions due to fossil fuel usage. When learners play around with all features, they should realize that it is not possible to earn high income from timber and continue to burn fossil fuels while keeping CO2 levels low. This should lead to the understanding that compromises are necessary and that the best option is to arrive at a "happy medium" situation wherein CO2 levels are kept relatively low though reduced or no fossil fuel emissions and limited deforestation such that there is still some, albeit lesser profit from the forest. It is the hope that individuals leave the learning activity with the knowledge that economically viable (not immensely profitable) forest management is possible while still focussing on keeping atmospheric CO2 levels in check. They should also have an improved awareness about forestry practices, the important role forests play in controlling CO2 levels in the air, and the urgent need to reduce fossil fuel emissions. In the best case, the learner is inspired and resolves to be more climate responsible and perhaps goes on to learn more about sustainable forest management or climate change mitigation methods.

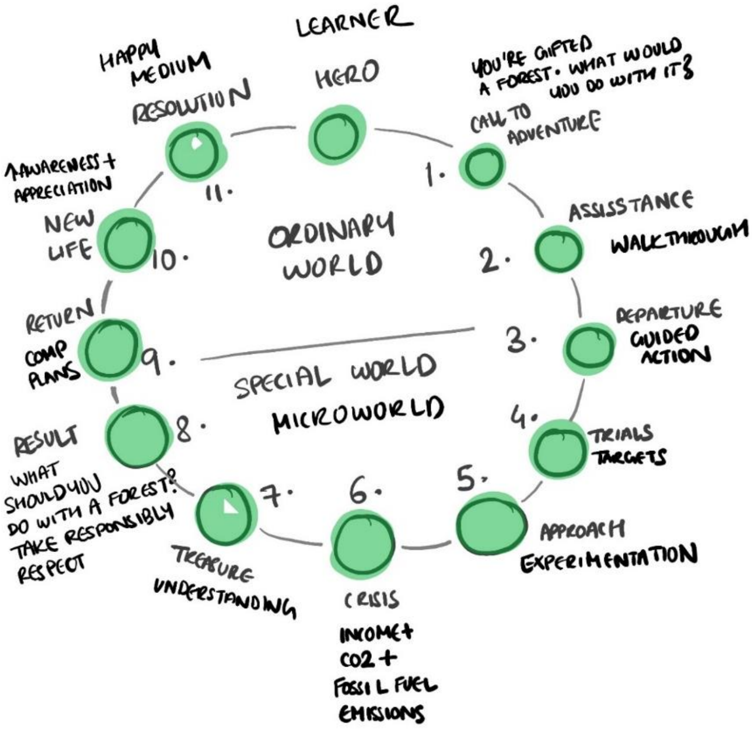


Figure 8. Mapping the Hero's journey framework to the learner's UX in MycroForest.

3.3 UI & HCI Design

This section explains the UI of MycroForest and reasoning that underpins its design.

3.3.1 App Pages

MycroForest comprises 4 web pages. Following passages explain what each page looks like, possible interactions, and its purpose.

Landing Page

This is the first page that the learner sees. It displays the name of the application, its icon, text summarizing the premise of this app that reads “Economically Viable Climate Aware Forest Management”, and instructions on how to proceed which reads “Press Enter”. This content is hidden by a dark veil and is revealed when the user hovers over it with their mouse that acts like a torch. This little exercise serves to pique the interest of learners and drop a hint as to the nature of the application being that it demands active participation. Upon pressing the “Enter” key on the keyboard, the dark veil disappears, content gets updated, and text that reads “Hi” with a prompt urging the user to click it, replaces the app icon. Towards the bottom of the screen, two words "Help" and "Word" also appear. Hovering over these, reveal navigation instructions that inform the learner that they must press the "H" and "W" keys to navigate to the "Help" and "World" page respectively.

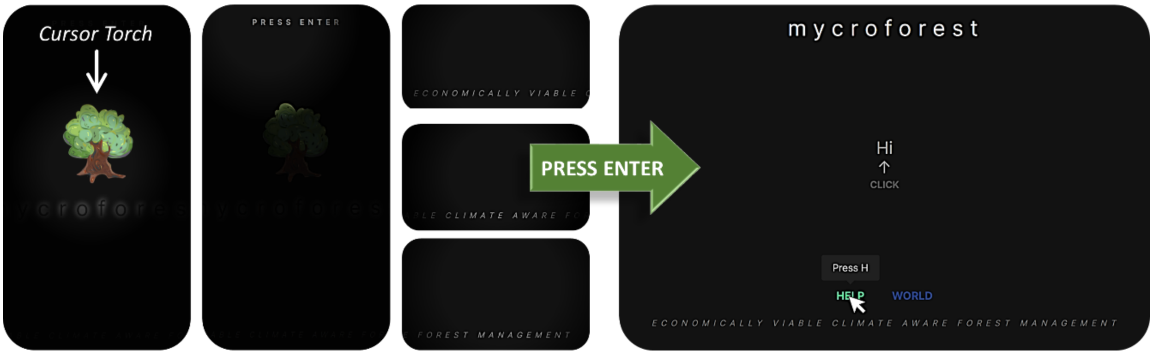


Figure 9. Landing page. Left: Interactive mouse cursor torch reveal content. Right: Introductory content that is revealed upon pressing the "Enter" key.

Clicking on "Hi" begins a dialogue which progressively introduces the learner to the app. The first time that a user starts this click-through session, they must complete it before they can navigate to other pages. Attempting to move to other pages mid-way, causes a message to appear that reads "Your enthusiasm is much appreciated, but I'm not done yet. Please continue clicking. I promise this won't take long". Each item in the following list is one piece of dialogue. When the learner clicks on the text, it fades to reveal the next dialogue until the last one is reached.

- "Hi."
- "I've been expecting you."
- "You've chosen well."
- "They say it's been here for at least 200 years."
- "The forest is healthy and fairly large."
- "I'd say it's a good size for a first time forest owner like yourself." – This suggests to the user that they will be assuming the role of a forest owner.
- "Your forest offers valuable resources like wood." – This hints at how the user will be able to sell wood and other resources to earn coins.
- "I'm sorry to hear about global warming and rapid climate change on Earth." – This directs attention to the theme of climate change.
- "But it's not a bother here; your forest regulates the carbon cycle." – This subtly informs about how the forest aids in managing atmospheric CO_2 levels in the microworld.
- "As your adviser, I've arranged for help. An interactive map will manifest when you press 'H' on your keyboard. It'll walk you through the lay of the land and all what you can do here." – This informs about the help page.
- "Help will also appear upon clicking the '?' symbol whenever available." – This informs about quick access "Help" that is available on the world and planner pages.

- “When you’re ready, just press ‘W’ to delve into the world.” – This informs about the world page.
- “Press ‘Escape’ to return to this page.” – This informs about how to navigate back to the landing page.
- “Explore away! ⟲” – This marks the end of the dialogue. Clicking on the reset icon ⟲ displays the “Hi” message once again.

<u>Help Page</u>

Pressing “H” on the keyboard reveals the help page with an interactive graph whose nodes correspond to components in the microworld. Double clicking a node causes a pop-up window to appear with text and images describing significance of that component and how the learner can interact with it. Each node shaped like a leaf may be clicked and dragged such that the other nodes and links follow in a fluid motion. This simply serves to add an element of enjoyment cause users to stay and explore topics which shall improve their understanding of the app.

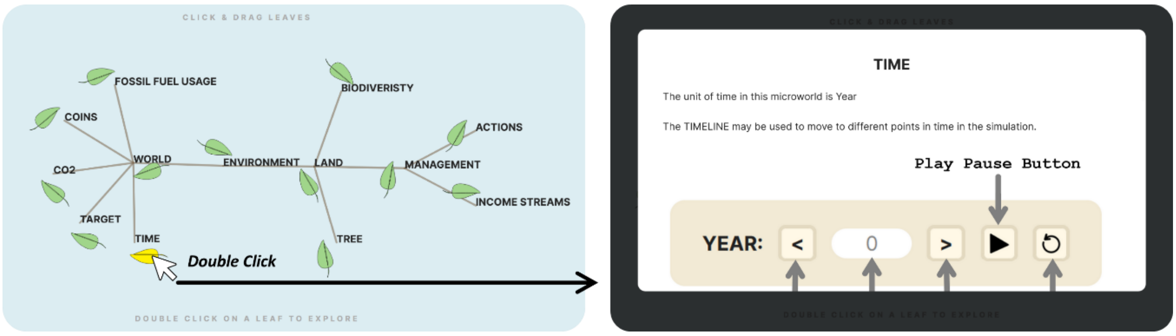


Figure 10. Help page with interactive graph. Double clicking a leaf node reveals pop-up text and graphics explaining significance and use of associated microworld component.

<u>World Page</u>

Pressing the “W” key on the keyboard takes the learner to the main Graphical User Interface (GUI) of the application. This is where users are expected to spend most of their time.

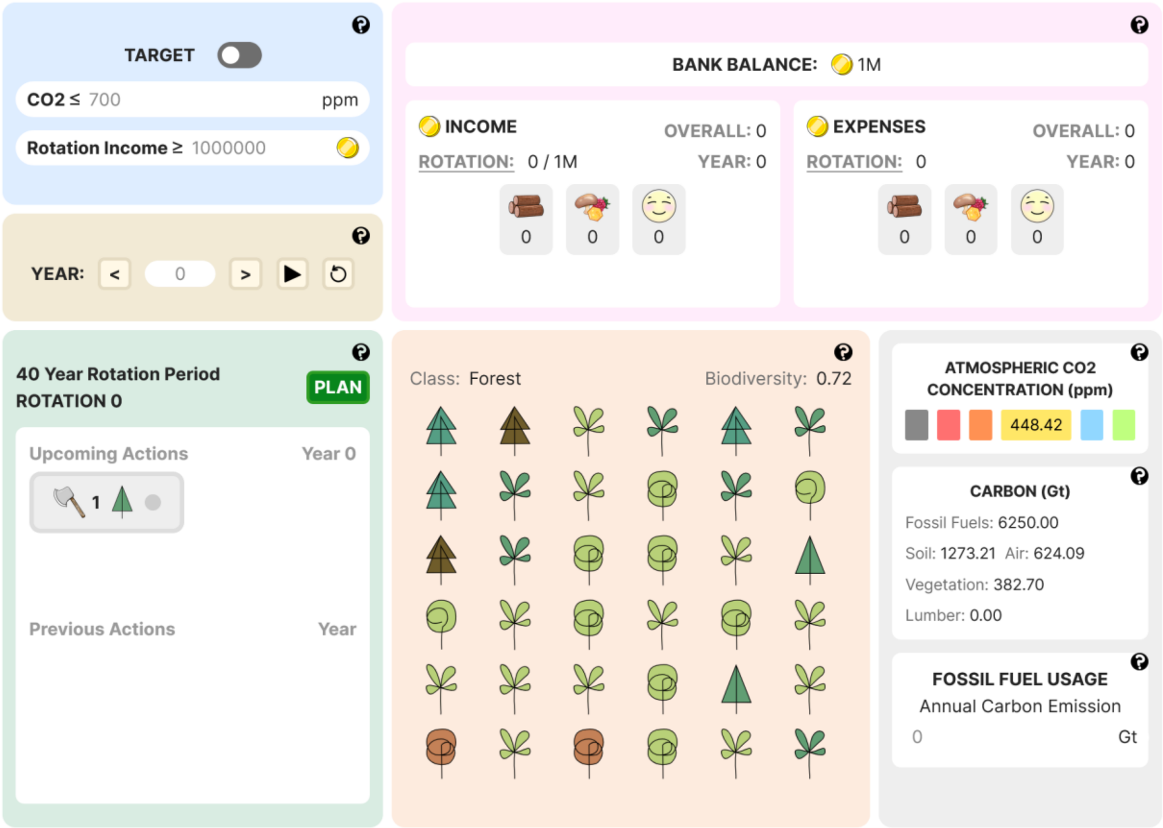


Figure 11. World page. This is the tool's main GUI.

Following paragraphs explain each UI element using parts of text and graphics displayed to learners when they click on the "?" icon in the tool or read about it in the Help page.

Land Plot

The land has 36 spots arranged in a 6 x 6 grid. Each of these 36 spots may either contain a tree or nothing. Hovering over land content reveals its type at the bottom of the plot. Different types of trees are displayed using different icons.

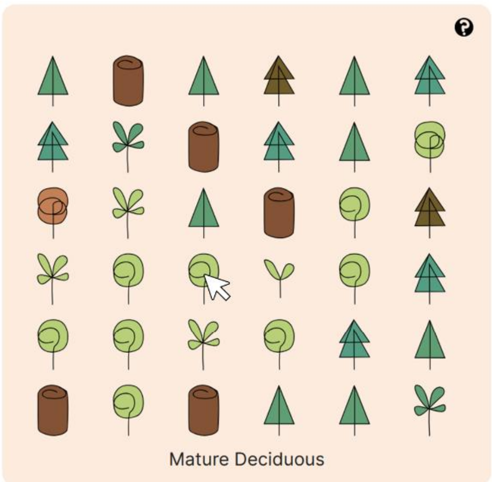


Figure 12. Land plot with mouse over interaction.

Timeline

The TIMLINE may be used to move to different points in time in the simulation.

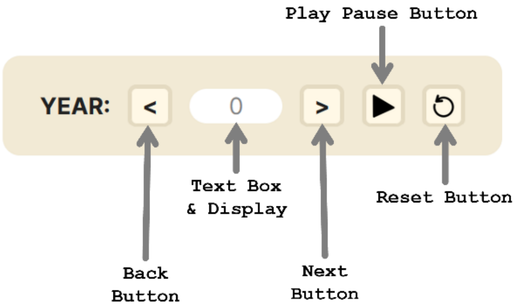


Figure 13. Timeline controls.

Clicking the PLAY BUTTON runs the simulation, and the current year in the microworld is updated with every timestep. The number in the display changes to reflect this. Once clicked, the play button changes to a PAUSE BUTTON. Clicking the pause button pauses the simulation and it changes back into the play button. The RESET BUTTON may be clicked to go back to year 0. The BACK and NEXT buttons can be clicked to go one year before or after.

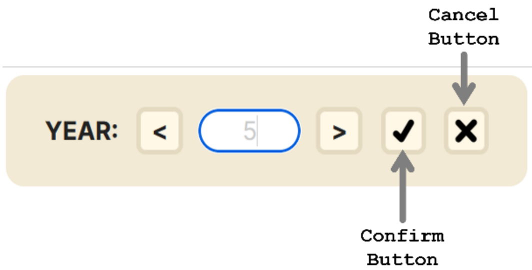


Figure 14. Timeline text field update interaction.

In the TEXTBOX, learners may type in any year within simulation range (0 to 300 years) and the microworld jumps to that point in time. Upon entering some input, the play/pause and reset buttons change to a CONFIRM BUTTON and CANCEL BUTTON as shown above. Clicking the confirm button applies the change to the year and cancel prevents this. If input is invalid (not an integer in the allowed range) then the input box turns red to indicate this and the change will not be applied even upon confirmation.

Plan Viewer

The PLAN VIEWER panel displays planned actions, the current rotation number and set rotation period. Once a plan has been drafted using the planner that can be accessed by clicking on the PLAN button, actions that were most recently processed along with the corresponding year is displayed under Previous Actions. Similarly, actions to be processed next along with the corresponding year, are displayed under Upcoming Actions. These action tags are horizontally scrollable if there are more of them than can fit within the view frame.

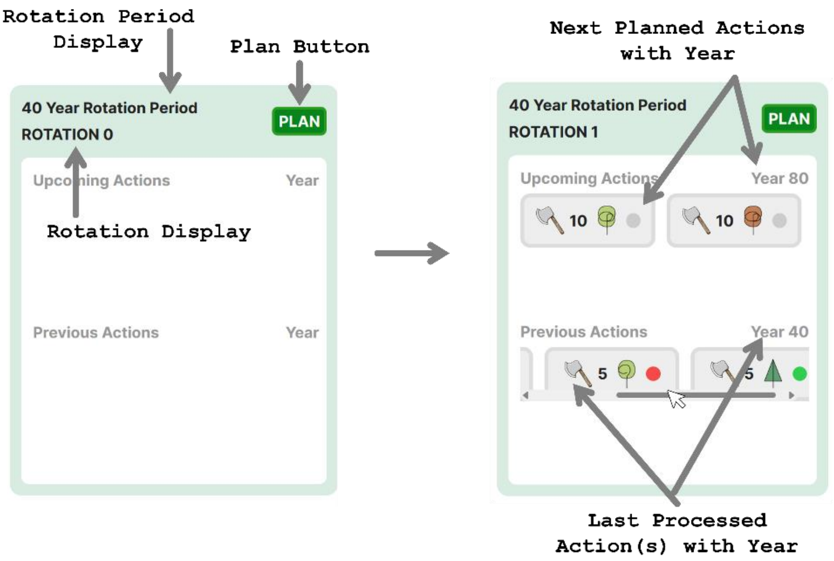


Figure 15. Plan viewer interactions.

Money Viewer

The MONEY NIEWER PANEL displays bank balance, income, and expenses. BANK BALANCE is the total amount of coins that the learner has at any given point in the simulation. Coins are the currency of this microworld.

INCOME refers to no. of coins earned. Overall income is how much the learner has earned so far in the simulation, yearly income is how much they've earned this year alone, and rotation income is how much they've earned in this rotation alone.

EXPENSES refer to how much the learner has spent overall, this year, and this rotation. Felling/planting a tree costs coins that comprise this expenditure.

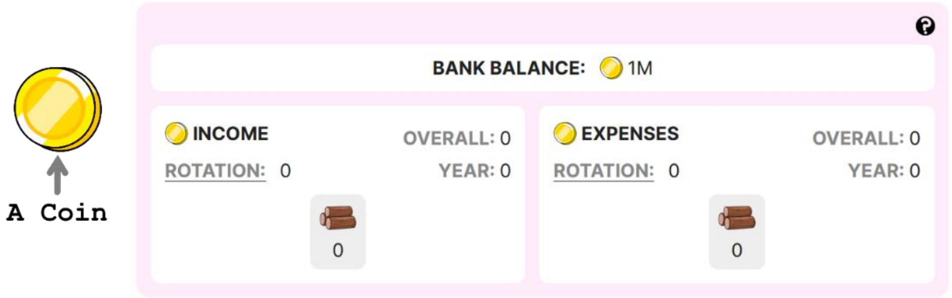


Figure 16. Money panel overview.

By default, it is income/expense per rotation that is visible below the icon representing type of income stream. Learners may click on 'OVERALL', 'YEAR' or 'ROTATION' to update this. Hovering over the icon reveals the name of the income stream.

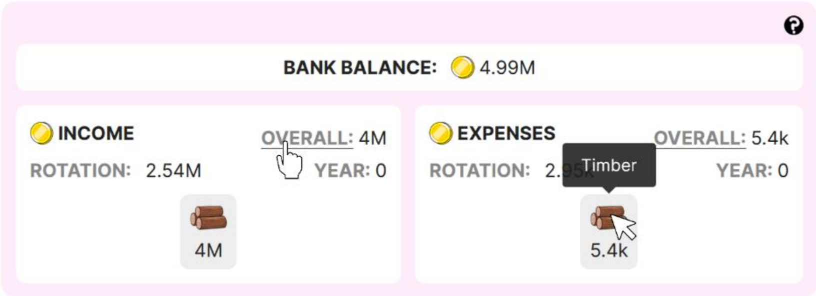


Figure 17. Money panel interaction.

When there are multiple sources of income, a breakup of income and expenses per stream is displayed using a colour coded proportion bar. Hovering over each colour displays the income stream and its contribution.

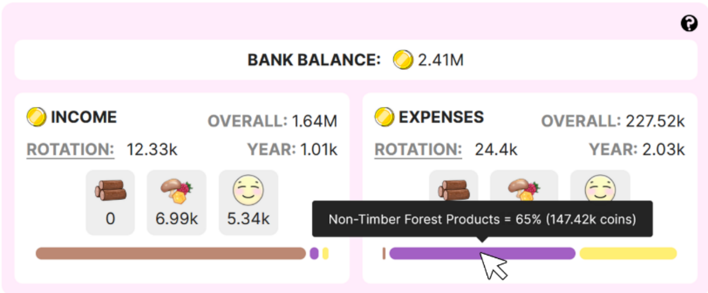


Figure 18. Income stream breakup.

CO2 Scale

Natural processes like respiration and anthropogenic (human generated) ones like burning of wood or fossil fuels, and so on, release carbon into the atmosphere in gaseous form, of which a large part is CO2. CO2 concentration in the microworld has been organized into an easy-to-read scale as shown below. Associated with each band in the scale, is a label that is indicative of the expected quality of life for humans at that level of atmospheric CO2 concentration after considering climate change related effects. Current levels of CO2 at each point in the simulation is displayed in the ATMOSPHERIC CO2 CONCENTRATION panel as shown below. The number within a coloured tile is the current concentration. Hovering over each tile, reveals its range and quality of life label.

Figure 19. CO2 concentration display panel.

Targets

Learners may set a target as part of challenges. The TARGET panel displays this as follows.

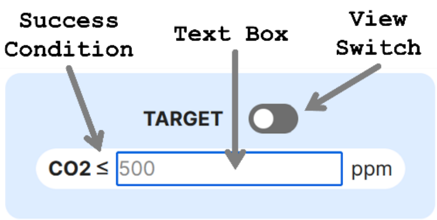


Figure 20. Target panel interaction.

Learners can type into the TEXTBOX, the CO2 concentration below which atmospheric CO2 levels must never dip. The VIEW switch can be toggled on and off. When on, the target panel displays whether the target is being currently met or not. If the success condition is satisfied, then a green border indicates this. If the target could not be met, then a red border shows this. The point in time at which the target first failed, is also indicated (notation Y2, Y3 and so on, means Year 2, Year 3, etc.).

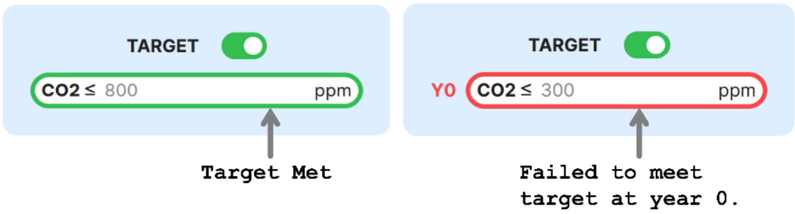


Figure 21. Atmospheric CO2 concentration target met or failed display.

Similarly, a target income value can also be set. This is the minimum income you're looking to earn every rotation. If learner fail to meet this target, the rotation at which this failure first occurred is displayed beside the target field using the notation of letter R followed by the rotation number.

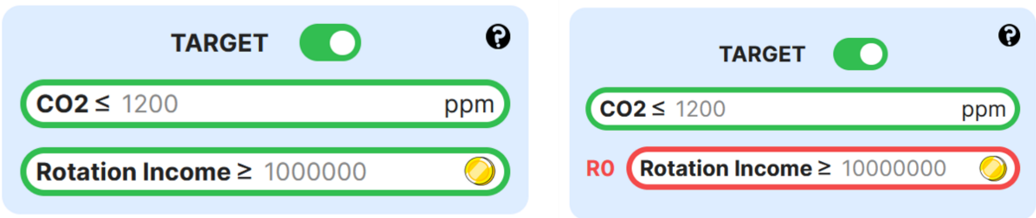


Figure 22. Income target met and failed display.

Fossil Fuel Usage

The FOSSIL FUEL EMISSIONS panel both displays and allows learners to set the amount of carbon released into the atmosphere annually due to humans burning fossil fuels for energy. By, default, annual emissions due to fossil fuel use is set to 0 GtC. This can be changed by typing any positive whole number into the textbox as shown below.

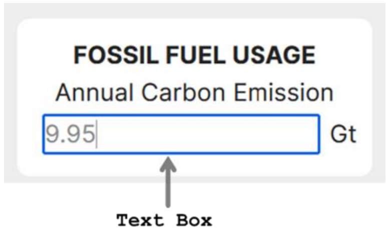


Figure 23. Fossil fuel emissions panel.

Carbon Composition Display

The carbon panel displays the exact amount of carbon in each reservoir throughout the simulation. In this world, there are 5 carbon reservoirs. Amount of carbon in all these reservoirs are expressed in Gigatonnes (Gt) of Carbon (1 Gt = 10^{12} kgs).

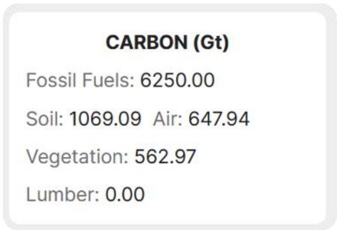


Figure 24. Carbon distribution panel.

Planner Page

The world page contains a "PLAN" button that leads to the planner page. The MANAGEMENT ACTION PLANNER here allows for creation of forest management plans involving planting or felling trees and activation of other streams of income from the forest. The "BACK" button on this page can be used to return to the world page.

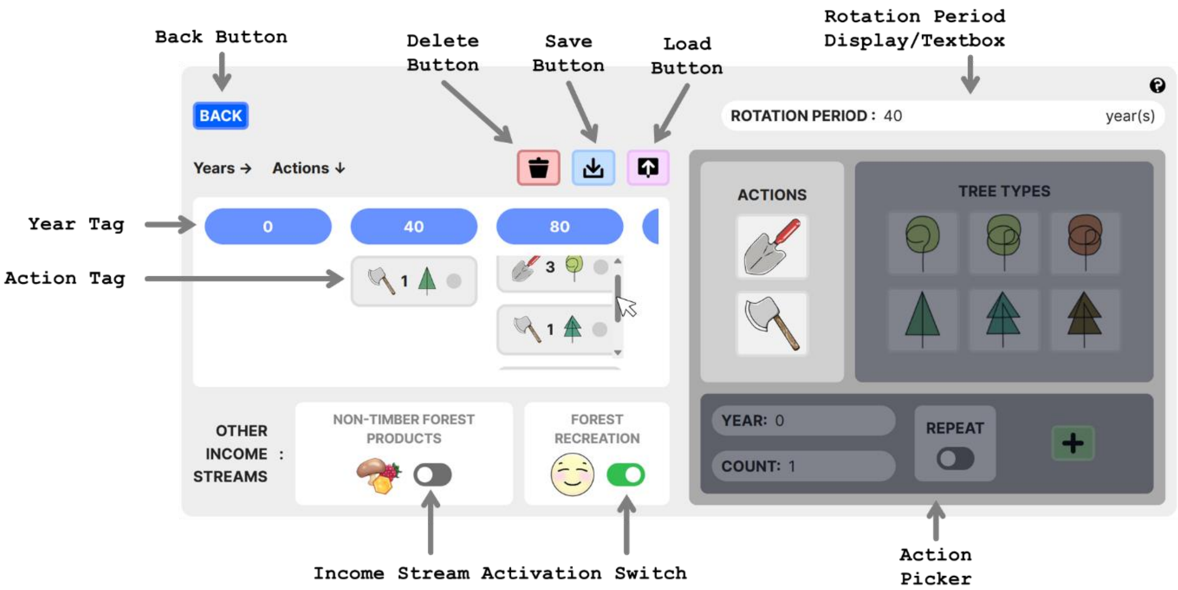


Figure 25. Planner page that contains a GUI that facilitates forest management plan creation.

There are two possible management actions to choose from.

1. **Felling:** Only mature, old growth, or senescent trees may be felled. Depending on the size of the tree felled, it can cost up to 3000 coins to fell a tree. The income that the

felled tree fetches will depend on the wood density of the tree and its size. Nevertheless, felling a tree always leads to some income from timber.

2. **Planting**: Irrespective of the life stage chosen from the action picker, upon planting, the tree of chosen type will start out as a seedling. Planting a tree of either type incurs a fixed cost of 277 coins.

To add a new action, first, the type of action must be selected. Then, the tree to apply that action to, must be selected. Finally, the maximum no. of trees to be affected as well as the year this action should be executed in, should be set using the text boxes. If invalid numbers are entered into these text boxes, then the change is not applied and the text turns red. If the REPEAT option is turned on, then this means that the picked action will be performed every rotation starting from the year associated with the picked action. Once happy with the settings, clicking the ADD BUTTON adds a new action tag to the plan.

Rotation period can be set by changing the value within the ROTATION PERIOD TEXT BOX. Invalid entries (integers ≤ 0, integers ≥ max no. of simulated years = 300, negative numbers, floating point numbers, input containing characters other than numbers) is highlighted in red and will not lead to an update of the rotation period value.

The blue year tags represent years at the beginning of each rotation as per set rotation period. This view frame is also horizontally scrollable. ACTION TAGS associated with actions added using the ACTION PICKER will appear under their corresponding year tags. These action tags under each year tag are vertically scrollable in case of view frame overflow. Clicking an action tag, selects it. Clicking a selected action tag, deselects it. Multiple tags may be selected at once. Selected actions may then be deleted by clicking the DELETE BUTTON. Double clicking the DELETE BUTTON deletes all planned actions. Clicking the SAVE BUTTON saves the current state of microworld along with the latest plan and other settings. he UPLOAD BUTTON can be used to load previously saved states.

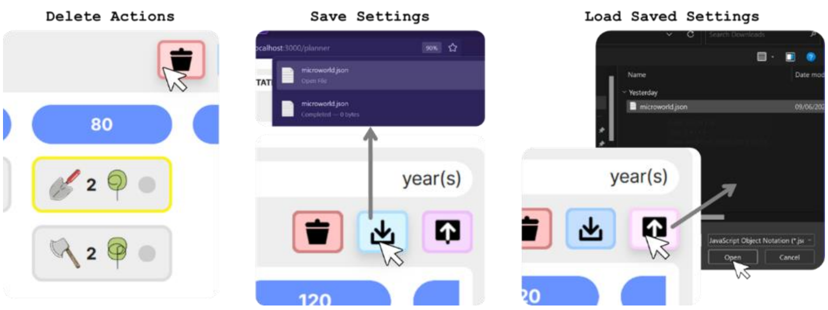


Figure 26. Management action planner: Delete actions and save or load plans interaction.

If the learner chooses to add an action for a year that falls within a rotation and not at the beginning of one, then such years appear in red to indicate this.

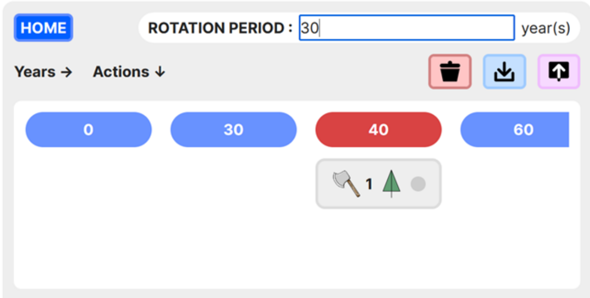


Figure 27. Within rotation action coloration difference.

An action tag displays information about the corresponding action and its execution status. If an action was successfully executed for all no. of the specified type of tree, then execution status is green. If it was only possible to execute this action for a fraction of the originally specified no of trees, then the status is yellow indicating that this action was executed for how many ever trees as was available on land at the time, although that was lesser than the specified count. A red status indicates that the action could not be executed at all (perhaps because there was no instance of the given tree type and age on land).

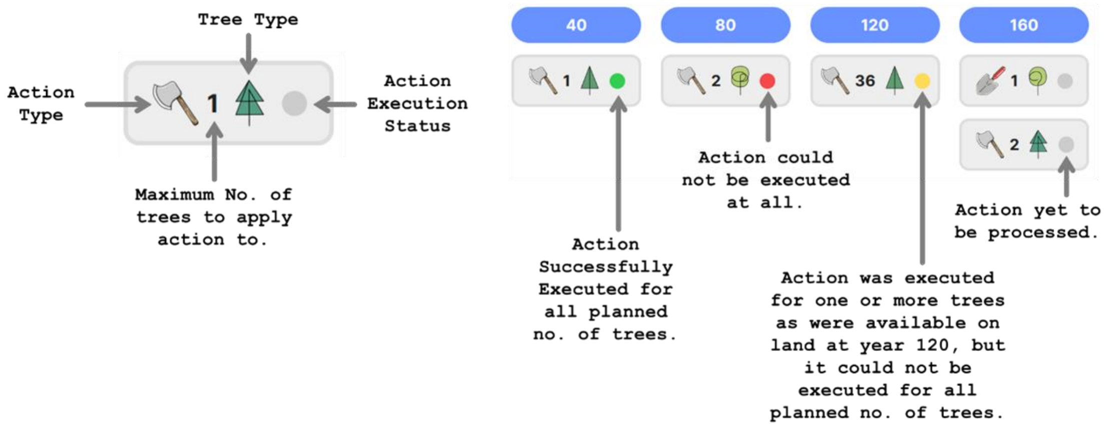


Figure 28. Significance of action tags.

Income can be generated from the forest via the timber income stream by selling wood from felled trees. When the fell action gets executed successfully, harvested timber is sold and gets used. There are also other ways of earning from a forest other than the TIMBER INCOME STREAM. Learners may harvest and sell other resources found in the forest like honey, mushrooms, and berries. Another option is to open the forest up for public recreational use and earn income from selling visitor permits. Switching on the corresponding switch activates each income stream.

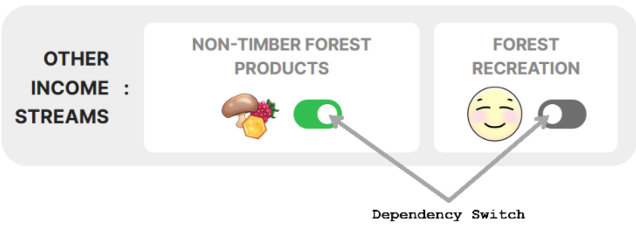


Figure 29. Other active and inactive income streams.

3.3.2 HCI Principles

Table 12 summarises HCI principles that MycroForest has tried to adhere to.

Norman's Model	***Task – Core Language Mapping***	***Jacob Nielsen's Usability Heuristics***
(i) Goal establishment.	(i) Articulation: User maps their goals to actions.	(i) Use simple language with no irrelevant information.
(ii) Intention formation.	(ii) Performance: System interprets user actions and responds correctly.	(ii) Speak the user's language.
(iii) Action sequence specification.	(iii) Presentation: System presents updated state.	(iii) Minimize memory load.
(iv) Action execution.	(iv) Observation: Users update mental model based on presented changes.	(iv) Maintain consistency.
(v) System state perception.		(v) Provide timely and apt feedback.
(vi) System state interpretation.		(vi) Clearly mark exits.
(vii) System state evaluation.		(vii) Incorporate shortcuts for expert users.
		(viii) Display good error messages.
		(ix) Design to prevent errors.
		(x) Ensure help is readily available.

Table 12. HCI principles summary.

Norman's Model & Task – Core Language Mapping: *ARTICULATION* → MycroForest presents a great use case for direct incorporation of Norman's Model. The tool allows explicit CO2 and income targets or ***goals*** to be set. Challenges as part of the learning activity guides learner ***intentions***. The primary interaction expected of users is that of forest management plan development. The management action planner provides an action picker and plan viewer that facilitate a simple way to craft plans as well as immediately view it. Such provision to view and edit plans easily caters towards ***principle (iii)*** from Norman's Model. Further, MycroForest allows learners to trigger ***action execution*** and step through their plans easily using the timeline's play, pause and step buttons. *PERFORMANCE + PRESENTATION* → The land plot, money viewer, CO2 panel, carbon panel and the targets panel all reflect **system state** changes after each timestep so that users may ***perceive*** all relevant consequences of their plan. MycroForest strives to make it easy for users to interpret cause-effect patterns. *OBSERVATION* → Thus, an option to pause and replay the simulation or jump to specific points in time is provided to aid in investigation of what exactly a plan does to the virtual forest. It is possible to save and reload starting forests and plans. Action execution status (successful, partially successful, failure) is also presented for further clarity. Changes to land content is graphically displayed and animated as the simulation runs so that users may detect changes more easily. All these factors hope to support ***learner interpretation*** of the system. Lastly, colour has been leveraged in both the targets panel and the CO2 panel to highlight idealness of conditions, thereby aiding learners in ***evaluating*** system state.

Jacob Nielsen's Usability Heuristics: The role of text in MycroForest is largely confined to explanatory reasons as the UI on main pages like the world and planner page is primarily graphics heavy. The learner only encounters paragraphs of text when they are learning to use the app using either the "?" icons or the help page. ***Language*** of this text is kept ***simple*** so that young adults find it its easily comprehensible. Icons depict ***familiar*** items that are largely unambiguous (axe = fell a tree, chopped logs = timber, plus = add, dustbin = delete, etc.). Slightly stylized tree icons come with an explanation that clarifies information (tree species and life stage) that they encode. All interactive elements are traditional and common ones (buttons, text boxes, toggle switches, scroll bars, mouse over action, click action, double click action, keypress action) that learners are most likely familiar with. The plan viewer displays action crafted in the planner page on the world page. Action execution status viewed on the world page gets reflected on the planner page. Plans including all world settings (targets, initial forest composition, active income streams, management actions) can be saved and reloaded. Learners can thus worry less about keeping their plans in ***memory*** and focus more on interpreting their results. All terms in MycroForest mean the same thing on every page. Display language (graphical and textual) is kept ***consistent***. As discussed earlier, the tool immediately provides ***feedback*** upon time updates and action execution by updating the UI to reflect system state changes. Users can reset the simulation anytime, delete entire plans/individual actions, reload a saved world, or simply refresh the browser to get a fresh starting forest and default settings. This facilitates ***undoing*** of mistakes or starting afresh if required. No shortcuts are implemented. ***Erroneous*** text box inputs are met with text turning red or a red border around the text box. Further, there are measures in place that ***prevent errors***. For example, it is not possible to load or reload the planner page without having navigated there from the world page. This prevents world state corruption. Comprehensive built in ***help*** is available in bite sized chunks so as not to inform but not overwhelm.

3.3.3 Data Visualization

Note: Content in this section is based on knowledge gained from lecture material put together by Prof. John Dingliana for the CS7DS4/CSU44056 – Data Visualization module that the author of this document has undertaken at Trinity College Dublin as part of the MSc. Computer Science programme (2023 – 24).

Centuries of research suggests that sight is the most important human sense. [71] Thus, data visualization is an integral part of software design. Presentation of content greatly influences a user's mental model of a system as well as the rate at which they are able to develop the right understanding.

What?

The Dataset w.r.t MycroForest is the underlying simulation model. Dataset type is temporal as system state changes over time. This model is visible to the user via system state variables displayed and thus this is the data that is visualized. Different types of data benefit from different visualization methods. Broadly, data can be quantitative (number) or categorical (not a number). Quantitative data can be discrete (integers) or continuous (real numbers). Categorical data may be binary (1/0, yes/no, true/false), nominal (not ordered, e.g. red, green, blue), ordinal (ordered; e.g. small, medium, large).

Data:	Years	Tree Type	Tree Age	Tree Position	Income
Description:	Current year in simulation.	Coniferous or deciduous.	Age of the tree.	Position [x, y] of tree on land grid.	Money earned.
Type:	Quantitative Discrete	Categorical Nominal	Quantitative Discrete	Categorical Nominal	Quantitative Continuous

Data:	Expenses	Biodiversity	Total Money	CO2	Carbon
Description:	Money spent.	How biodiverse is the land?	Bank balance.	Atmospheric CO2 concentration.	Amount of carbon in various reservoirs.
Type:	Quantitative Continuous	Quantitative Continuous	Quantitative Continuous	Quantitative Continuous	Quantitative Continuous

Data:	Action Type	Action Tree Affected	Action Year	Action Num Trees Affected	Is Action Successful
Description:	Fell or plant.	Type and age of the tree targeted by the action.	Year at which the action is to be executed.	The no. of trees that the action is to affect.	Successful, partially successful, failure.
Type:	Categorical Nominal	Categorical Nominal	Quantitative Continuous	Quantitative Discrete	Categorical Ordinal

Data:	Is Action Repeated	Target Values	Is Target Met	Is Income Stream Active	Rotation Period
Description:	Whether this action is to be repeated periodically.	Set CO2 or income target.	Whether target is met.	Whether an income stream is active.	Set rotation period.
Type:	Categorical Binary	Quantitative Continuous	Categorical Binary	Categorical Binary	Quantitative Discrete

Table 13 identifies key data attributes that are visualized in MycroForest and their types.

Data:	Years	Tree Type	Tree Age	Tree Position	Income
Description:	Current year in simulation.	Coniferous or deciduous.	Age of the tree.	Position [x, y] of tree on land grid.	Money earned.
Type:	Quantitative Discrete	Categorical Nominal	Quantitative Discrete	Categorical Nominal	Quantitative Continuous

Data:	Expenses	Biodiversity	Total Money	CO2	Carbon
Description:	Money spent.	How biodiverse is the land?	Bank balance.	Atmospheric CO2 concentration.	Amount of carbon in various reservoirs.
Type:	Quantitative Continuous	Quantitative Continuous	Quantitative Continuous	Quantitative Continuous	Quantitative Continuous

Data:	Action Type	Action Tree Affected	Action Year	Action Num Trees Affected	Is Action Successful
Description:	Fell or plant.	Type and age of the tree targeted by the action.	Year at which the action is to be executed.	The no. of trees that the action is to affect.	Successful, partially successful, failure.
Type:	Categorical Nominal	Categorical Nominal	Quantitative Continuous	Quantitative Discrete	Categorical Ordinal

Data:	Is Action Repeated	Target Values	Is Target Met	Is Income Stream Active	Rotation Period
Description:	Whether this action is to be repeated periodically.	Set CO2 or income target.	Whether target is met.	Whether an income stream is active.	Set rotation period.
Type:	Categorical Binary	Quantitative Continuous	Categorical Binary	Categorical Binary	Quantitative Discrete

Table 13. Visualized data attributes and their types.

Why?

Data visualizations typically serves one of 2 purposes. They may be explanatory when the data story (interesting or meaningful idea like an association between variables, a trend, etc.) is known and the visualization is orchestrated to convey this known idea to the viewer. Exploratory visualization on the other hand often presents almost all available data to the viewer who then investigates or explores it to possibly discover a data story. Here the visualization designer is unaware of valuation conclusions or meaningful observations that may or may not be present in displayed content. The model is built on informed decisions driven by research. It is built to resemble a known system. Thus, at the broadest level, the purpose of data visualization within MycroForest is ***explanatory***.

Task abstraction is the next, deeper level of data visualization. It refers to identification of what viewers might do with the data. The actions – targets framework captures this well. Briefly put, this framework considers possible actions that users may perform (verbs) on certain target potions or characteristics (nouns) of visualized data. Following are few action – target task abstraction examples. Actions are blue, and targets are magenta.

- Prospective business owners might analyse consumer trends regarding their product and consume information as they discover key customer bases. They may also analyse and produce their own data about striking features in the dataset. For example, annotating customers by derived age categories might have revealed that most of them are millennials.
- Doctors may search a brain scan to look up and confirm the shape of the frontal lobe, locate the hippocampus, browse for possible known neural activation paths, or explore to see if there are unexpected abnormalities.

- An air crash investigator might query flight data to compare it with data from past crashes in hopes of identifying similarities. They may summarise instrument readings from normal flights by plotting distributions and extract data extremes like min and max values to see if crash related values would be outliers.

Similarly, using MycroForest, learners may produce forest management plans and compare results of various such plans against each other to discover dependencies between order and choice of management actions and system state change trends over time such as changes in forest composition, atmospheric CO2 concentration, income earned from the forest, the biodiversity score, etc. Users may explore different strategies as they browse through varying values for other settings like rotation period lengths and activation of income streams to locate plans that achieve goals like carbon sequestration maximization, income generation maximization, or both. In the process they learn about challenges and best practices w.r.t economically viable climate aware forest management.

<u>How?</u>

Graphically depicting data involves picking appropriate encoding channels. Encoding channels refer to graphical primitives that a visualization is composed of. There are 8 such channels or attributes of graphical elements that may be altered to encode variances in data. They are position, shape, size, brightness, colour, orientation, texture, and motion. These channels have certain characteristics. They may be selective (allows easy distinguishability), associative (supports grouping), ordinal (displays clear change in order) or quantitative (allows for quantification of difference between data points). The range of unique data point types that a channel can support is another channel characteristic referred to as range.

Often, more than one channel or more than one instance of a channel may be preset within the same visualization. Some such combinations like that of position + colour is preferred due to greater visual separability over others like colour + colour (e.g. using multiple hues of a colour to grade variables grouped by colour). Once encoding channels are determined, they are incorporated into visualization idioms which are essentially just specific types of graphs (e.g. scatter plot, line plot, pie chart, etc.). Idioms may simply encode data by arranging it and mapping it to specific channels. They can also allow for manipulation of data through depicting change and facilitating selection or navigation. Different idioms can be combined within a visualization through techniques like juxtaposing, partitioning, or superimposing them. Lastly visualization idioms can be designed to help reduce data and manage complexity though incorporation of data filtering, aggregation, or embedding.

Thus, several design decisions are involved in presenting content such that the visualization “addresses a clear objective” while “avoiding distortion” of data and “handles complexity” in the dataset well enough so as not the distract or overwhelm the viewer when informing them. Following paragraphs explain such decisions that inspired main graphical displays in MycroForest.

Most data attribute values in MycroForest get updated every timestep as the simulation runs. This change over time is captured using the motion encoding channel through animation wherein land content symbols, action plan viewer action tags, and all money as well as CO2 and carbon related numbers on the world page get updated after every time step.

The **land plot** visualizes Tree Age, Tree Type. Tree Age can range from 0 to 100 years while they are alive. They may remain on land for more years after they die until completely decayed. Using a different colour or shape to precisely show how long a tree has remained on land will only overwhelm the viewer. To manage this complexity, trees of different ages were organized under 6 age groups and an interaction was introduced where learners can hover over a tree icon to reveal its precise species and age. Similarly, Biodiversity score is a continuous value in the 0 to 1 range. To improve differentiability, the land was classified as "Unforested", "Plantation", "Forest", or "Ecosystem" based on increasing order of biodiversity score. Figure 30 shows how both colour and shape was varied to distinguish between tree types and age groups. Once dead, behaviour of both trees is same. Hence, dead trees are depicted using the same symbol for both species. The land in MycroForest is a grid with 6 rows and 6 columns. Each row – column intersection is a land position. This set up is very compatible with a scatter plot. Thus, the scatter plot idiom was used to encode position of trees on land. Change in composition over time is animated and thus encoded using the motion channel.

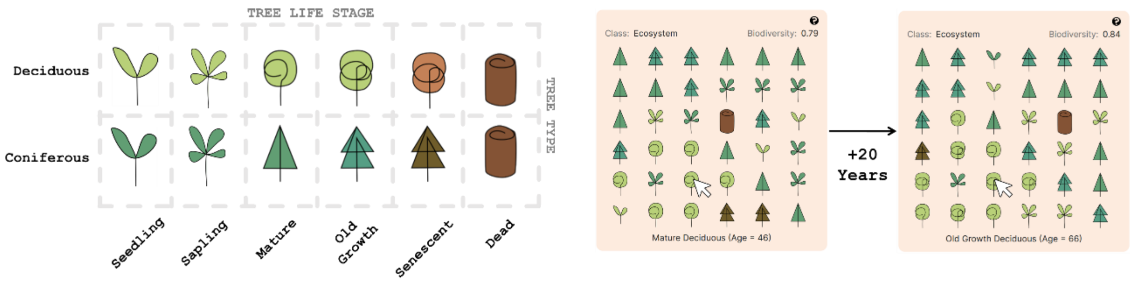
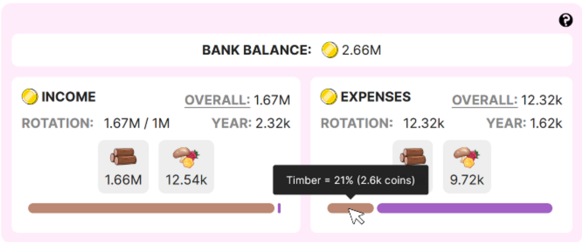


Figure 30. Land plot visualization that leverages colour, shape, position, and motion encoding channels.

The **money viewer** panel displays Income, Expenses, Total Money, and Is Income Stream Active data. Here, as well as in all other graphical elements, the precision of displayed numbers is restricted to at most 2 decimal points as greater precision does not add to the learner's understanding and would only serve to distract them. There are 3 possible income streams (Timber, NTFP, Recreation) and two types of figures (income, expenses) that change over time. Thus, complexity of data is high. The total bank balance and overall income and expenses over the entire simulation so far, is displayed using text. But this hides some information such as money earned / spent per rotation and year. Thus, figures were grouped into 3 time-based levels (per rotation, per year, overall) and displayed at different positions of the screen. Displaying these 3 figures for all the 3 income streams will present the user with too many numbers at a time to take in. To manage this, only figures related to active income streams are displayed. When there is more than one active income stream, by default, steam wise split of income/expenses is displayed only for "per rotation income". Users can view this breakup for any time level by clicking on the heading for that time level. The fact that this time level is clickable is indicated by the text gaining an underline upon hover. The currently selected or last clicked time level's heading retains that underline even when the mouse pointer is not over it to show that this is the selected level. Also, to make comparison easier, when there is more than 1 active income stream, a stacked bar idiom is used to quickly convey proportion contributed to by each income stream. Hovering over a bar, colour coded to map to specific income streams, reveals more detail such as name of income stream, precise contribution percentage and exactly how many coins were earned or spent. As the simulation runs, these figures change over time. Thus, the money panel leverages the position, colour, size (size of each bar in stacked bar plot), and motion encoding channels to organize and display money related data. Aggregation and interactive reveal are used to manage complexity.



- Pink and white colour for separation & colour coded bars.
- Size of stacked bars hint at contribution proportions revealed on hover.
- Time level data separated using position.

Figure 31. Money panel visualization that leverages colour, size, position, and motion encoding channels.

Both the planner and the plan viewer visualize forest management plans created by learners that comprise management actions. Each management action is a combination of 5 data attributes (Action Type, Action Tree Affected, Action Num Trees Affected, Is Action Successful, Action Year). There are 2400 possible unique actions (fell 6 unique age-species combination of tree and plant 2 species of tree per year of the simulation that spans 300 years). This complexity due to high dimensionality was reduced using following methods.

- Encode 4 action attributes into 1 symbol or visual element wherein colour is used to distinguished between different action execution statuses (red = failed, amber = partially successful, green = successful).
- Not every year is visualized in the Planner. Only years marking the beginning of each rotation is displayed using a blue year tag. They are positioned such that only a portion of all year tags are visible at a time. Learners may use the scroll bar to reveal others. Colour is used to distinguish years within a rotation (red year tag) from those that mark the beginning of one (blue year tag). Colour is also used to indicate selection of an action tag.

- In the plan viewer, only last processed and upcoming action tags are displayed separated using position (upcoming on the top and last processed on the bottom). Learners can click on the PLAN button to view the planner for details.

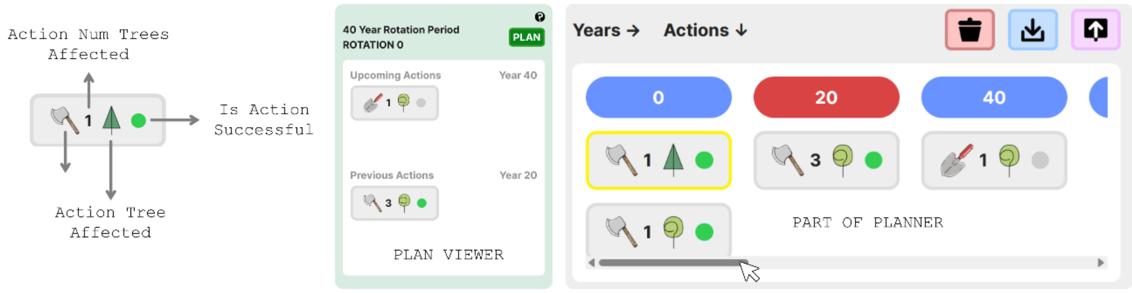


Figure 32. Management plans visualized using position, colour, and motion (plan viewer content changes over time) encoding channels.

CO2 concentrations change over time and are quantitative continuous values with high range. Thus, once again, to improve interpretability, these values were categorized into categories based on impact on human life due to climate change and colour coded. Only the current precise value is displayed and will get updated each timestep. Hovering over any colour reveals its category, thereby saving screen space needed for a legend.

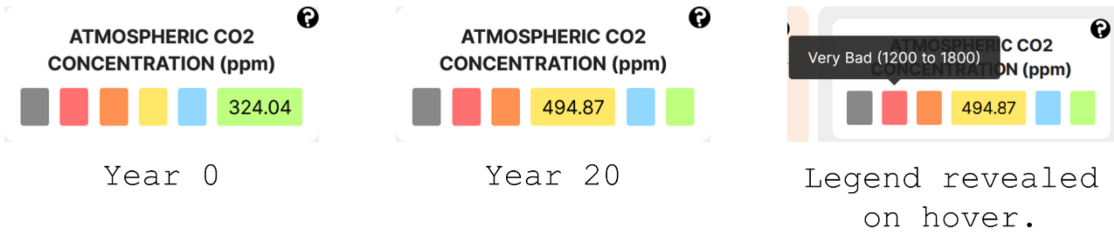


Figure 33. Colour and motion (updates over time) encoding channels used in the CO2 panel.

Another notable display design decision is the use of red and green colours to indicate whether a target has been achieved (green) or not (red).

Lastly, the decision was made to use a toggleable switch component as means of input for attributes like “Is Serious Mode”, “Is Income Stream Active” and “Is Action Repeated” whose values the learner can set since these components are implemented to have a distinctly separate colour and shape in ON and OFF positions which encode the categorical binary nature of these attributes well.

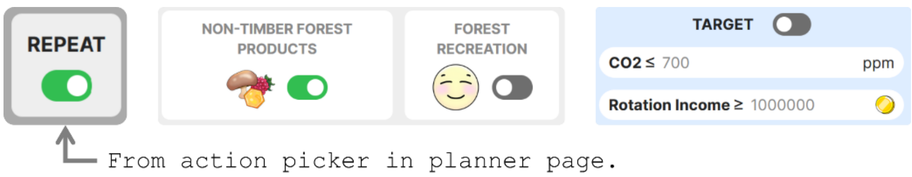


Figure 34. Use of switches.

Thus, overall, key encoding channels leveraged are colour, position, size, and motion with position + colour being the most used combination visible even in the general layout of the world and planner pages (each group of related graphical elements separated from others by placing them inside a different coloured panel) as this is generally considered to be the best (no ambiguity) combination w.r.t visual separability.

3.4 System Architecture

Structurally, MycroForest can be thought of as being composed of a simulation model, UI components, and input variables as shown in Figure 35. MycroForest App Structure.

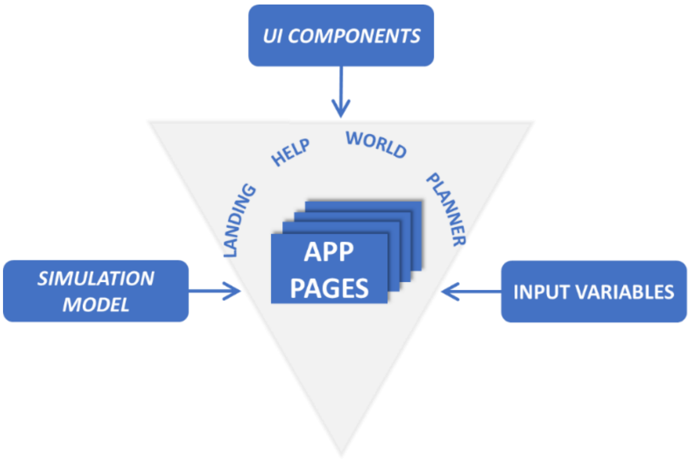


Figure 35. MycroForest App Structure

3.4.1 Simulation Model

This section presents the conceptual model that the simulation is based on as well as research that inspired it.

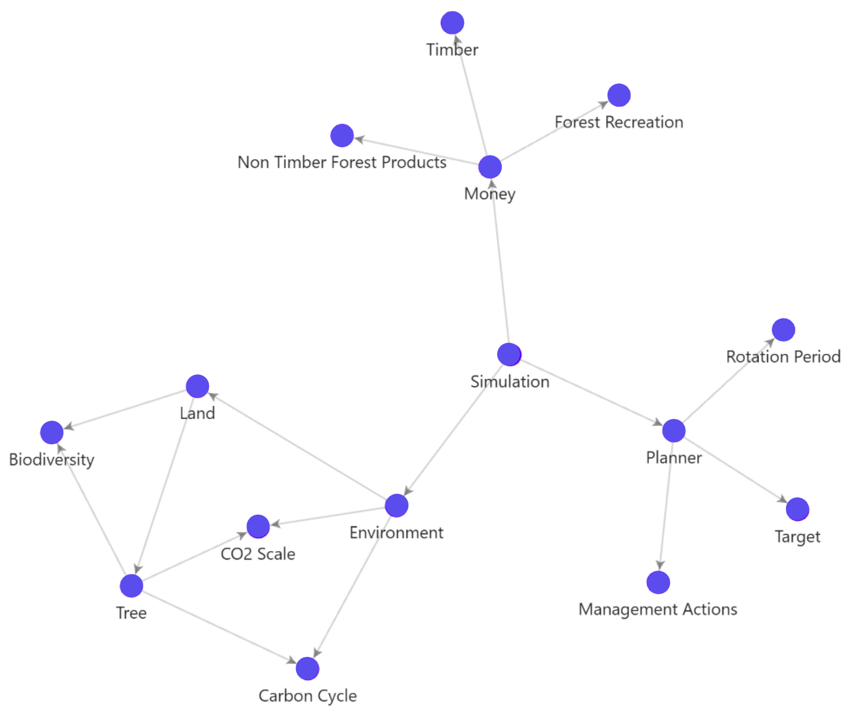


Figure 36. Graph representation of simulation conceptual model entities. Click on a node to navigate to its explanation.

Figure 36. Graph representation of simulation conceptual model entities. above is a graph representation of the simulation conceptual model. Each node represents a key idea or component as explained below.

Simulation

The simulation is the master component from which all other components may be reached. Its primary purpose is to coordinate all world elements and initialize the microworld. The simulation contains the microworld's Environment, and a Planner to keep track of user generated forest management plans. It triggers state update of all world components in accordance with passage of time and prompts update of the UI to reflect model changes. Furthermore, the simulation keeps track of forest resources and manages influx and outflux of Money.

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Environment

The environment is composed of the atmosphere, Land, and carbon reservoirs. In this microworld, there are 5 carbon reservoirs as follows. Carbon moves between them to emulate a simplified Carbon Cycle.

1. **Soil**: The soil holds carbon in the form of organic material (plant/animal remains, microbes, etc.) or minerals. [72]
2. **Fossil Fuels**: Of all the CO2 locked away in the earth, around 5 to 10000 Gigatonnes (Gt) is present as fossil fuels. [72] Fossil fuels are essentially remains of dead organisms from Earth's distant past that upon having been buried deep underground and exposed to great pressure and temperature over time has turned into energy dense oil, solids (coal), and gas.
3. **Atmosphere:** The mass of the atmosphere is about 5.1e+18 kg = 5.1e+21g. [73] Given the mass of CO2 (solute) in the air (solution) in grams and the mass of the atmosphere in grams, concentration of CO2 in Parts Per Million (PPM) is computed as $\frac{mass_{solute}}{mass_{solution}} \times 1e+6 = \frac{mass_{CO2}}{mass_{air}} \times 1e+6$. [74, 75] The CO2 Scale categorizes ranges of CO2 concentration in the air into different classes based on its implication on quality of human life after having accounted for associated climatic conditions.
4. **Vegetation**: The plants on land sequester carbon dioxide (CO2) from the atmosphere. Carbon sequestration refers to the process through which CO2 is removed from the atmosphere and held in solid or liquid form. [76]
5. **Lumber**: This is a man-made reservoir. It refers to all wood that's preserved in use (furniture, construction, etc.) and not burned for energy. When we preserve wood, we significantly slow down its breakdown and re-entry into the carbon cycle via natural decay. [77, 78]

When the simulation is created, there is a need to initialize carbon reserves with starting carbon amounts. The following paragraphs explain how these starting amounts were arrived at.

On earth, the amount of carbon in the air, soil, vegetation, and fossil fuels is estimated to be around 800, 2300, 550, and 10000 GtC respectively. [72] In order to allow for an initial CO2 concentration that sustains plant growth in the microworld, it was necessary to scale down the amount of carbon in the air from 800 GtC as on earth to 500 GtC. Thus, starting values for amount of carbon in each reservoir in the microworld is based on the following composition that though smaller, is the same ratio as on earth.

- $\text{Air} = 500\ \text{GtC}.$
- $\text{Soil} = 500 \times \frac{2300}{800} = 1437.5\ \text{GtC}.$
- $\text{Vegetation} = 500 \times \frac{550}{800} = 343.75\ \text{GtC}.$
- $\text{Fossil Fuels} = 500 \times \frac{1000}{800} = 6250\ \text{GtC}.$

At the initial stage in the simulation, all carbon in soil and vegetation is assumed to be in the air. As plants grow, they capture and store this carbon in themselves and the soil. Thus, starting amount of CO2 in the microworld is as given below.

- $\text{Air} = 1437.5 + 343.75 + 500\ \text{GtC} = 2281.25\ \text{GtC} = 2281.25 \times 10^{15} \approx 2.28\text{e}{+}18\ \text{gC}.$
- $\text{Soil} = 0\ \text{gC}.$
- $\text{Vegetation} = 0\ \text{gC}.$
- $\text{Fossil Fuels} = 6250\ \text{GtC} = 6250 \times 10^{15} \approx 6.25\text{e}{+}18\ \text{gC}.$
- $\text{Lumber} = 0\ \text{gC}.$

Table 14. Carbon distribution among reservoirs. summarizes this distribution of carbon among the various carbon reservoirs represented within the microworld.

Reservoir:	*Fossil Fuels*	*Soil*	*Air*	*Vegetation*	*Lumber*
Earth GtC:	10000	2300	800	550	0
Scaled GtC:	6250	1437.5	500	343.75	0
Starting gC:	6.25E+18	0	2.28E+18	0	0

Table 14. Carbon distribution among reservoirs.

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CO2 Scale

Atmospheric CO2 concentration is expressed in Parts Per Million (ppm). This is the standard. PPM is a measure of the concentration of a substance in a solution or gas. It is a proportion, just like percent. 80 percent is 80 parts out of 100. 80 ppm is 80 parts out of 1,000,000. Here, ppm indicates the number of parts of CO2 per 1 million parts of the total air in the atmosphere. [75]

CO_2 concentration in the microworld has been organized into a scale as shown below. Associated with each band in the scale, is a label and colour that is indicative of the expected quality of life for humans at that level of atmospheric CO_2 concentration after considering corresponding climate change effects.

CO2 Atmospheric Concentration (PPM) →	< 200	200 to 350	350 to 430	430 to 700	700 to 1200	1200 to 1800	>= 1800
Human Life →							

Color Scale (Increasing Optimality) →	*Impossible*	*Very Bad*	*Bad*	*Ok*	*Good*	*Best*

Figure 37. Quality of human life based associated with concentration of CO2 in the atmosphere.

Similarly, another scale was developed to categorize various levels of photosynthetic efficiency of plants at different atmospheric CO_2 concentrations.

CO2 Atmospheric Concentration (PPM) →	< 200	200 to 350	350 to 430	430 to 700	700 to 1200	1200 to 1800	>= 1800
Photosynthesis Efficiency →							

Color Scale (Increasing Optimality) →	*Impossible*	*Very Bad*	*Bad*	*Ok*	*Good*	*Best*

Figure 38. Photosynthetic efficiency associated with concentration of CO2 in the atmosphere.

Above scales were developed based on following information.

- Photosynthesis is more effective at CO_2 concentrations ranging from 700 to 1800 with around 1000 being max efficiency. Beyond 1800, conditions may start to become toxic for plants. [79]
- Below about 200 ppm concentration of CO_2, photosynthesis is extremely difficult with it being impossible less than or equal to 150 ppm. [80]
- Atmospheric CO_2 levels during human evolution ≈ 200 to 300 ppm. [81]
- Pre-industrial atmospheric CO_2 levels ≈ 280 ppm. [81]
- 20th century atmospheric CO_2 levels ≈ 300 to 250 ppm. [81]
- Atmospheric level of CO_2 that would push the world past its target for avoiding dangerous climate change ≈ 430 ppm. [81]
- One of our best estimates of an atmospheric CO_2 level that would be a tipping point beyond which global temperatures would rise by 8 to 10 $°C$ ≈ 1200 ppm. [82]
- Lowest known atmospheric CO_2 level ever based on findings from ice cores ≈ 172 ppm (650,000 to 800,000 years ago). [83]

In the scale regarding quality of human life, when CO_2 in the air falls below 200 ppm or rises above 1800 ppm, this corresponds to impossible living conditions because at the lower end, photosynthesis becomes difficult and at the higher end, global warming is expected to lead to inhospitable climate. In the microworld, while values in the 200 to 350 ppm range is ideal, CO_2 level is regarded as manageable if it stays in the green, blue, or yellow range between 200 to 700 ppm. This range is wider than on Earth where tolerable levels would more likely be between 200 to 500 ppm. This is because unlike in the real world, in this microworld, shifts in atmospheric CO_2 is exaggerated because carbon absorbed and released by trees is scaled by a large number to allow for just 36 trees to mimic all forests on Earth and significantly impact carbon levels in the environment. If CO_2 levels are in the 700 to 1200 ppm range, then it is considered bad for human life because this nears the expected tipping point beyond 1200 ppm beyond which it is difficult to revert to ideal conditions. Since this dangerous point is exceeded when atmospheric CO2 levels are in the 1200 to 1800 ppm range, this is categorized as "Very Bad" for human quality of life.

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Carbon Cycle

The carbon cycle refers to movement of the carbon element between the various states and locations in which it exists on our planet. Carbon is plentiful on Earth with most of it bound to rock in the lithosphere. Remaining carbon may be found dissolved or calcified in the ocean, in minerals or organic material in the soil, as CO2 or other gasses in the air, and in life including plants and animals. A large amount of it is also trapped as fossil fuels deep in the earth. Any location where carbon is found in large quantities is referred to as a carbon reservoir. [72] The movement of carbon between these reservoirs can be categorized into two types of carbon cycles, namely the slow and fast carbon cycle. [72]

- **Slow Carbon Cycle:** This cycle moves carbon between air, water, and rock slowly over 100 to 200 million years. Air bound carbon dissolved in water rains down as a weak carbonic acid which slowly reacts with rock to chemically weather them thereby releasing minerals like calcium, magnesium, potassium, etc. as well as carbon. These ions end up in the ocean via rivers where they are utilized by organisms that transform them into hard material like calcium carbonate that gets deposited as sediment on the ocean floor and gets compressed over time to produce rock such as limestone. Lastly, volcanic activity returns some carbon locked away deep within the earth into the atmosphere to complete the cycle. [72]
- **Fast Carbon Cycle:** This cycle primarily concerns the biosphere or life on earth and it's fast enough for effects to be visible within a human lifetime. Plants and phytoplankton can absorb CO2 from the atmosphere and turn it into sugar through a chemical reaction termed as photosynthesis. When carbohydrates produced by photosynthesizers are broken down to produce energy either by themselves or by other organisms that directly or indirectly consume them, carbon dioxide and other carbon compounds are released back into the air through respiration. Carbon in life is also released into the soil and air when the organism dies and decays. [72]

Left undisturbed, the slow and fast carbon cycles maintain amount of carbon in each reservoir fairly in the same range of values over millennia. Human activities like burning fossil fuels for energy moves a large quantity of carbon from the slow to fast carbon cycle quickly so as to significantly alter carbon balance between reservoirs. Additionally, deforestation and anthropogenic land use changes reduce carbon sequestration ability of the biosphere and soil, further aggravating the problem of carbon saturation thereby leading to ocean acidification, global warming, and consequently, erratic weather. [72]

MycroForest models key elements of the fast carbon cycle and ignores the slow one as effects of the latter is largely negligible within the 300 years that the simulation spans.

Following paragraphs explain how carbon is transferred between the 5 modelled reservoirs (air, soil, vegetation, lumber, fossil fuels) in the microworld.

Tree Growth & Decay

In the microworld within MycroForest, vegetation refers to the trees. Trees both absorb and emit carbon. This carbon transfer mechanism is slightly different w.r.t each of the growth, biomass maintenance, and decay phases of a tree's existence. Corresponding modelling variations are as follows.

- **Growth**: As previously discussed, plants absorb carbon from the air in the form of CO2 for photosynthesis. This means that carbon in plant biomass originates from the air. In the microworld, carbon absorbed by a tree each time it grows is computed as the amount of carbon in new growth. Let a tree have grown in volume by $\Delta Volume_{tree}\ m^3$. Let density of the biomass of the tree be $Density_{tree}\ g/m^3$. Then, the tree's weight should have increased by $\Delta Mass_{tree} = Diameter_{tree} \times \Delta Volume_{tree}$. Of the total weight of the tree, around 50% is dry weight. [84] Thus, $\Delta Mass_{tree}^{dry} = 0.5 \times \Delta Mass_{tree}$. The amount of carbon in the new volume of the tree is about 47.5% of its dry weight. [84] So, $Carbon_{tree}^{absorb} = 0.457 \times \Delta Mass_{tree}^{dry}$. This absorbed carbon will get added to the total amount of carbon in the vegetation reservoir and subtracted from the air reservoir such that $Carbon_{veg} = Carbon_{veg} + Carbon_{tree}^{absorb}$ and $Carbon_{air} = Carbon_{air} - Carbon_{tree}^{absorb}$.
- **Maintenance:** In addition to increase in height and/or diameter, a tree will also need to replace biomass lost due to damage or natural shedding. [44] The amount of carbon in this biomass that is replaced is referred to here, as maintenance carbon. This carbon is modelled as being subtracted from the air and added to the soil without levels in the vegetation reservoir increasing or decreasing since the net amount of biomass lost to the soil is more or less same as the amount that is absorbed from the air to replenish it. Let the volume of biomass that is replaced for maintenance be equal to 1% of a tree's total volume $\Delta Volume_{tree}^{maintain} = 0.01 \times Volume_{tree}$. This proportion of 1% is a number that works well with other existing microworld settings and was arbitrarily chosen as it was not possible to find real-world numbers for this figure. Just as before, $\Delta Mass_{tree}^{maintain} = Density_{tree} \times \Delta Volume_{tree}$, $\Delta Mass_{tree}^{maintainDry} = 0.5 \times \Delta Mass_{tree}^{maintain}$, $Carbon_{tree}^{maintain} = 0.475 \times \Delta Mass_{tree}^{maintainDry}$. This amount of maintenance carbon is subtracted from the air and added to the soil such that $Carbon_{air} = Carbon_{air} \times Carbon_{tree}^{maintain}$ and $Carbon_{soil} = Carbon_{soil} \times Carbon_{tree}^{maintain}$.
- **Decay**: As trees decay, the carbon stored in them re-enters the air and soil reservoirs from the vegetation reservoir. If a tree has died and remains on land, 15% of the carbon stored in it is released into the atmosphere and soil per year. [85] Thus, amount of volume decayed each time step is set to equal 15% of the volume of the tree at the time of death. Let amount of carbon that is lost during decay each year be fixed at $Carbon_{tree}^{decay} = 0.15 \times Carbon_{tree}^{t}$ where t = time right before the tree died.

Thus, weight of the dead tree lost to decay would be $Mass_{tree}^{decay} = 2Carbon_{tree}^{decay}$ and consequently, volume would be $Volume_{tree} = \frac{Mass_{tree}^{d}}{Density_{tree}}$ where $Density_{tree}$ is the density of wood. That is, after each year, volume of a dead tree that remains in soil, changes as $Volume_{tree} = Volume_{tree} - Volume_{tree}^{decay}$. Amount of volume decayed each time step is set to equal 15% of the volume of the tree at the time of death. Of the amount of carbon decayed each year, around 35% may end up in the soil with 65% getting released back into the atmosphere. [86] So, $Carbon_{soil} = Carbon_{soil} \times 0.35 \times Carbon_{tree}^{decay}$ and $Carbon_{air} = Carbon_{air} \times 0.65 \times Carbon_{tree}^{decay}$.

Soil Release

Presence of organic matter in soil makes it an important carbon reservoir. It naturally releases a certain portion of stored carbon into the air through processes like respiration of microorganisms. The approximate amount of carbon in the soil is 2300 Gt. Around 60 Gt of carbon is lost per year. [72] Thus, in the microworld, the amount of carbon that the soil releases back into the atmosphere each year is set to $\frac{60}{2300} \times 100 \approx 30\%$ of the carbon in the soil. Therefore, annual soil carbon release $Carbon_{soil}^{release} = 0.03 \times Carbon_{soil}$ such on each 1 year time update, $Carbon_{soil} = Carbon_{soil} - Carbon_{soil}^{release}$ and $Carbon_{air} = Carbon_{air} + Carbon_{soil}^{release}$.

Timber Usage

Harvested wood or timber has many uses. It may be burned for heating and power generation or can be used in construction as well as to make products like paper. In this microworld, uses for harvested timber have been categorized into either "energy" or "lumber" where the former refers to all use involving burning of wood and the latter represents all use cases where the wood is preserved. On average, around 50% of harvested wood worldwide is used to produce energy. [87] The mass of carbon is computed from mass of harvested timber multiplied by factors for dry weight % and carbon % as previously shown. Thus $Carbon_{timber}^{energy} = 0.5 \times Carbon_{timber}$ and $Carbon_{timber}^{lumber} = 0.5 \times Carbon_{timber}$

It is assumed that 100% of the carbon in wood used to generate energy is released into the air and that 100% of the carbon in wood used as lumber is preserved. This means that every time harvested wood gets used up, carbon gets added to both the lumber and air reservoirs as $Carbon_{lumber} = Carbon_{lumber} + Carbon_{timber}^{lumber}$ and $Carbon_{air} = Carbon_{air} + Carbon_{timber}^{energy}$.

Timber is obtained when a tree is felled. When a tree is chopped, around 25% (roots = 21.3% [88] + the stump + some foliage) of that tree is assumed to remain on land while the rest of it (75%) is harvested. Thus, $Carbon_{timber} = 0.475 \times 0.5 \times Mass_{timber}$ where $Mass_{timber} = 0.75 \times Mass_{harvestedTree}$.

In the real world, it's likely that not all burned wood ends up in the atmosphere since some of it may be turned to ash etc. However, most of it does indeed re-enter the atmosphere and hence this is a safe assumption to make w.r.t this microworld.

Also, for simplicity, in this microworld, it is assumed that wood which is used for lumber is preserved responsibly such that its potential lifespan in the use phase is maximized. Thus, carbon stored in lumber is not released back into the air in the simulation timeframe. In reality however, carbon storage in preserved wood or lumber is not as straightforward. Amount of carbon sequestered in wood products depends on several factors at the wood production, use, and end of life stages. In the production phase, amount of carbon in harvested wood varies depending on the tree type as different species have different wood densities. Hardwood from deciduous tropical species is denser and hence is preferred to make durable goods. But this demand often leads to irresponsible sourcing of wood which ultimately leads to more carbon being released than what is preserved in wood and accounted for by new growth. If wood is sourced responsibly and preserved such that new growth is encouraged in its place, then this can result in an increased carbon sink effect even after taking into consideration, emissions involved in transport of harvested wood and its processing. In the use phase, wood products keep sequestered carbon from re-entering the fast carbon cycle until its end of life when it begins to degrade. At this stage, the best course of action is to recycle it into secondary wood products like a particle board as that would extend its life and keep carbon locked away for longer. This can be beneficial even when considering the energy needed for recycling. Another, less desirable option is to burn it to produce greener energy compared to that produced via burning of fossil fuels. These are, however, ideal scenarios. It is an unfortunate truth that a lot of harvested wood end up in landfills in or ever before their end of life stage where they rot quickly and in addition to CO2 may also release more potent greenhouse gasses like methane (CH4). Also, while improving the durability of wood is a good approach to maintaining its role as a carbon safe, several methods of wood modification to make it harder or better suitable to substitute materials like plastic or concrete involves intense processing and use of toxic preservatives like CCA or ACQ which ultimately does more harm than good in terms of energy needed for modification and toxic waste. [77] Nevertheless, w.r.t to this microworld, the assumption that carbon in lumber is not returned to the air is a sound one because if responsibly produced and used, wood can indeed lock away carbon out of the fast carbon cycle for centuries. [78]

Fossil Fuel Usage

As previously discussed, under normal conditions carbon from fossil fuels is released into the atmosphere very slowly over millennia via the slow carbon cycle. But since the industrial age, humans have extracted, processed, and burned resulting petroleum based oil, coal, and gas for energy thereby quickly releasing a large about of carbon from fossil fuels into the environment. In 2023 alone, 36.8 Gigatonnes of CO2 (GtCO2) ≈ 10 Gigatonnes of Carbon (GtC) was added into the atmosphere by humans. [72, 89]

By default, in the environment, amount of carbon added into the atmosphere from the fossil fuels carbon reserve, computed as $Carbon_{fossilFuels} = Carbon_{fossilFuels} - Carbon_{fossilFuels}^{release}$ and $Carbon_{air} = Carbon_{air} + Carbon_{fossilFuels}^{release}$, is set to be 0 GtC. The learner is provided the option to set this $Carbon_{fossilFuel}^{release}$ parameter to any positive value.

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Land

The land in MycroForest wherein trees grow is represented as a grid with 6 rows and 6 columns amounting to a total of 36 spots. Each spot may host 1 live Tree. Thus, the land can contain up to 36 living trees. The value of 36 spots is an arbitrary choice that is intentionally kept relatively small so that it can be visually tracked while also ensuring its big enough for different forest management plans to produce varying results.

Assuming trees are grown in rows with average distance between them being 25 ft, then 1 acre of forest could comfortably support around 83 trees (as per this tree spacing and distance calculator). Therefore, 36 trees would occupy 0.43 acres = 1740.15 m^2. Thus, the size of land in this microworld is approximated to span 1740 m^2. This is too small to represent the size of a real forest (the average size of a privately owned forest in Ireland is around 8 ha = 80,000 m^2 [90]). But, given only 36 trees in this microworld, scaling real world figures associated with forests such that they are relevant to a 1740 m^2 piece of land should help map real world figures to those in the microworld more accurately.

Land content determines the amount of Biodiversity it harbours which in turn, influences tree growth rate, ability of trees to recover from stress, and money earned from some income streams.

Spot Availability

In the microworld, a tree can only grow if a suitable spot is available on land. A spot on land is considered free and available for new growth only if one of the following conditions is true.

- There are no trees in the spot.
- There is only one dead tree in the spot such that it has decayed to the point where $Height_{tree}^{max} = 0.5 \times Height_{tree}^{max}$. The value of 0.5 is arbitrary, but this rule serves to emulate how in nature, new growth may arise from the remains of a dead tree even as it is still decaying.

Thus, each spot on land can have at most one live tree.

In code, each position in the 2D 6×6 grid representing the land is mapped to a list. This list may only ever contain at most 2 Tree objects. The object at position 0 in this land spot list is the latest addition to the land spot and is always the only object that gets displayed on the UI.

Initialization

When the simulated world is first created, seedlings are planted as per a predefined species composition of 60% coniferous trees and 40% deciduous trees. The microworld is set to have 92% free space and 8% spots having seedlings such that 60% of those seedlings are coniferous and 40% are deciduous. This leads to there being 2 coniferous seedlings and 1 deciduous seedling and 33 empty spots. [91] This choice is based on composition of forests in Ireland. As the forest grows wild and changes over time, this composition may change. This is because not all other parameters in the microworld are based on values from Ireland. Furthermore, there likely being other variables influencing forest composition that has not been modelled might explain this change in composition over time. Nevertheless, this is a good assumption for starting composition.

Once initialized, the forest is left to grow for 200 years. The resulting old growth forest is the starting forest that the players work with. The starting position of seedlings is random. Thus, one can get a different forest on each browser refresh. Learners may save specific forests and reload them later.

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Tree

Trees in MycroForest may be one of 2 types, deciduous, and coniferous. This is an abstraction of the multitude of species on Earth. The term deciduous here refers to trees like oak, maple, mango, sandalwood tree, etc. which shed leaves in winter or bears fleshy fruits and/or flowers while the term coniferous refers to evergreen trees like cedar, fir, spruce, larch, etc. that largely reproduce via cones, remains full and green throughout seasons and has modified needle like leaves. The categorization of “coniferous” and “deciduous” was chosen over others like “hardwood” and “softwood” because unlike the latter which can be misleading given that there exist “hardwood” species with soft wood and vice versa, the former presents cleanest separation. [92] Properties of either category as shall be discussed below, assumes values that are averages of multiple trees under that category and are not therefore based on any single tree or species.

Table 15. Difference between coniferous and deciduous trees. below lists differences between properties of the two species as implemented in MycroForest. Property values are based on certain real world observations. On average, coniferous trees are taller [93, 94], more long lived [95], have softer wood [92, 96], mature slower [97] and reproduce less often [98] compared to deciduous trees.

Coniferous	Deciduous

Maximum height = 70 m. [93]	Maximum height = 40 m. [94]
Reproduction interval = 2.5 years. [99]	Reproduction interval = 1 year.
Wood density = 6e+5 g/m^3 [96]	Wood density = 7e+5 g/m^3 [96]
Evergreen. Does not shed leaves seasonally. Thus, % of carbon lost and replenished per year in addition to growth (maintenance carbon %) = 1%. [92]	Sheds all leaves in autumn and regrows them in spring. Thus, maintenance carbon is assumed to be = 40%. [92]
No. of years spent in each stage of life in increasing order = grows from seedling to sapling after 4 years, matures at age 26, becomes old growth at age 60 and enters the senescent stage at age 90 before dying at age 100.	No. of years spent in each stage of life in increasing order = grows from seedling to sapling after 3 years, matures at age 21, becomes old growth at age 47 and enters the senescent stage at age 70 before dying at age 80.

Table 15. Difference between coniferous and deciduous trees.

As seedlings, both trees are assumed to have the same height of 0.2 m as it was hard to distinguish between species [100]. Also, given knowledge from aforementioned sources, tree age groupings created, as shown in Figure 39, is based on informed assumptions.

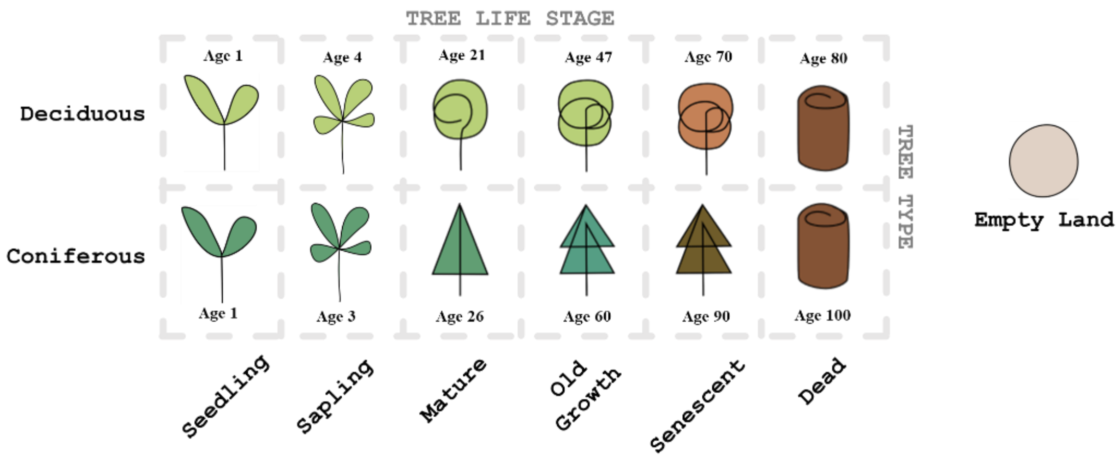

Figure 39. Possible land content with ages.

Trees in the microworld are modelled to live and die as they do in the real world. When they are alive, they grow and can reproduce. After death they decay until no more mass remains. Also, live trees are under stress due to environmental factors and aging. Increased amounts of stress negatively effects growth [101], but certain conditions like high biodiversity in the forest can help reduce the impact of stress. Trees may recover from environmental stress when conditions are favourable again. [102] Following passages explain how each such key mechanisms is modelled within MycroForest.

Stress

Modelling tree mortality as a consequence of stress is a common approach. MycroForest growth model incorporates the following real world observations regarding effects of stress on tree vigour as have other models in the past [101, 103].

- Growth of trees decline when under environmental stress.
- Trees under high stress or significant amounts of stress for long periods enter breakdown mode followed by quick death.
- Demand for photosynthates (products of photosynthesis) or other resources (water, nitrogen, phosphorus, etc.) exceeding supply is one key inducer of stress in plants.
- Stress that plants are under increases when there is more of a particular resource than ideal such as when heat is too high, there is too much CO2 or water etc.
- When conditions become favourable again, trees can recover from stress. From the Tree Decline Recovery Seesaw model presented in [102] captures the relationship between tree vigour and stress well.

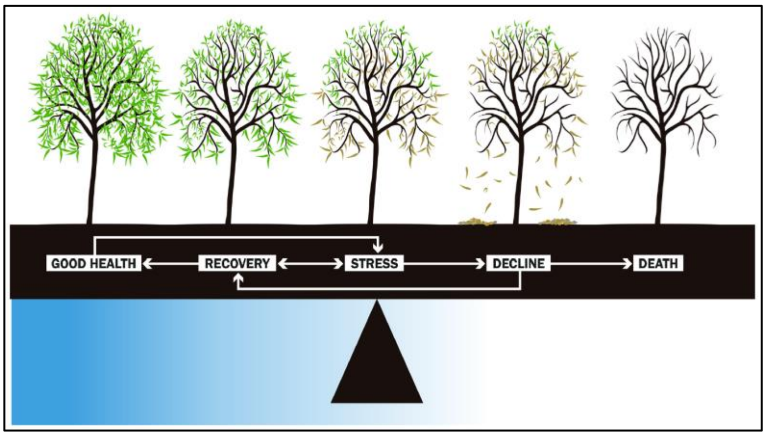

Figure 40. The Tree Decline Recovery Seesaw model illustrating how health of a drought stressed tree shifts between varying stages. Physical changes like leaf re-growth and loss indicates recovery and decline respectively. [102]

In MycroForest, trees have a "stress" property, and they die only when $Stress_{tree} \geq 1$.

Living trees are under stress due to environmental conditions (atmospheric $CO2$ concentration) and time (age).

$$Stress_{tree} = \min(1, Stress_{tree} + Stress_{tree}^{env})$$

$$Stess_{tree} = \min\,(1, Stress_{tree} + Stress_{tree}^{age})$$

In this microworld, availability of CO2 is the only environmental stressor modelled due to it being most associated with climate change. In reality however, there are a multitude of environmental stressors both biotic like pests or disease and abiotic like temperature, competition among trees, natural disasters, etc. [104] Modelling these would be out of scope and will likely add unnecessary complexity. Instead, all other environmental factors are assumed to be ideal. Stress due to atmospheric CO2 concentration is computed based on the tree's tolerance to CO2 levels in the air. Seedlings and saplings (premature trees) are more vulnerable to atmospheric stress than mature trees.

$$Stress_{tree}^{env} = Factor_{stress}^{co2}$$

$$Factor_{stress}^{co2} = ToleranceMap_{CO2}(LifeStage_{tree}, CO2_{air})$$

Table 16 shows assumed mapping between CO2 availability in the air and stress induced in the tree. This tolerance mapping was developed based on the previously presented CO2 Scale that links atmospheric CO2 concentration to photosynthetic efficiency.

CO2		
Availability (ppm)	***Stress per Year***	
	Premature	*Mature*
< 200	1	1
< 430	0.01	0.001
< 700	0.0001	0.00001
< 1200	0	0
< 1800	0.0005	0.00005
>= 1800	0.1	0.01

Table 16. Tolerance of trees to CO2 availability.

Age related stress is maximum when a tree reaches maximum lifetime age. It increases by a small, fixed aging stress factor $Factor_{stress}^{age} = 0.01$ every year after a tree enters the senescent stage. This captures decline in health associated with old age.

$$IF \quad Age_{tree} = Age_{tree}^{max} \quad THEN \quad Stress_{tree}^{age} = 1 \quad ELSE$$

$$IF \quad LifeStage_{tree} = "senescent" \quad THEN \quad Stress_{tree}^{age} = Stress_{tree}^{age} + Factor_{stress}^{age}$$

When conditions are favourable, trees recover from past stress. Healthier plants (those under less stress) recover faster. Rate of recovery is determined by a fixed stress recovery factor $Factor_{stress}^{recover} = 0.2$ that was arbitrarily chosen based on the informed assumption that recovery from stress is generally gradual. [102]

$$Stress_{tree} = max(0, Stress_{tree} - (Factor_{stress}^{recover} \times Health_{tree}))$$

$$Health_{tree} = (1 - Stress_{tree})$$

Living

If after considering latest environmental and age related stress, a tree is still alive, the following actions may take place.

- **Recovery:** The tree may recover from stress as mentioned previously.
- **Growth**: Physical growth of a tree involves both gaining added volume and gaining maintenance volume. Maintenance volume refers to biomass gained to replenish existing volume that is assumed to have been either naturally shed (self-pruning) or lost due to damage. Maintenance volume is computed as an arbitrary fixed percent of the existing volume of the tree; $Volume_{tree}^{maintain} = Volume_{tree} \times Factor_{volMaintain}$. This $Factor_{volMaintain}$ is assumed to vary between species as $Factor_{volMaintain}^{deciduous} = 0.4$ and $Factor_{volMaintain}^{coniferous} = 0.01$ based on knowledge that deciduous trees seasonally shed leaves while coniferous trees love very little

biomass this way. Generally, in the real world, due to several reasons beyond the scope of this project, height of trees is limited. However, most researchers agree that diameter of most trees continue to grow throughout their lives although this slows down significantly after they mature. Continued growth in diameter is often referred to as being part of "secondary growth". This combination of primary and secondary growth is modelled in MycroForest as follows. For simplicity, volume of a tree is assumed to be similar to that of a cylinder. Note that growth volume, height, or diameter in the notation below refers to the amount of new growth. This is different from new volume, diameter, or height which refers to the aggregate sum of the old value and new growth resulting in the latest value.

$$Volume_{tree}^{growth} = \max\left(0, Volume_{tree}^{new} - Volume_{tree}\right)$$

$$Volume_{tree}^{new} = \pi \times \left(\frac{Diameter_{tree}^{new}}{2}\right)^2 \times Height_{tree}^{new}$$

$$Diameter_{tree}^{new} = min\left(Diameter_{tree}^{max}, Diameter_{tree} + Diameter_{tree}^{growth}\right)$$

$$Height_{tree}^{new} = \min\left(Height_{tree}^{max}, Height_{tree} + Height_{tree}^{growth}\right)$$

$$Diameter_{tree}^{growth} = GrowthRate \times Diameter_{tree}^{growthMax}$$

$$Height_{tree}^{growth} = GrowthRate \times Height_{tree}^{growthMax}$$

Once the tree has reached maximum height, secondary growth takes place.

$$Diameter_{tree}^{new} = Diameter_{tree} + Diameter_{tree}^{growthSec}$$

$$Diameter_{tree}^{growthSec} = 2 \times \sqrt{\frac{Volume_{tree}^{growthSec}}{\pi \times Height_{tree}}}$$

$$Volume_{tree}^{growthSec} = Volume_{tree}^{growthMax} \times Factor_{growth}^{sec}$$

Where the secondary growth factor is assumed to be $Factor_{growth}^{sec} = 0.01$ and

$$Volume_{tree}^{growthSec} = \pi \times \left(\frac{Diameter_{tree}^{growthMax}}{2}\right)^2 \times Height_{tree}^{growthMax}$$

Growth declines as stress increases. However, since more biodiverse forests are more resilient, the Biodiversity stress reduction factor $Factor_{stress}^{bRed}$ can help counter negative effects of stress on growth. [105]

$$GrowthRate = 1 - max\left(0, Stress_{tree} - Factor_{stress}^{bRed}\right)$$

Maximum growth height per year is based on the age of the tree at the beginning of its mature stage and how tall it can get. Maximum growth diameter is simply computed based on maximum growth height using the relationship assumed to be $Height_m = Diameter_{cm}^{2/3} \Rightarrow Diameter_{cm} = Height_m^{3/2}$ where $Height_m$ is hight of a tree in meters and $Diameter_{cm}$ is the diameter of a tree in centimetres. [106] Thus, given $Diameter_m = \frac{Height_m^{3/2}}{100}$, maximum amount that the tree can grow by as part of primary growth at each time step can be computed as follows.

$$Height_{tree}^{growthMax} = \frac{Height_{tree}^{max}}{Age\ at\ the\ beginning\ of\ the\ mature\ lifestage}$$

$$Diameter_{tree}^{growthMax} = \frac{\left(Height_{tree}^{growthMax}\right)^{3/2}}{100}$$

All growth volume so gained (maintenance + primary + secondary growth) leads to carbon sequestration as part of the Carbon Cycle as previously discussed.

- **Reproduction**: Trees may reproduce every reproduction interval $RprIvl$ no. of years only if there is a free space adjacent to the tree and the tree is in either the mature or old growth life stage with $Stress_{tree} \leq Factor_{stress}^{reproduce}$ where it is assumed that $Factor_{stress}^{reproduce} = 0.5$. This mechanism keeps the forest populated over time. The two types of trees have varying of years after which they may reproduce.
$$RprIvl^{deciduous} = 1\ year \quad and \quad RprIvl^{coniferous} = 2.5\ years$$
Both types of trees can reproduce only if there is at least one free spot adjacent to itself. Most conifers reproduce via cones or rely on wind dispersion while a large no. of deciduous trees produce fruits that appeal to a wide variety of fauna which carry the fruits that they ingest and dispose them further from the parent tree. Biotic means of dispersal (by means of animal carriers) can result in wider seed spread. [92] Thus, deciduous trees can spawn seedlings in 2 more spots 2 steps away from them parent in addition to immediately adjacent positions as can coniferous trees. depicts this.

x-2 y+2	x-1 y+2	x y+2	x+1 y+2	x+2 y+2
x-2 y+1	x-1 y+1	x y+1	x+1 y+1	x+2 y+1
x-2 y	x-1 y	x y	x+1 y	x+2 y
x-2 y-1	x-1 y-1	x y-1	x+1 y-1	x+2 y-1
x-2 y-2	x-1 y-2	x y-2	x+1 y -2	x+2 y-2

COLOR	POSITION MEANING
Magenta	Parent tree.
Yellow	Possible adjacent position where a seedling may spawn only if the parent is a deciduous tree.
Green	Possible adjacent position where a seedling may spawn if the parent is either a deciduous or coniferous tree.

Figure 41. Positions around a parent tree where new seedlings may spawn.

- **Death & Decay**: Either naturally over time or when they are chopped (chopping induces maximum stress), once $Stress_{tree} = 1$, they die. Once dead, trees decay as mentioned under the Carbon Cycle section.

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Biodiversity

Biodiversity refers to the variety of different life forms that a forest supports. This is generally regarded as a good indicator of a forest's health. Greater the biodiversity, greater the health of the forest and the more resilient it is due to several factors like associated increased genetic variability leading to faster adaptation to change, increased tree diversity meaning lesser chance of complete forest die out due to diseases or pests that target specific species and overall better ability to maintain ecosystem functions like healthy nutrient cycles due to extensive mycorrhizal networks, etc. [107, 108] The 3 main values related to biodiversity that is computed within MycroForest are Biodiversity Score B, Biodiversity Category B_{cat}, and Biodiversity Stress Reduction Factor $Factor_{stress}^{bRed}$.

Mixed forests with trees of varying ages are healthy. They host rich biodiversity. Even dead trees (dead wood) contribute towards increased biodiversity (fungi, insects, etc). [107-111]

Thus, biodiversity score shall consider species $B_{species}$ as well as age B_{age} composition of the forest and following rules are assumed.

- A forest with 50% coniferous trees and 50% deciduous ones (maximum species mixing) receives highest biodiversity score of 1.
- If no trees, then biodiversity score $B_{species} = 0$.
- For each coniferous tree, if there exists a deciduous tree then $B_{species} = B_{species} + 1$.
- For each remaining coniferous or deciduous tree for which there is another tree of the same type $B_{species} = B_{species} + 0.3$.
- For each remaining coniferous or deciduous tree for which there is no other tree of any type $B_{species} = B_{species} + 0.05$.
- The final $B_{species}$ score shall min max scaled to a value between 0 and 1 as $B_{species} = \frac{B_{species}}{36}$ since land is comprised of 36 spots.

Further, it is assumed that a forest most closely resembling a real old growth forest in age composition harbours most biodiversity and receives a score of 1. This score drops to 0 based on how much the virtual forest's age composition differs from that of the real forest. Figure 42, Figure 43, and Figure 44, present tree age composition of an old growth forest in Vienansalo Wilderness, Eastern Fennoscandia. [111]

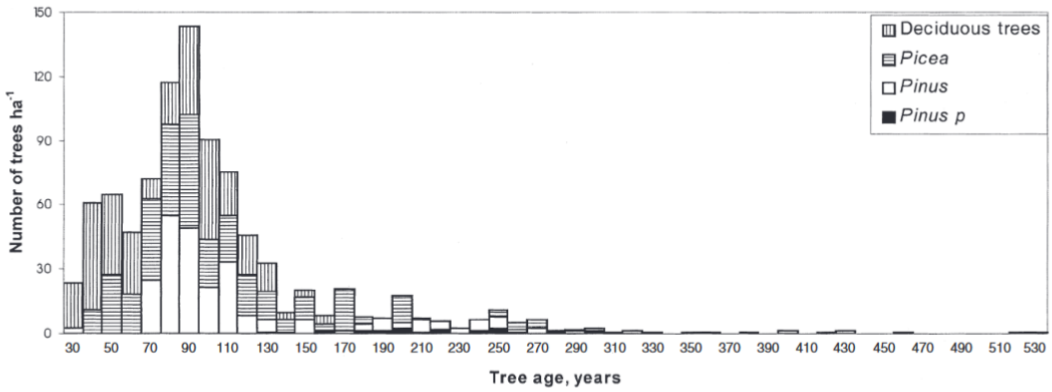

Figure 42. Distribution of no. of mature trees by age per hectare based on data from an old growth forest in Vienansalo Wilderness, Eastern Fennoscandia. [111]

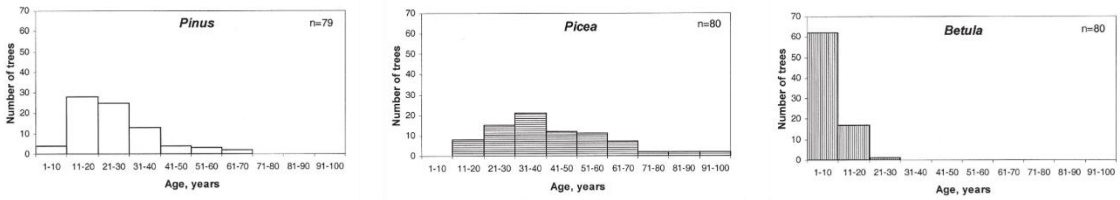

Figure 43. No. of seedlings and saplings per hectare based on data from an old growth forest in Vienansalo Wilderness, Eastern Fennoscandia. [111]

Table 1. Number (ha^{-1}) and species distribution of natural and human-harvested stumps in the studied plots.

Sample plot:	1	2	3	4	5	6	7	8
Natural stumps								
Pinus	15	20	10	45	35	30	10	35
Picea	95	5	0	0	5	5	0	0
Deciduous	30	20	10	10	30	45	0	10
Unknown species	70	20	5	0	0	5	15	
Total	210	65	25	55	70	85	25	45
Human-harvested stumps								
Pinus	25	30	25	5	20	25	0	5
Picea	0	0	0	0	5	0	0	0
Deciduous	0	0	0	0	0	0	0	0
Total	30	30	25	5	25	25	0	5

Figure 44. No. of dead tree stumps per hectare based on data from an old growth forest in Vienansalo Wilderness, Eastern Fennoscandia. [111]

Since age of the oldest and youngest trees in this forest differ from that in the microworld, to mimic age composition of the real forest, there is a need to map age group ranges in the microworld to corresponding ranges in the real forest. This scaling was done to obtain Table 17. Mapping of tree ages in the microworld to those observed in a real forest.. by computing $y = \frac{(x-a)\times(d-c)}{b-a} + c$ where x = number on the original scale, y = corresponding number on the new scale, a and b = minimum and maximum value on the original scale respectively and, c and d = the minimum and maximum value on the new scale respectively.

TREE AGE MAPPING								
Life Stage	***Microworld***				***Real Forest***			
	Deciduous		Coniferous		Deciduous		Coniferous	
	Min	Max	Min	Max	Min	Max	Min	Max
Seedling	0	3	0	4	0	15	0	50
Sapling	3	21	4	26	15	30	50	100
Mature	21	47	26	60	30	100	100	133
Old Growth	47	70	60	90	100	162	133	525
Senescent	70	80	90	100	162	212	525	575

Table 17. Mapping of tree ages in the microworld to those observed in a real forest.

Based on tree age groupings from Table 17 and approximate tree per hectare counts gleaned from Figure 42, Figure 43, and Figure 44, an approximate ideal age composition as in Table 18 was arrived at with seedlings and saplings making up 15% of the forest, mature trees comprising 35% of it, old growth trees and senescent trees contributing to 20% of it and dead trees accounting for the remaining 30% of it.

TREE AGE COMPOSITION						
Life Stage	***Real Forest***					
	Deciduous		Coniferous		Mean %	Approx. Round
	Count	%	Count	%		
Seedling	65	11.50	115	13.05	12	15
Sapling	25	4.42	45	5.11	5	
Mature	220	38.94	241	27.36	33	35
Old Growth	95	16.81	160	18.16	17	20
Senescent	5	0.88	10	1.14	1	
Dead	155	27.43	310	35.19	31	30
Total	565	100.00	881	100.00	100	100

Table 18. Ideal proportion of each tree age category.

Calculating age related biodiversity score involves computing the following for each of the 4 age groupings (seedlingSapling, mature, oldGrowthSenescent, dead) and then computing the average to obtain final value for B_{age}.

- No. of trees, $TreeCount_{ageGroup}$.
- Ideal proportion of trees of this age group, $Prop_{ageGroup}^{ideal}$.
- Current proportion of trees of this age group, $Prop_{ageGroup} = \frac{TreeCount_{ageGroup}}{36} \times 100$.
- Maximum possible error $Error_{ageGroup}^{max} = max\left(\left(100 - Prop_{ageGroup}^{ideal}\right), \left(Prop_{ageGroup}^{ideal} - 0\right)\right)$.
- Minimum possible error $Error_{ageGroup}^{min} = 0$.
- $Error_{ageGroup} = Abs(Prop_{ageGroup} - Prop_{ageGroup}^{ideal})$.
- After min-max scaling, $Error_{ageGroup}^{scaled} = \frac{Error_{ageGroup} - Error_{ageGroup}^{min}}{Error_{ageGroup}^{max} - Error_{ageGroup}^{min}}$.
- $B_{age}^{ageGroup} = 1 - Error_{ageGroup}^{scaled}$.
- $B_{age} = \frac{\sum_{ageGroup} B_{age}^{ageGroup}}{4}$.

Final biodiversity score is then computed as $B = \frac{B_{species} + B_{age}}{2}$.

Based on the knowledge that ecosystems are more biodiverse than new forests or plantations [107] and that biodiversity is proportional to forest resilience as previously discussed, the following land categorization and biodiversity based stress reduction values in Table 19 were formulated.

Biodiversity Score Range	Land Category (B_{cat})	Biodiversity Reduction Factor ($Factor_{stress}^{bRed}$)
$0 \leq B \leq 0.25$	Unforested	0
$0.25 \leq B \leq 0.5$	Plantation	0.01
$0.25 \leq B \leq 0.75$	Forest	0.1
$0.75 \leq B \leq 1$	Ecosystem	0.3

Table 19. Assumed mapping between biodiversity score range and land category as well as biodiversity stress reduction factor.

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Planner

The planner in MycroForest is an object that maintains the learner's working forest management plan. It's a mapping of years in the simulation timeline to Management Actions.

Targets set the learner is also kept track of in the planner along with the latest Rotation Period setting.

Furthermore, the planner contains switches which can be used to set whether other streams of income are to be considered active or not.

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Management Action

A management actions are actions that learns can choose to be done that affects the forest.
Creating a new management action involves selecting the following.

- The type of action.
- The type of tree (species, age) the action is to be applied to.
- The no. of trees that are to be affected.
- The year in which this action is to be executed.
- Whether this action is to be repeated periodically.

There are 2 types of management actions as follows.

1. **Fell**: Felling a tree causes the following events.
   - The price to fell a tree is paid if possible. If there aren't enough funds in the bank, then this activity fails to get executed.
   - It is assumed that around 25% (roots = 21.3% [110] + stump + some foliage) of a felled tree remains on the land and will decay over time. Thus, when felled 75% of the tree is considered to have been harvested. The corresponding volume so obtained gets added to available timber resource stock.
   - Harvested timber is sold with 50% of it getting used to generate energy [87] and the remaining 50% going towards lumber.
2. **Plant**: Planting a tree involves the following.
   - The price to plant a tree is paid if possible. If there aren't enough funds in the bank, then this activity fails to get executed.
   - This action is only executed if there is a free spot on land adjacent to the parent where the seedling may be placed. If a free spot is identified, a new seedling appears on land.

Note: Trees in the microworld, as previously mentioned, can reproduce naturally. They can also be planted by the learner, but even if this is not done, as long as there is a parent tree on land in its mature or old growth life stage, a new seedling may sprout at a free position adjacent to it.

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Target

This microworld allows for 2 types of targets to be set.

1. **CO2 Level:** If the CO2 level exceeds this set target at any point in the simulation, then this means that the current plan fails to meet this target. The year in which this target failed to be met for the first time will be indicated beside the corresponding text field.
2. **Income**: If the current plan failed to generate enough income to exceed or equal this set income value, then that means this target has not been met. The year in which this target failed to be met for the first time will be indicated beside the corresponding text field.

Any time that a target is successfully met, the corresponding text field on the UI gains a green border. This turns red in case of failure to meet the target.

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Rotation Period

In MycroForest, it is possible for trees to be felled or planted every X no. of years. This X is the rotation period. It exists to allow for management actions such as fell and plant to be scheduled at the beginning of each rotation. This type of planning in rotations mimics real world forestry and agriculture practices. In this context, a rotation is generally defined as "the number of years between the formation or regeneration of a crop and its harvest". [112]

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Money

The virtual currency within the microworld is coin. In MycroForest there are 3 possible ways to earn from the forest as follows.

1. Timber
2. Non Timber Forest Products (NTFPs)
3. Forest Recreation

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Timber

Timber in the microworld refers to wood harvested upon felling a tree, of which 50% is used as lumber and the rest is burned for energy. [87]

Availability

Availability of this resource depends on the number and size of trees that were felled each time step.

Income

At the end of each simulation timestep, the amount (in kg) of wood that was harvested in that step is sold and used. In the real world, different types of wood have varying prices. On average, the price of wood can be assumed as being \$1.5 per lb = \$3.3 per kg ≈ €3.03 per kg. [113] Thus, in the microworld, timber fetches 3 coins per kg.

Expenditure

Felling the biggest trees can cost up to 3000 coins [114]. This maximum amount is multiplied by percent of full growth the tree has reached at the time of chopping to obtain felling cost equal to the height of the tree divided by its maximum height and then multiplied by the max felling cost.

$$Cost_{fell} = \frac{Height_{tree}}{Height_{tree}^{max}} \times 3000$$

Planting a tree of either species costs 277 coins [115].

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Non Timber Forest Products

Income from forests may come in the form of non-timber forest products (NTFPs) like mushrooms, berries, or honey.

Availability

A good number for wild ***mushroom*** yield from a European forest can be assumed to be 44.5 kg/ha/year based on yield from a Spanish forest. [116] That is 44.5 kg per 10000 m^2 per year = 0.00445 kg/year/m^2. Thus, for the1740 m^2 micro forest, that's around 7.743 kg/year ≈ 8 kg/year.

On average, around 20 kg of ***honey*** can be harvested from one bee hive per year [117]. n Europe, density of wild honeybee colonies has been estimated to be around $0.26/km^2$. [118] This means there may be around 2.6e-8 colonies per m^2. Thus, a 1740 m^2 micro forest can have 4.524e-5 bee colonies, each outputting 20 kg of honey per year to result in total honey generation of around 9.05e-4 kg/year.

With intensive ***berry*** picking, it is possible for a group of people to harvest around 10 kg of wild berries per year by foraging close to home. [119] Based on this, it is assumed that 5 kg of berries are foraged from the forest in the microworld per annum.

Overall, total availability of NTFPs would thus be around 13 kg/year. This income stream is not as dependable as timber. Thus, the decision was made to model availability using a normal distribution where mean is assumed to be $\mu = 14\ kg/year$ and standard deviation is assumed to be $\sigma = 2.5$.
This income stream is dependent on both biodiversity score and amount of deadwood in the forest (saprophytes like mushrooms thrive on deadwood [120]) as follows.

- Let the maximum availability of NTFPs before considering effects of biodiversity score and abundance of deadwood be $Availability_{ntfp}^{max} \in N(14, 2.5)$.
- W.r.t the impact of biodiversity score, the mean of the normal distribution is assumed to be highest when biodiversity score = 1.0. Thus, given B = biodiversity score, $Availability_{ntfp} = max\left(0, Availability_{ntfp}^{max} - \left(Factor_{avail} \times Availability_{ntfp}^{max} \times (1 - B)\right)\right)$. Here, $Factor_{avail} = 0.5$ is a scaling factor to reduce harshness of impact of slight reductions in biodiversity.
- W.r.t the impact of proportion of deadwood on land, given $DW = \frac{no.\ of\ spots\ on\ land\ with\ deadwood}{total\ no.\ of\ spots\ on\ land}$, $Availability_{ntfp} = Availability_{ntfp} + \left(Factor_{avail} \times Availabilty_{ntfp}^{max} \times DW\right)$. Once again, the scaling factor $Factor_{avail}$ smoothens changes in availability for changes in deadwood proportion.

Income

In Ireland, as of 2024, wild mushrooms can fetch around €80/kg [121], wild berries can fetch around €25/kg [122], and wild honey can fetch around €65/kg [123]. Thus, price fetched per kg for NTFPs may be assumed to be 170 coins/kg.

Expenditure

Harvesting NTFP requires a work force. It takes a person a little over 20 hours to cover one acre = 4046.86 m^2 by foot [124]. That's about 0.005 hrs per m^2. Thus, covering the 1740.15 m^2 of forest land in the microworld would take 1 person around 8.6 hrs. Let the employee take 15 hours to harvest (forage & gather) products (mushrooms, honey, berries) from 1740.15 m^2 of forest. Say, the worker needs to cover the equivalent of the whole forest 3 times a year for harvests, then they would need to work for 45 hrs/year. Let there be 2 workers, at a wage of 18 coins/hr [125], maintenance cost $= 2 \times 45 \times 18 = 1620$ coins/year. If there are not enough funds to pay forest workers, then this income stream's availability is set to 0.

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Forest Recreation

Forests may be opened to the public for recreational use which can include forest trails, picnicking spots, and other activities like camping. This can fetch money.

Availability

As of 2022, there are 808,848 ha = 8088480000 m^2 of forest in Ireland. It is expected that these forests receive around 29105759 visits per annum [126]. Based on this, no. of visits per m^2 of forest per year may be computed as $\frac{29105759}{8088480000} \approx 0.0036$ visits/year/m^2. Thus, on average, a 1740 m^2 forest in this microworld can be expected to receive around 7 visits/year. These no. of visits too, can vary significantly based on several factors like climate, economic situations, etc. Thus, here too, availability is modelled to be drawn from a normal distribution with $\mu = 7$ and $\sigma = 2.5$ as $Availability_{rec}^{max} \in N(7, 2.5)$. One feature that will most likely affect no. of visits is biodiversity score of the forests as people generally prefer visiting healthier forests rich in life. Thus, availability of visitors here, depends on biodiversity score B as $Availability_{rec} = max\left(0, Availability_{rec}^{max} - \left(Availability_{rec}^{max} \times (1 - B)\right)\right)$.

Income

Income from forests open to public recreation may be generated via multiple means as follows.

- Admission/Parking Charge = 5 coins [127, 128]
- Guided tours = 10 coins [127, 128]
- Special activities (Zip Lining, Mushroom Picking, etc.) = 30 coins [127, 129, 130].
- Group Events (Birthday Parties, Yoga, etc.) = 20 coins/individual [131]

Assuming 1 of all visits to be guided tours, another 1 to be a special activity and the rest to be normal visits with 1 group (20 individuals) activity per year, income per year may be computed as $10 + 30 + (Availabilty_{rec} \times 5) + (20 \times 20)$ coins.

Expenditure

Opening a forest for public recreation can involve establishment and maintenance of infrastructure.

Establishment of infrastructure would have associated one-time expenses. In 2006, restoration of around 44 hectares $= 440000\ m^2$ of forest land cost about €8,000,000 [31]. Adjusting for change in currency value, in January 2024, that's around €10,114,114 (using this [CPI Inflation Calculator]). Thus, in this microworld, the initial one-time cost to make forest land suitable for recreational activities can be considered to be around $\frac{10114114}{440000} \approx 23$ coins per m^2. Thus, for a 1740 m^2 forest, this would be around 40020 coins.

Established infrastructure would also need to be maintained. Maintenance would require employees and also resources, both of which cost money.

It was not possible to find definitive numbers that hint at how many employees may be required to maintain forest recreation facilities. This varies greatly. An estimate for no. of workers per m^2 of forest was arrived at for the microworld based on no. of people that Coillte (owns large areas of forest in Ireland), with around 4.4e+9 m^2 of managed forest land [132], employs. In 2016, it employed around 862 people [133]. Considering no. of employees to be 850 people, no. of people employed per m^2 may be computed as $\frac{850}{4.4e+9} = 1.93e-7$ employees$/m^2$. Thus, no. of employees for the 1740 m^2 forest in the microworld $= 1740 \times 1.93e-7 = 0.00034$.

If each employee works for 8 hours a day for 5 days a week for 52 weeks a year, then each employee works around 2080 hours a year. In Ireland, as of 2024, forest workers get paid around €18 per hour [125]. Thus, maintenance cost due to employee wages per m^2 of forest for a 1740 m^2 forest can be computed as $0.00034 \times 2080 \times 18 \approx 13$ coins/year.

Purchase of resources needed to maintain facilities every year would also contribute to maintenance cost. Once again, it is difficult to come across numbers for this. Thus, here it is assumed to be a fraction (1%) of the initial establishment cost $= 0.01 \times 40020 \approx 400\ coins/year$.

Thus, total maintenance cost for a 1740 m^2 forest would be $400 + 13 = 413$ coins/year.

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3.4.2 Input Variables

Input variables here, refer to a collection of 41 global variables that comprise all informed simulation hyperparameter choices based on research. These settings are separated from the rest of the program to facilitate easy experimentation with different simulation settings without needing to update code. Table 20. Categorized input variables. displays these variables organized into 9 categories for better comprehension.

<table>
<tr><td colspan="2" rowspan="2"><u>Tree</u>
BIODIVERSITY_STRESS_REDUCTION_FACTOR
C_PC_TREE
C_WEIGHT_SCALE_FACTOR
DECAY_HEIGHT_THRESHOLD
HEIGHT_MAX
HEIGHT_START_SEEDLING
LIFE_STAGE_TREE
REPRODUCTION_INTERVAL
REPRODUCTION_STRESS_THRESHOLD
TOLERANCE_CO2
TREE_REMAINS_AFTER_FELL
SEC_GROWTH_PC
STRESS_AGING
STRESS_RECOVERY_FACTOR
WOOD_DENSITY
WOOD_DRY_WEIGHT_PC</td><td><u>Carbon Dynamics</u>
C_START
C_PC_DECAY
CO2_FOSSIL_FUEL_ANNUAL_EMISSION_START
TREE_VOLUME_MAINTENANCE_PC
DECAY_PC_SOIL
SOIL_RELEASE_PC</td></tr>
<tr><td><u>Land</u>
BIODIVERSITY_CATEGORIES
LAND_AGE_COMP
LAND_FREE_PC_START
LAND_SIZE
SPECIES_COMPOSITION_START</td></tr>
<tr><td><u>Finances</u>
COST_MGMT_ACTION
FUNDS_START
INCOME_SOURCES</td><td><u>Time</u>
INIT_NUM_YEARS
TIME_MAX
SIMULATION_DELAY</td><td><u>Targets</u>
TARGET_CO2_START
TARGET_INCOME_START</td></tr>
<tr><td colspan="2"><u>Forest Management</u>
ROTATION_START
TIMBER_USAGE
AVAILABILITY_SCALE_FACTOR</td><td><u>Air</u>
AIR_MASS
ENV_SCALE
ENV_SCALE_COLORS</td></tr>
</table>

Table 20. Categorized input variables.

Given below are brief descriptions of the significance of each of these variables.

<u>Tree</u>: This category comprises settings related to tree agents within the simulation.

- BIODIVERSITY_STRESS_REDUCTION_FACTOR = A mapping of land category (Unforested, Plantation, Forest, Ecosystem) to a value in the range 0 to 1. This value is the factor that stress which trees are under gets reduced by as a result of land biodiversity. Greater biodiversity often implies greater resilience and hence more recovery from stress.
- C_PC_TREE = The proportion of carbon in dry mass of a tree.
- C_WEIGHT_SCALE_FACTOR = The factor by which carbon absorbed or released by a tree is scaled so that a very small no. of trees may simulate carbon absorbed and released at rates similar to that of all of Earth's forests.
- DECAY_HEIGHT_THRESHOLD = The proportion of the original height of the live tree which when a decaying tree should be reduced to before a new seedling may grow at that spot on the land.
- HEIGHT_MAX = Maximum height of the tree.
- HEIGHT_START_SEEDLING = Height of a seedling when it first spawns.

- LIFE_STAGE_TREE = Each life stage category mapped to the no. of years after which the tree shall be considered to belong to that age group.
- REPRODUCTION_INTERVAL = No. of years after which trees may reproduce.
- REPRODUCTION_STRESS_THRESHOLD = The value that stress must be below for a tree to be able to reproduce.
- TOLERANCE_CO2 = Atmospheric CO2 levels mapped to stress that the tree will be under when at that level.
- TREE_REMAINS_AFTER_FELL = Proportion of the original tree that remains on land after it has been chopped.
- SEC_GROWTH_PC = Proportion of maximum growth volume that accounts for secondary growth.
- STRESS_AGING = The amount of stress that a tree is under after it enters the senescence life stage.
- STRESS_RECOVERY_FACTOR = The proportion of a tree's remaining health by which value it can recover from stress.
- WOOD_DENSITY = Density of wood in g/m^3.
- WOOD_DRY_WEIGHT_PC = The proportion of a dry weight in a tree's mass.

<u>Carbon Dynamics</u>: This category comprises settings related to amount of carbon that is in or gets transferred between carbon reservoirs in the microworld.

- C_START = Each carbon reservoir (air, soil, vegetation, lumber, fossil fuels) mapped to the amount of carbon in g within it at the initialization of the world.
- C_PC_DECAY = The proportion of carbon in a tree that is lost per decay action.
- CO2_FOSSIL_FUEL_ANNUAL_EMISSION_START = The default amount of CO2 that is released into the air at the beginning of the simulation.
- TREE_MAINTENANCE_PC = The proportion of carbon in a tree that gets moved from the air to the soil as the tree ages to represent the amount of biomass that trees replace for reasons other than growth such as damage or natural shedding.
- DECAY_PC_SOIL = The proportion of carbon in the decayed portion of a tree that gets transferred into the soil. The remainder is transferred into the air.
- SOIL_RELEASE_PC = The proportion of stored carbon that soil naturally releases into the air every year.

<u>Land</u>: This category comprises settings related to the land upon which the forest grows.

- BIODIVERSITY_CATEGORIES = A mapping between names under which the land gets classified based on biodiversity and corresponding biodiversity score value range that shall result in this categorization.
- LAND_AGE_COMP = The ideal proportion of trees belonging to each age group.
- LAND_FREE_PC_START = The proportion of free spots on the land when the microworld is initialized.
- LAND_SIZE = The no. of rows and columns that comprise the land grid.

- SPECIES_COMPOSITION_START = The proportion of each species of tree (deciduous, coniferous) on land at microworld initialization.

Finances: This category comprises settings related to money that is to be paid or may be earned.

- COST_MGMT_ACTION = Maximum no. of coins that would need to be paid to execute each forest management action (fell, plant).
- FUNDS_START = No. of coins in the bank at microworld initialization.
- INCOME_SOURCES = A mapping between the name of each income source and related information such as no. of coins earned per unit of corresponding resource sold, whether this income source is active upon initialization and the color, label as well as icon associated with that income stream.

Time: This category comprises settings related to simulation time.

- INIT_NUM_YEARS = No. of years the simulation runs for prior to the forest being presented to the user. This is to simulate the learner coming into procession of a pre-existing forest as is almost always the case in the real world.
- TIME_MAX = The maximum no. of years for which the simulation can be run.
- SIMULATION_DELAY = The minimum no. of milliseconds of delay before each time step is visualized. That is, this is the animation frame refresh delay in milliseconds.

Targets: This category comprises settings related to targets that learners can set to keep track of their performance.

- TARGET_CO2_START = Default starting maximum atmospheric CO2 level target.
- TARGET_CO2_INCOME = Default starting minimum income per rotation target.

Forest Management: This category comprises settings related forest management.

- ROTATION_START = Default rotation period.
- TIMBER_USAGE = The proportion of harvested wood that gets allocated for specific uses (lumber, energy).
- AVAILABILITY_SCALE_FACTOR = A scaling factor to smoothen changes in availability of NTFPs in accordance with changes in biodiversity score or proportion of deadwood on land.

Air: This category comprises settings related to properties of the air.

- AIR_MASS = Total mass of the atmosphere in grams.
- ENV_SCALE = A mapping of various CO2 levels to the danger level category w.r.t human quality of life.
- ENV_SCALE_COLORS = A mapping of each atmospheric CO2 level category to a specific color by which to represent it.

3.4.3 UI Components

UI components are built using ReactJS and encapsulate visual and interactive elements of the MycroForest. Page specific components are those components that are used only within a single page. These are more specialized when compared to the page agnostic components that may be useful across pages. Many components are output-only, meaning that their existence is solely justified by the need to display information to the user. Others are input-only such that their primary purpose is to provide an interface via which users may provide input that gets incorporated into the simulation model. Few other components both output data and accept user input. These are input-output components. Together, this component architecture as displayed in Figure 45 keeps code modular and enhances maintainability and reusability.

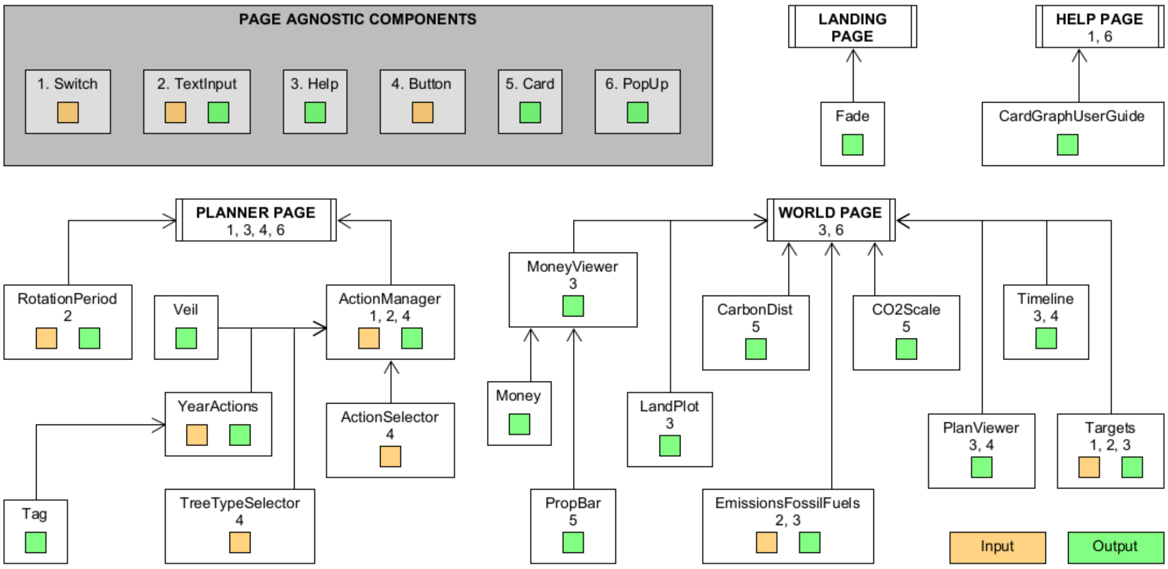


Figure 45. Illustration of how UI components relate to each other. Application pages may be thought of as root components. Page specific components are linked via arrows either directly or indirectly with their parent page. Page agnostic components are displayed within a grey box on the top left corner and are numbered. Is the number corresponding to a page-agnostic component appears within the box representing a page-specific or root component, then this means that the latter incorporates one or more instances of the former. Green boxes in components indicate that this container outputs data. Similarly, an orange box indicates that it accepts input from users.

3.5 Detailed Technical Design

This section describes some key development decisions w.r.t MycroForest.

3.5.1 Tech Stack & Technical Architecture

3.5.2 Avoiding Bad Software Design

<u>Note</u>: Content in this section is based on knowledge gained from lecture material put together by Prof. Siobhán Clarke for the CS7CS3 – Advanced Software Engineering module that the author of this document has undertaken at Trinity College Dublin as part of the MSc. Computer Science programme (2023 – 24).

Generally, bad code has the following 4 defining characteristics as shown in Table 21. It is difficult to change, prone to breaking, difficult to reuse, and contains hacks instead of appropriate fixes. While developing MycroForest, measures were taken to prevent such consequences of bad design. The code adheres to the Model View Controller (MVC) design pattern and the Object Oriented programming paradigm. The web pages are composed of reusable React components and temporary fixes were largely avoided.

PROBLEM		COUNTER MEASURES TAKEN
RIGIDITY	Difficult to change.	Separation of concerns by sticking to the Model View Controller design pattern. Underlying model is separate from React components and is organized into classes in an Object-Oriented Fashion.
FRAGILITY	Prone to breaking.	Modular testing (app and specific components tested immediately after implementation of each new feature). GitHub for version control. Lessen rigidity.
IMMOBILITY	Difficult to reuse.	Choice to use ReactJS allows for creation of reusable components. Example: <Button/>, <Switch/>, <Card/>, <Veil/>, etc.
VISCOSITY	Hacks over the right thing.	Temporary fixes were avoided or immediately replaced as soon as correct solution was identified. Example: Decision to change structure of code early on and start afresh instead of continuing work on initial prototype code.

Table 21. Countermeasures taken against common characteristics of bad software design.

Figure 48 provides a glimpse of Model View Controller separation in code. Following the MVC design pattern [135] is an excellent way to adhere to one of the most foundational of fundamental programming principles, Separation of Concerns (SoC). SoC advocates that any complex Software System be designed to be a conglomeration of smaller, simpler, specialized components with distinct functions [136]. The OO idea of encapsulation also encourages this. The primary purpose of this is to enhance code maintainability and promoting code reusability.

Currently, all code files in the app folder associated with the simulation model may be found within a separate "model" folder whereas all React Components are placed within another "components" folder. Code related to each displayed application web-page is confined to its own separate page.jsx file as per the NextJS convention. The MVC design pattern is visible in every page and component ".jsx" file. Broadly, the model here, captures simulation logic and rules while the view is what the user sees. So, the model comprises content of files in the model folder and, in React, view would be the JavaScript XML (JSX) that is returned. The code above the return statement in each component file in the components folder and web page can be considered as the controller because it receives/processes input from the learner or other UI components and interfaces with the simulation model to trigger simulation updates and UI updates to reflect simulation state changes. Thus, this code acts as an intermediary between the Model (underlying conceptual model) and the View (content presented to the learner). Figure 48 illustrates this separation through a simple example.

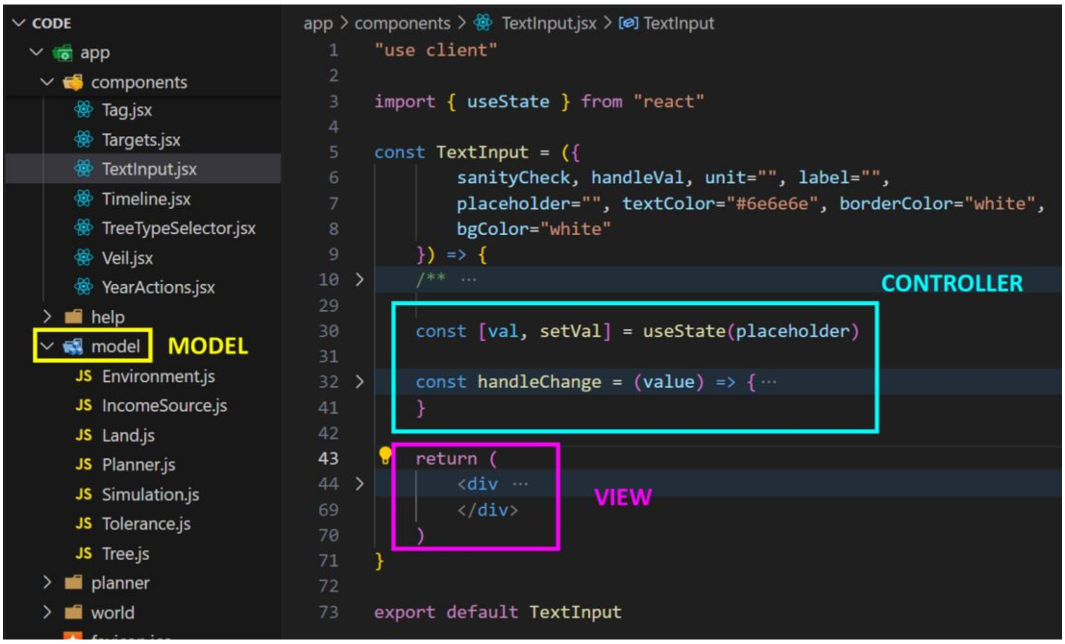


Figure 48. Model View Controller separation in code.

The entire simulation model exists within a global sim variable in the world/page.jsx file. All UI component code as well as the controller logic in the planner/page.jsx file access this same model. It is the single source of truth for the underlying simulation. This design agrees with another Software Engineering principle, Single Source of Truth (SSOT) [136].

The importance of following software engineering best practices was experienced first-hand during the development of this project. Figure 49 is a screen shot that shows the difference in code structure between an early prototype of this application and the current version.

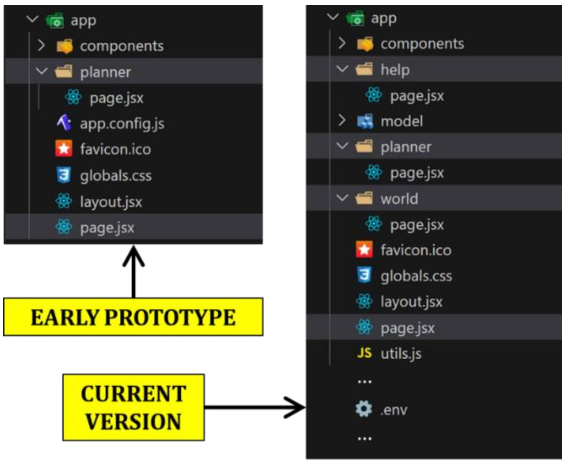


Figure 49. Early prototype v/s now. Difference in code structure.

The underlying simulation model of the prototype is very similar to the current model. UI components, though fewer (since was not complete), still serves the same purposes as their counterparts do in latest code (e.g. old LandPlot similar to new LandPlot, old timeline and new Timeline serve same purpose, old planner has similar plan viewer).

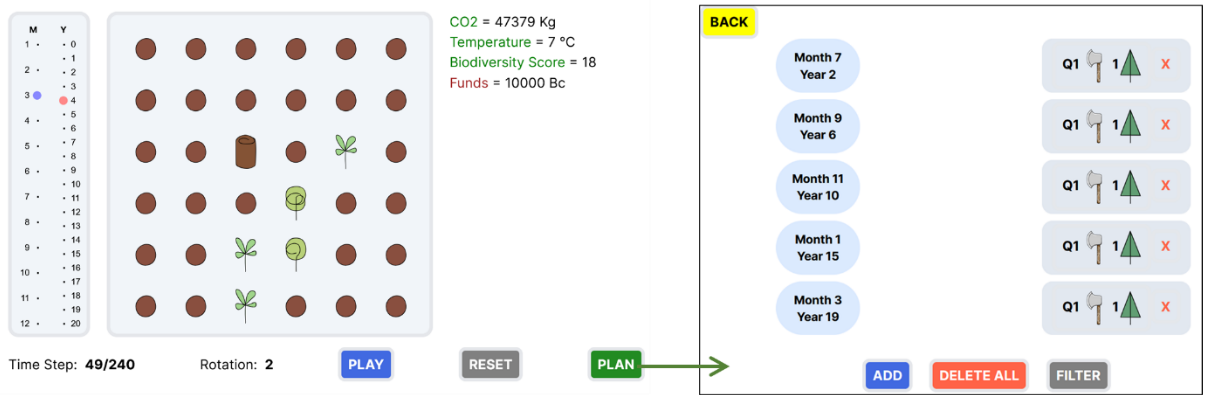


Figure 50. Early prototype.

Code organization, however, is drastically different between the early prototype and current version of the application. For instance, in the first approach, there was little separation between configuration and code. Input variables to the simulation model was defines in the same file app.config.js file as other global functions used in the UI components. Accessing these variables required wrapping all of them in one object and exporting. Thus, to use even one of these variable values, other files had to import the entire object using the line "`import GlobalConfig from '../app.config.js'`". In the latest version, all simulation model hyperparameters (input variables) are maintained separate from the rest of the application in an environment file (.env). Any other program file can access individual variables using code like "JSON.parse(process.env.NEXT_PUBLIC_<VARIABLE_NAME>)". This made it much easier to change configurations (edit hyperparameter values, introduce new input variables, delete existing ones) without affecting the rest of the code. The latest version maintains global miscellaneous functions used by multiple files in another utils.js file that is separate from the .env file with critical simulation model configurations.

Another notable difference between old and new codebases is the monolithic nature of the former compared to the more modular latter approach. In the early prototype, the simulation model classes, and all other functions were placed in a single World.jsx component that was imported into the main landing page. This was in violation of the MVC design pattern and many other software engineering best practices like Single Responsibility Principle (SRP) and Don't Repeat Yourself (DRY). At the time, the focus was on brining designed simulation model on paper to life in code and to see if the idea of using a timeline in conjunction with a custom scatter plot to depict changing land composition was viable. This prototype also helped confirm compatibility and utility of selected technology stack. Programming the application with the sole intention of evaluating soundness of theoretical ideas in practice led to tunnel vision and software development best practices to a back seat. Soon, this monolithic codebase was extremely difficult to work primarily because the code was very hard to change. Hours had to be invested in investigating highly coupled function calls to find the right spot wherein to introduce new code. And doing so, often broke functionality at other parts of the code (e.g. adding the ability to delete a planned action caused the timeline to stop updating.). This difficulty prompted a complete upheaval of the codebase such that a new GitHub project (current one) was created such that this time, good coding practices were incorporated throughout development. Quick temporary hacks were no longer favoured over more long term solutions.

The current codebase is very flexible. Multiple changes were made in response to supervisor feedback leading up to the Bridge 2 College session with minimal code breakage and need to re-write entire code sections. A most notable example of this is when Dr. Caldararu suggested that the initial design of only one tree per land spot be altered to allow at least another decaying tree to co-exist on a single land spot to mirror how plants often regenerate as previously existing trees are still decaying. This lower time between death and regeneration in important to model as it directly affects the amount of CO_2 in the air. The more rapidly regenerated tree sequesters some of the carbon lost due to decay and prevent it from ever entering the atmosphere. This change involves multiple code changes (land content representation changed from 2D array to 3D array, isLandEmpty() function significantly altered to consider a spot with a partially decayed tree as empty for new plant growth, etc.). Given the modular and well-commented codebase, it was possible to identify areas that needed to be changed and administer changes quickly. The new feature was implemented and deployed in just 1 day. With the old code structure, this likely would have taken multiple days.

3.5.3 Object Oriented Programming in JavaScript

[137]

Although originally a procedural (function based) programming language, JS supports Object Oriented Programming (OOP) very well. This is especially so, after the introduction of Ecma Script (ES) 6 syntax. Classes and objects are the fundamental units of OOP. A class is a definition of an object. It is a blueprint using which multiple objects may be created.

Objects in JS look like ObjectName = { prop1: value, prop2: value, …}. Underneath syntactic sugar, ES6 classes work just like constructor functions and implement prototypal inheritance, which was an earlier way to achieve OOP behaviour in JS.

```
class ExampleClass {
    #privateProperty
    constructor(argument1) {
        this.#privateProperty = argument1
        this.publicProperty = 23
        this._protectedProperty = “Hello World”
    }
    #privateMethod = (hushHush) => { console.log("Shh…", hushHush) }
    publicMethod = (argument2) => { console.log(argument2) }
}

class ExampleChildClass extends ExampleClass {
```

```
    constructor() {
        super("Bernie")
    }
    publicMethod = () => {console.log("Hello World")}
}
```

All methods or functions in JS support abstractions as they may be nested or used in conjunction with other function outputs. The constructor is a special method used to initialize objects. The "new" keyword is used to create a new Object. E.g., exampleObject = new ExampleClass("John"). Here, "publicProperty" is a public attribute that all objects in the program belonging to any class can access through exampleObject.publicProperty. Attributes or functions whose name is preceded by a "#" symbol, are private to the defining class and cannot be accessed outside it. This allows encapsulation. Prepending a "_" symbol to an attribute or function indicates its "protected" status, meaning that child classes can access this attribute but objects from other classes should not. This rule is not enforced by the programming language. It is developer etiquette. Inheritance is facilitated by the extends keyword. If the same name is used for a function or method, it is redefined thereby enabling polymorphism.

The simulation model in MycroForest is implemented in abidance of OO principles to ensure code modularity, reusability, maintainability, flexibility, extensibility and good organization.

3.5.4 Simulation Model

Figure 51 graphically captures the Object Oriented design of the simulation conceptual model in code.

Objects of the blue `Tree`, `Land`, and `Environment` classes comprise ABS components, and the green `Planner` class drives DES. In code, the world page.jsx file defines a global `sim` variable which contains an object of the yellow `Simulation` class. This object is the gateway to the simulation model. The `Simulation` class's primary purpose is to act as coordinator and perform time synchronization.

Following paragraphs shall explain key aspects of each of the 10 classes that constitute the simulation model structure.

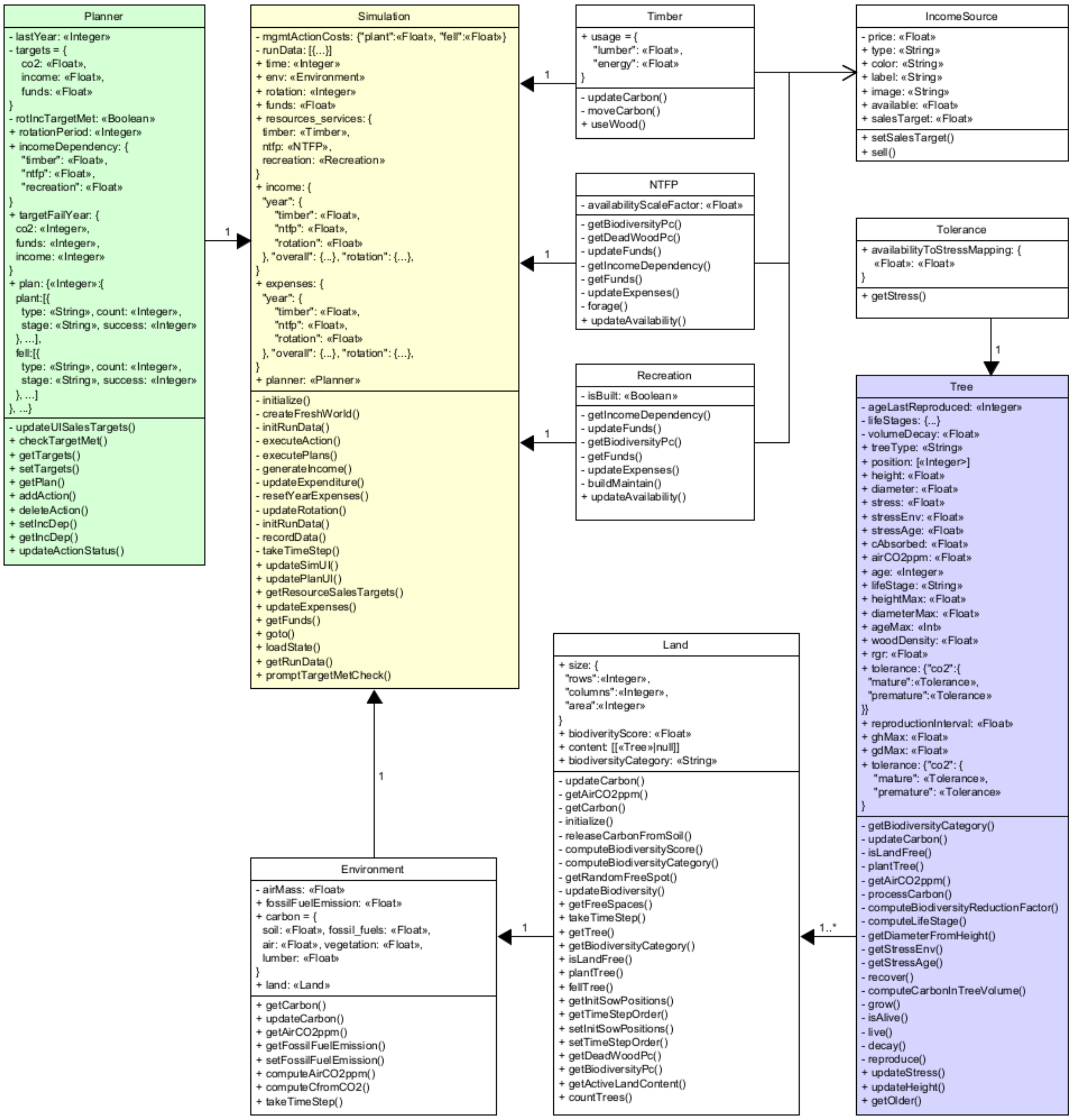


Figure 51. Simulation model class diagram.

Class – Planner

The core functionality of this class is to facilitate creation and updating of forest management plans as well as other learner decisions like CO2 target value, income target value, income stream activation status, and rotation period value. Key attributes include `plan`, `targets`, `rotationPeriod`, and `incomeDependency`.

The active forest management plan is stored within the `plan` attribute as a JS Object (key - value mapping) with keys being years and values being another Object comprised of 2 keys, "plant" and "fell" for each possible management action mapped to yet another object containing action information. Action information includes count = no. of trees affected, stage = life stage of trees affected, type = type of trees affected, and success = -1 if this action has not been processed yet, 0 if it failed, 0.1 if it was partially successful and 1 if it was fully successful. This `plan` acts like the calendar or priority queue in a typical DES wherein, actions planned under earlier years get executed before successive ones. Figure 52 displays the object structure of a `plan` beside its graphical representation.

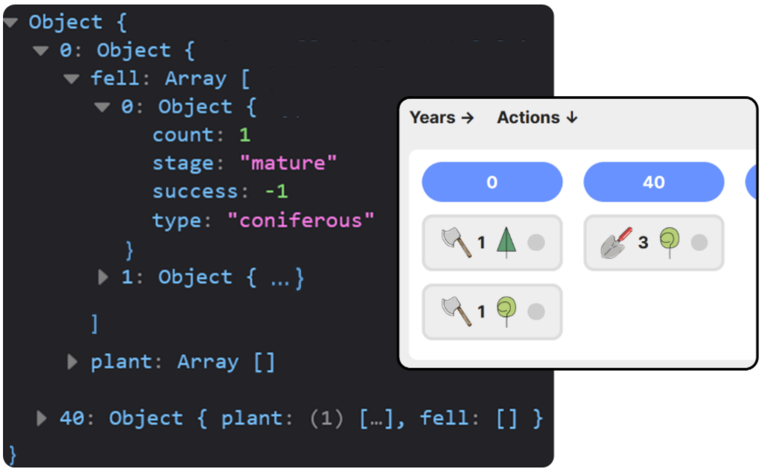


Figure 52. Code representation of management plan.

Alternatively, `plan` could have been maintained in memory as an array of year – action mappings like `[{year:1, action: {actionType: "plant", count: 1, treeType: "coniferous", …}, …]`. This was the first conceived approach. But it was abandoned for the current approach since the former would entail more time complexity (worst case O(n) where n = length of the array = 300 since simulation spans 300 years) given the need to search through the array to find years associated with actions to be deleted corresponding year when actions need to be deleted. Furthermore, in the current approach, only years during which there is at least one action planned, is present as a key within the JS object in the `plan` variable to avoid unnecessary memory consumption. The next "event" or set of management actions under the next planned year, gets executed only when simulation time equals that year. This, therefore, is an implementation of "Next Event" time advance.

Functions `addAction(…)` and `deleteAction(…)` are called when a new action is to be added to the plan or an existing one is to be deleted. The function `checkTargetMet(…)` returns whether or not the given atmospheric CO2 value or rotation income value meets current set targets or not. When learners update target text fields in the UI, the `setTarget(…)` function from this Planner class is called to update the private `targets = {co2: float, income: float}` attribute value.

Other objects and program components that the object of this Planner class interacts with includes the `Simulation` object and UI components like `RotationPeriod`, `Targets`, and `ActionManager`. The `Simulation` object runs a private `executePlans(…)` function every timestep which acts like a listener for planned management action events. All actions scheduled for the current simulation time year, get executed. The `RotationPeriod`, `Targets`, and `ActionManager` React components interact with the `Planner` object either directly or indirectly through the `Simulation` object to update attributes `rotationPeriod`, `targets`, and `incomeDependency` to reflect learner inputs.

Class – Environment

An object of this class comprises environmental conditions of the simulation, including atmosphere, land, and carbon reservoirs `carbon = {air: Big(2.28e+18), soil: Big(0), vegetation: Big(0), fossil_fuels: Big(6.25e+18), lumber: Big(0)}` (starting values loaded from environment file containing all Input Variables). This class provides functions like `getCarbon()` and `updateCarbon(…)` that facilitate carbon flow. Objects of the `Land`, `Tree`, and `Timber` classes leverage these functions to add or remove carbon from reservoirs.

The public `getAirCO2ppm()` function defined in this class is an important one. It computes CO2 concentration in the air based on amount of carbon in the air reservoir `carbon[air]` in grams and mass of the atmosphere `airMass.` Mass of carbon in the air is not the same as mass of CO2 in the air since CO2 has 2 Oxygen atoms in addition to a carbon atom. Thus, the `getAirCO2ppm()`function calls another, private `co2massFromCmass(carbon[air])` function defined in this class to compute mass of CO2 based on mass of C in the air and molar mass of CO2 assuming that all carbon in the air is present as CO2 for simplicity. Following code snippets illustrate this.

```
this.getAirCO2ppm = () => {
      /** Computes the concentration of CO2 in the air given
        * mass of Carbon in the Air.
        * @return: Concentration of CO2 in the atmosphere in
        *          parts per million (ppm).
        */
      const airC = this.carbon.air // Current mass of carbon in the air.
      // 1. Compute mass of CO2 in the air.
      const massCO2air = this.#co2massFromCmass(airC) // gCO2
      // 2. Compute CO2 concentration.
      const ppm = (massCO2air.div(this.#airMass)).mul(1e+6).toNumber()
      return ppm
}

#co2massFromCmass (cMassBig) {
      /**
        * Given mass of carbon, returns that of CO2
        * assuming all carbon is found in the form of CO2.
        * @param cMassBig: Mass of carbon as a Big object.
        * @return co2Mass: Mass of CO2 as a Big object.
        */
      const molarMassCO2 = 44.01
      const molarMassC = 12.01
      return cMassBig.mul(molarMassCO2/molarMassC)
}
```

This class also maintains a `fossilFuelEmission` attribute which keeps track of the amount of carbon in grams currently set to be released into the air from the fossil fuel reservoir per year, emulating anthropogenic fossil fuel usage. Initially, this variable was a public attribute declared within the constructor as `export default class Environment {constructor(…) {let fossilFuelEmission = …}}`. Later, it was changed to be a public "static" variable by declaring it outside the constructor as `export default class Environment {static fossilFuelEmission = … constructor(…) {…}}`. This is because when the simulation is reset to year 0, the environment object is recreated. Value of `fossilFuelEmission` may be changed by the user. It is a decision that the user makes. When a preexisting Environment object is replaced with a new one, all its public variables are re-initialized with default values. This would mean that the user needs to re-enter the `fossilFuelEmission` value every time they go to year 0 in the simulation. It is to avoid this that `fossilFuelEmission` was made a "static" public variable. Unlike public instance variables that get created and destroyed along with each instance or object of a class, static variables will retain their value as long as there is at least one object of that class in the program. The `getFossilFuelEmission()` and `setFossilFuelEmission(…)` functions in this Environment class are used by the `EmissionsFossilFuels` React component through which learners both view and set current fossil fuel emission levels.

This `Environment` class also contains a `takeTimeStep(…)` function that is called from within a `Simulation` object's `takeTimeStep(…)` function as part of the "Time Step" simulation time advance implementation. `Environment`'s `takeTimeStep()` involves first emulating the fossil fuel usage by moving current set annual emitted amount of carbon from the fossil fuels reservoir to the air reservoir followed by triggering the `takeTimeStep()` function of the `Land` object stored in `Environment`'s `land` attribute.

An Environment object in a key component in the ABS modelling carbon flow because it both acts like an agent and independently updates carbon reservoirs (air, fossil fuel) in its time step update function (`takeTimeStep()`) and is also the environment that other classes interact with since it provides functions that other class objects can use to update carbon reservoirs.

Class – Land

An object of this class keeps track of content (tree or empty land) in the virtual forest. Its main responsibilities are as follows.

- **Spatial Representation:** The `size` attribute stores predefined no. of rows (6) and columns (6) that form the grid structure of the land.
- **Land Content Management:** The `content` attribute holds information about the distribution of trees within the land. It is a 2D array where each element represents a grid cell and can either be an empty list `[]` or contain a at most two `Tree` objects such that only one among them is alive. Initially, each land [x, y] position could contain wither null or a single Tree object (dead/alive) only. This was abandoned for the current design because it allows a new tree to grow while a dead one is partially

decayed. This behaviour was implemented in adherence to the suggestion from Dr. Caldararu and thereby better model real world plant behaviour.
The `plantTree(…)` and `fellTree(…)` function may be called to add or remove trees on the land. These functions are used by the Simulation class while executing forest management actions planned by the learner. A tree can only be added if there exists a free spot on the land. The `isLandFree(…)` function checks if a given spot on the land is free. If the given position falls outside the size of the land, then it is invalid and hence not free.

A spot on the land is considered free for planting if it is empty (`content[x, y] = []`). It is also considered to be free if there is only one decayed tree on it with a fraction of original max height remaining. At any point in the simulation, only the last added tree to the list of land contents in any spot is considered to be the active land component and will get displayed on screen. The `getActiveLandContent()` function returns this the land spot's active content. If another tree exists on the land in addition to the active tree, then it is dead and has partially decayed. It continues to decay in the background but is not displayed on screen. Only the live tree is displayed on screen as this is what the learner can interact with (it is not possible to chop, fell, or execute any other action on decaying trees).

When the simulation is initialized, the land is empty. Seedlings are planted as part of the private `initialize()` function and allowed to grow and reproduce for 200 years. It is this 200-year-old forest that the learner sees when they view the world page for the first time. This emulates how in the real world, most forest owners come into possession of forests that has already existed for many years. The alternative would be to present learners with empty land and allow them to decide land composition (proportion of land occupied by seedlings and proportion of each species among those seedlings) and grow a forest from scratch through inoculating the land with seedlings through the plant management action. Upon discussion with Dr. Caldararu, and Dr. Tangney, the decision was made to go with the current approach of the learner coming into procession of an existing forest with predefined starting composition as this is more realistic. This is also the approach adopted by creators of similar tools [3-5]. Due to randomness starting seedling positions, each browser refresh yields a different land composition. Another random element is the order in which the time step update function of each tree on land is triggered as part of. This presented a challenge in that when learners move to the planner page and return back to the world page, composition of land would be different as it needs to be re-initialized given that webpages are by default, stateless. To overcome this issue, two global variables (initSowPositions and timeStepOrder) were introduced to keep track of the positions at which starting seedlings were planted as part of initialization and the first random order in which tree ages were updated. Now, each time the land is re-initialized, and 200 years' worth of growth is computed upon the viewer navigating back to the world page from the landing page, the same starting composition and growth order from the first initialization stored in the global variables is followed to reproduce the same land state.

- **Soil Carbon Release:** In the real world, the soil naturally loses a certain portion of its carbon content to the air every year. The `releaseCarbonFromSoil()` function simulates this. The `Land` class is considered an ABS agent because is interacts with the `Environment` object and moves carbon between reservoirs.
- **Biodiversity Tracking:** Computing biodiversity of the land based on content is a task exclusive to the Land class object. The private `updateBioDiversity()` function calls two private functions `computeBiodiversityScore()` and `computeBiodiversityCategory()` that does this and computes $B = \frac{B_{species}+B_{age}}{2}$ as discussed in section 3.4.1. B calculation requires counting no. of trees on land. This is facilitated by the `Land` class's `countTrees()` function wherein relevant tree counts are retuned in an object of form `{deciduous: count, coniferous: count, seedling: count, sapling: count, mature: count, old_growth: count, senescent: count, dead: count}`.
- **Simulation Advancement:** `Land`'s `takeTimeStep()` function implements time step update within the `Land` class. It loops through every tree on land and triggers its aging to further propagate simulation time advancement through other world entities. Then, it moves a certain portion of carbon from the soil reservoir to the air reservoir to emulate how soil naturally loses some carbon to the atmosphere each year in the real world. Finally, computations updating the biodiversity score and category are performed.

<u>**Class – Tree**</u>

The `Tree` class represents an individual tree as an agent within the forest simulation. It encapsulates `takeTimeStep()`attributes and behaviours that define a tree's lifecycle, growth, and interactions with the environment.

Tree properties can be categorized as being related to identity (`treeType`, `position`), physical characteristics (`height`, `diameter`, `heightMax`, `diameterMax`, `woodDensity`), growth (`ghMax`, `gdMax`, `reproductionInterval`), environmental interactions (`stress`, `airCO2ppm`, `tolerance`, `volumeDecay`) and life cycle (`lifeStages`, `age`, `ageMax`).

Arguably the most important function within the Tree class is `getOlder()` as this is the function that the Land class invokes in its `takeTimeStep()`. This function emulates all independent annual life functions of a tree such as aging, recovering from stress, growing, or reproducing if the tree is alive or the process of decaying, if it is dead.

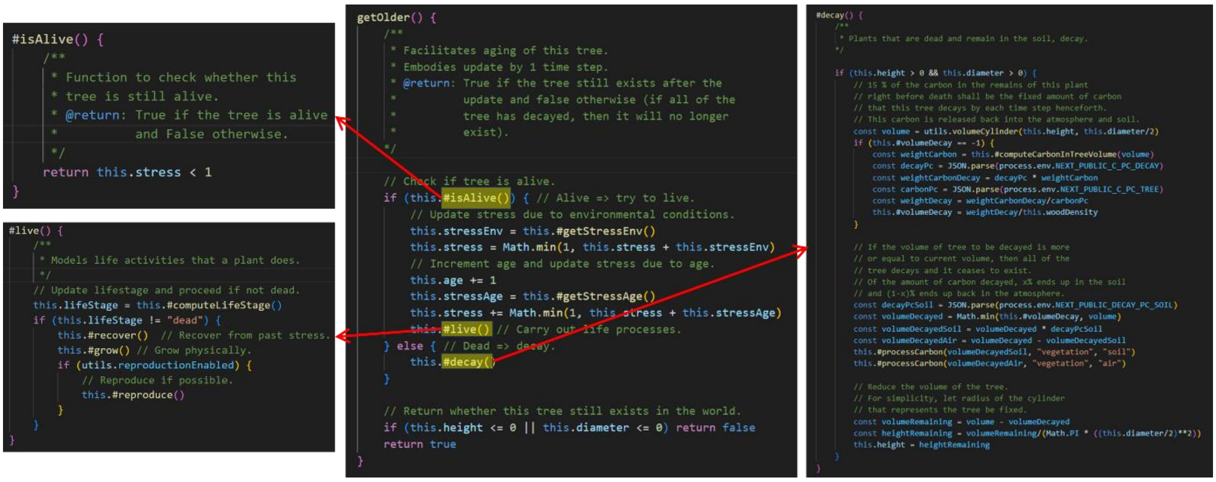


Figure 53. Tree class growOlder() and composite functions.

Trees die when `stress` that they are under due to environmental conditions like too little or too much CO2 or stress due to aging as they near their maximum age limit, exceeds 1. Each time per simulation time step when `getOlder()` executes, if the tree is alive, then its age is incremented by one and latest environmental and age related stress gets compounded to existing stress. Next, the live process is called. Here, trees recover from a portion of past stress at a rate proportional to remaining health via the private `recover()` function. The private `grow()` function is important as this models the tree gaining volume and consequently moving carbon from the air to vegetation reservoir. The `grow()` function leverages the private `processCarbon(…)` function which interacts with the `Environment` class through use of its `updateCarbon()` function to move carbon from one reservoir to another. Trees pull carbon needed to build growth volume from the air and move it into the vegetation reservoir to indicate its assimilation into tree biomass. The `growth()` function also triggers movement of carbon from the air reservoir into the soil reservoir to model carbon added to the soil as part of shed biomass that is replaced by the tree. The `processCarbon(…)` function essentially moves given volume of carbon from one reservoir to another. Amount of carbon transferred is multiplied by a scale factor = 2.5e+8. This is to overcome the challenge of a small no. of trees having to move enough carbon to mimic effect of entire forests on Earth. If a tree is dead, then the `decay()` function run instead of the `live()` function when `getOlder()` is called. This move function transfers a certain portion of carbon from the vegetation reservoir into the air and soil reservoirs to represent the rotting process that adds biomass to the soil in the form of humus and released CO2 into the air as a byproduct of microbe respiration.

Class – Tolerance

The purpose of the tolerance class is to manage the mapping between environmental conditions and corresponding stress induced in trees. Given availability of a resource the `getStress(…)` function returns the amount of stress a tree shall be under at that resource availability level. Currently, the only environmental stressor considered is CO2. Thus, the private attribute `availToStressMap` stores predefined availability to stress mappings w.r.t atmospheric CO2 concentration only. This class was built to be extendable. If there are to be more resources considered in the future, this class may be defined as a generic template and classes related to those other factors (say, sunlight, water, temperature) may extend this class.

<u>**Class – IncomeStream**</u>

Generating income involves selling a product (here, timber or NTFPs) or a service (here, recreational activities in the forest). This class captures general characteristics of an income stream. Most notable attributes are `available` (how much of this resource or service is available) and `#price` (selling price of one unit of this resource/service). This class defines only one function, `sell()` which returns income generated from selling available resources (= available × price).

<u>**Class – Timber**</u>

This class extends the `IncomeStream` class. Selling timber is one way to earn from the forest. What distinguishes this class from its parent is the added `useWood()` function which simulates available timber being used for 2 purposes, both as lumber (e.g. in building construction, furniture making) and to generate electricity. Both these uses of wood results in differing amounts of carbon emissions. The function #moveCarbon() adds/removes carbon from/to the air/lumber carbon reservoir as required to emulate how use of wood as lumber locks carbon from the environment away in preserved wood whereas burning it immediately releases all the carbon in it into the air.

<u>**Class – NTFP**</u>

This class also extends the `IncomeStream` class as selling Non-Timber Forest Products (NTFPs) such as honey, berries, and mushrooms can also fetch income. Harvesting these resources however incurs additional costs in terms of employee wages. Thus, the NTFP class includes a `#forage(…)` function that computes expenses related to employing worker to forage the berries. Another difference between this income stream and Timber in the microworld is that availability of timber was dependent on the learner's decision to fell trees. When a tree is felled, a portion of its mass becomes available as timber. With NTFP, as explained in section 3.5.4, less dependable availability is modelled using a normal distribution whose mean depends on other factors like biodiversity score and amount of deadwood in the environment. Thus, this class defines a `updateAvailability()` function that is called by the Simulation object in its takeTimeStep() function to compute the about of NTFP resource available in the time step.

Class – Recreation

This class also extends the `IncomeStream` class. Here, visit permits to the forest or tickets for events like a birthday celebration or a guided walk etc. are sold to generate income. This too is a less reliable source of income compared to timber. Thus, no. of visitors is modelled using a normal distribution in the `updateAvailability()` function within this `Recreation` class. This stream also has employee wages related expenses as a workforce is necessary to offer and manage recreational services provided. Additionally, this stream also incurs an initial one time cost for building infrastructure to facilitate forest recreation. Both these expenses are computed by the `#buildMaintain()` function.

Class – Simulation

An object of this class is the gateway to the entire simulation conceptual model. It coordinates all other objects in the simulation and implements the time step time advance mechanism by means of 2 functions, the `takeTimeStep()` function and the `goTo()` one.

The `takeTimeStep()` function within this class triggers parameter updates of all simulation objects for 1 year. Following code snippet shows how the `takeTimeStep()` function triggers all simulated processes for the year.

```
#takeTimeStep() {
	/** Step forward in time by one step. */
	this.#resetYearExpenses()
	const rotationUpdated = this.#updateRotation()
	this.#executePlans(this.time)
	this.time += 1
	this.env.takeTimeStep()
	this.resources.ntfp.updateAvailability()
	this.resources.recreation.updateAvailability()
	this.#updateExpenditure(rotationUpdated)
	this.#generateIncome(rotationUpdated)
	this.promptTargetMetCheck()
	this.#recordData()
}
```

This `takeTimeStep()` function is triggered by the `goTo()` function. The `goTo()` function is very important because it is the primary mechanism for navigating through the simulation's timeline that is called every time the user interacts with the timeline UI component. This function accepts the year in the simulation to navigate to, as input. This is the target time. The difference between the target time and the current simulation time, i.e. timesteps, is then computed. If the target year is after the current simulated year, then the `takeTimeStep()` function is computed timesteps no. of times and simulation time is incremented. If the target year is before the current simulated time, then the simulation is reset to its initial state using `createFreshWorld()` before calling `takeTimeStep()` timesteps no. of times. Finally, the `updateSimUI()` function is called to refresh the UI with latest state changes.

When the learner presses play on the timeline UI component, behind the scenes, a continuous loop is established, advancing the simulation by one year every 100 milliseconds. This mechanism, coupled with frequent UI updates, creates the illusion of smooth animation. The goTo(year) function is invoked iteratively for every subsequent year to drive this process.

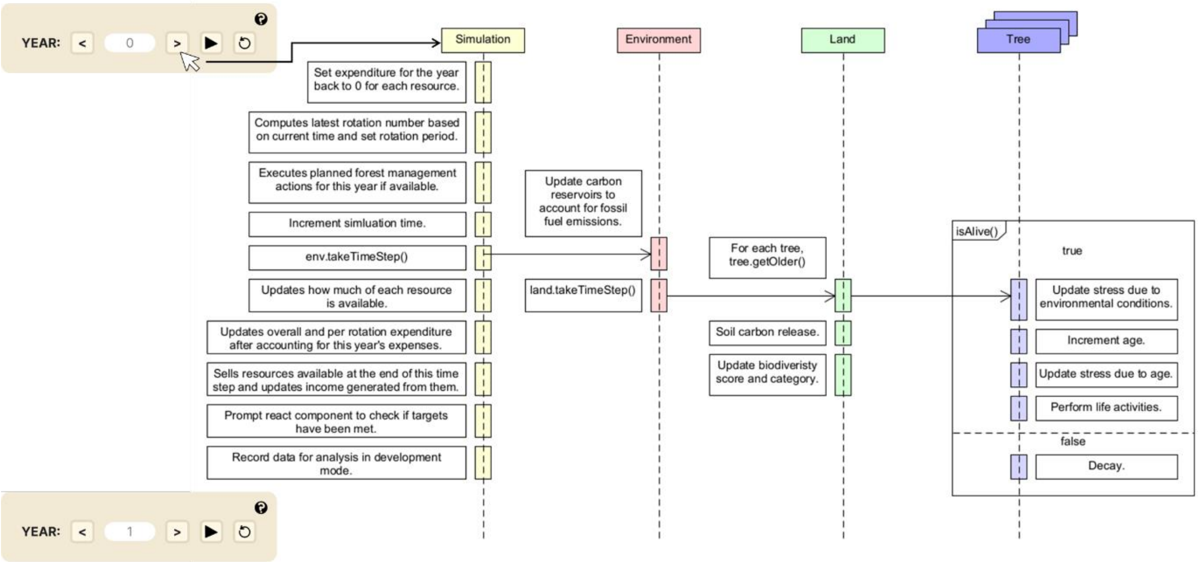


Figure 54. Graphical display of event flow within one user initiated timestep.

Summary

TO DO.

4 Implementation

This section outlines development methodology adopted and briefly discusses key challenges faced.

4.1.1 Development Methodology

The development of MycroForest followed an Agile methodology. It was an iterative process comprising 3 broad stages, planning, building, and deployment with research conducted as and where required. Typically, an iteration would involve a whiteboarding phase, then a more concrete visualization stage, followed by coding.

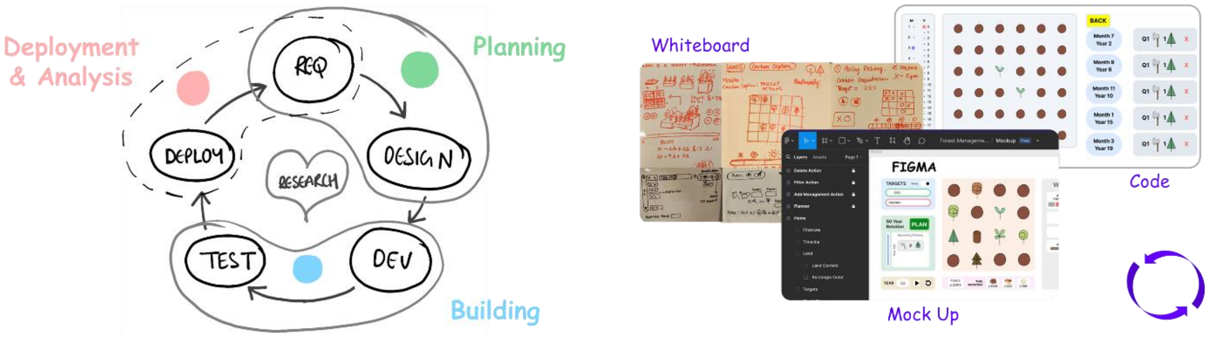


Figure 55. Agile strategy and iterative workflow.

Agile is a popular process management strategy adopted by several teams worldwide with great success resulting in measurable (profits, success rates, etc.) improvements in productivity [138]. The main advantages that it provides includes greater flexibility (frequent changes allowed), lower risk (complex projects broken down into smaller parts), better communication (demands greater inter-team and team-client collaboration) and increased client satisfaction (focus on frequent delivery keeps end-user informed, interested and able to provide frequent feedback). While applicable in a no. of domains like business and logistics, it is a very widely adopted Software (SW) Development (Dev) strategy. [139]

There exist several flavours of Agile for SW Dev such as SCRUM, KanBan, and XP, [139] but the Agile strategy itself if a broad set of ideas originally laid out in Official Agile Manifesto. The overarching aim here is to "deliver working software frequently", "welcome changing requirements", and regularly reflect on how to improve effectiveness, all the while paying "attention to technical excellence".

Established Agile frameworks (SCRUM, KanBan, XP) expect adherence to clearly laid out steps. They are aimed at medium to large teams working in a corporate setting for clients/customers. In light of this academic, single developer project, the decision was made to adopt a more general Agile methodology, especially since other academic commitments were expected to interfere with the ability to diligently stick to steps in an established framework.

The adopted 3-stage strategy (planning, building, analysis, research), although simple, still adheres to Agile ideology because it allows for frequent delivery of project artefacts and/or working software as well as encourages regular project evaluation. Features to be implemented were broken down into small parts and added to a list somewhat like a product backlog (inspired from Scrum) wherein features were checked off after implementation and testing. Figure 56 provides a glimpse of a portion of this product backlog table. This was a great way to prioritise and stay focused. Meetings with the supervisor and/or co-supervisor were organized every 2 to 3 weeks, sometimes every week, almost regularly throughout, except for holidays/exam periods. Efforts adopted to ensure delivery of a new valuable project artifact (e.g. simulation concept model update, UI mock-up, etc.) or developed working feature as part of the tool at every meeting was largely successful. Regular feedback so obtained, pending functional requirements, and bugs discovered during testing of an integrated feature, fed into creation of new tasks in the product backlog table.

Task	Effort (3 > 2 > 1)	Importance (3 > 2 > 1)	Status
Add button response.	3	1	To Do
Update biodiversity score to promote mixed ages.	3	3	In Progress
Help as "info" buttons.	3	3	Done
New growth while decaying.	3	2	Done
Disable key press until intro is complete once first started.	2	1	Done
Help page visited leaf.	2	1	Abandoned

Figure 56. Portion of product backlog like list of tool features maintained during development.

Throughout development, GitHub was used for version control, and it was linked to the web application hosting platform Vercel, as part of the continuous integration and continuous development pipeline. Every time a new feature is pushed to GitHub, a new version of MycroForest incorporating this change is automatically deployed.

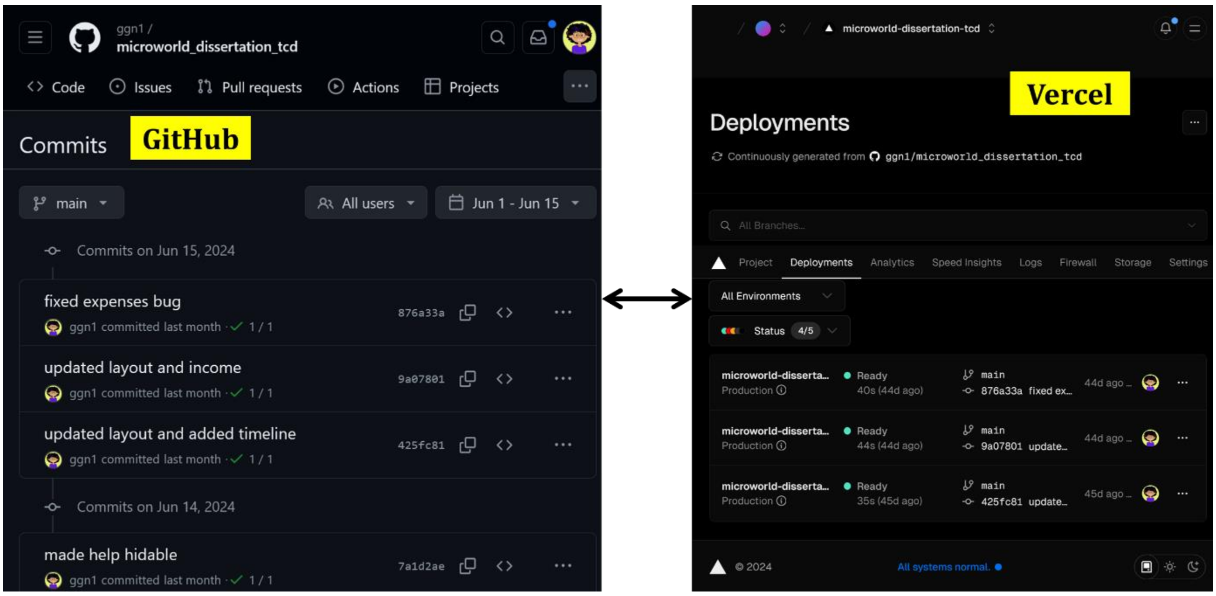


Figure 57. GitHub - Vercel CICD.

4.1.2 Project Timeline

Figure 58 displays the rough project plan created in December 2023 (coloured Gray) beside the actual schedule followed throughout this project (coloured green).

Dissertation - Project Plan v/s Execution Timeline			
Tasks	*Start Date*	*Days*	*End Date*
Exploring possible topics.	09-Sep-23	3	12-Sep-23
Finalize topic with a supervisor.	12-Sep-23	6	18-Sep-23
Research.	17-Oct-23	255	27-Jun-24
Finalizing research and question.	20-Nov-23	20	10-Dec-23
Research - Literature review.	10-Jan-24	40	19-Feb-24
First simulation model with no UI.	19-Jan-24	18	05-Feb-24
Early Prototype	05-Feb-24	11	15-Feb-24
Evaluation, Research, Update	16-Feb-24	90	15-May-24
Finalize mechanisms to model.	22-Feb-24	10	03-Mar-24
Capture model in rules & diagrams.	04-Mar-24	10	14-Mar-24
Make UI mock-up.	16-Mar-24	5	21-Mar-24
Make low-fi prototype.	24-Mar-24	10	03-Apr-24
Test low-fi prototype.	01-May-24	5	06-May-24
Improve.	08-May-24	10	18-May-24
Focused Development.	16-May-24	34	18-Jun-24
Develop MVP (high-fi prototype).	20-May-24	20	09-Jun-24
Test hi-fi prototype.	12-Jun-24	10	22-Jun-24
Bridge To College Learning Session.	19-Jun-24	1	19-Jun-24
Refine based on feedback.	20-Jun-24	8	27-Jun-24
Refine application.	24-Jun-24	30	24-Jul-24
Write final report - draft 1.	28-Jun-24	35	01-Aug-24
Refine Report & Submit.	03-Aug-24	10	12-Aug-24
Field experiment.	25-Jul-24	5	30-Jul-24
Finish/Refine Written Thesis.	01-Aug-24	18	19-Aug-24
Write Dissertation	22-Feb-24	179	19-Aug-24

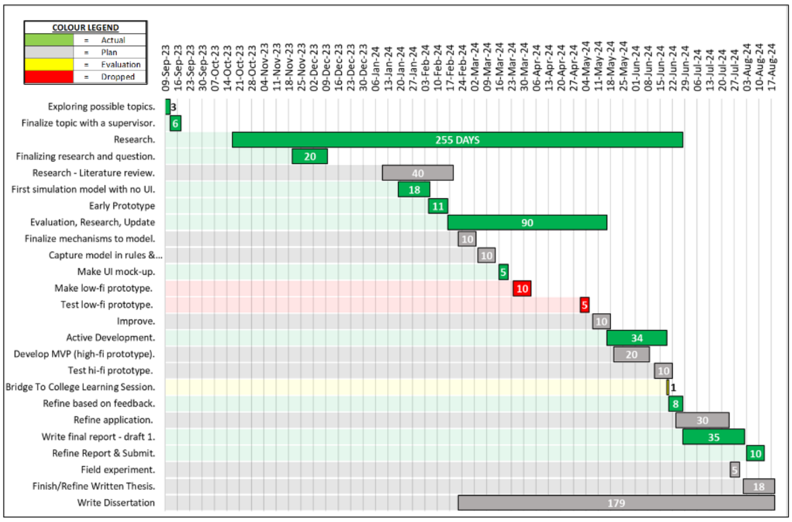


Figure 58. Project Timeline - Plan v/s Actual. Gray colour represents the original plan. Green colour is associated with the actual schedule of planned task execution. Red indicates originally planned tasks that were dropped, and yellow highlights the Bridge to College Learning session when students used and evaluated MycroForest.

Only 2 of all originally planned tasks, the task of making a low fidelity prototype (e.g. a board game equivalent of the tool using pen, paper and carboard) and testing it, were skipped (coloured red) in favour of directly trying to create a limited capability, early prototype of MycroForest in Software. This was because (i) the simulation model was too complex to keep track of manually, and (ii) trying to build parts of the application as Software from the get-go was an excellent early opportunity to test viability of ideas and technology choices. All other planned tasks were executed in some capacity. There are differences in task duration and order between the estimated and real schedule. This is because at the time of drafting the schedule, it was not possible to be certain about the amount of time that would need to be dedicated to other modules comprising the MSc. Computer Science program at TCD. For example, the research or literature review task, contrary to the original plan, spans almost the entirety of this project. This is because, given the interdisciplinary and experimental nature of this project as well as the agile, iterative development workflow adopted, frequent intermittent research was necessary to support decision making throughout the project timeline.

Information regarding actual dates and no. of days spent on tasks, as well as order in which tasks were completed were gathered from the commit history on GitHub. All activities related to this project from the very beginning is available on GitHub over 2 repositories. The first repository contains primarily documentation. It also contains the early prototype. When the decision was made to re-organize the codebase in order to better adhere to good SW design principles thereby making the code more flexible, more maintainable, and less rigid, a new project was created within a new GitHub repository which contains the current version of the app. The starting date for the research task was obtained by examining the date of creation of research material downloaded on the local machine.

Following points briefly state key activities that comprised notable periods of development along with images displaying associated outcomes.

- **(19 Jan 2024 – 05 Feb 2024):** Development began with programming of simulation model v1. In the first version of the conceptual model underlying the simulation, in addition to atmospheric CO2 levels, temperature and water were also considered as environmental stressors. The land plot was to be divided into 4 quadrants to mimic how forest estates are subdivided into sub-plots in the real-world. A single time step modelled 1 day, and the simulation was to monitor time advancement in terms of days, months, and years. Seasons and associated temperature differences were also to be considered. Market demand for Timber was to be the primary target that learners would try and meet.

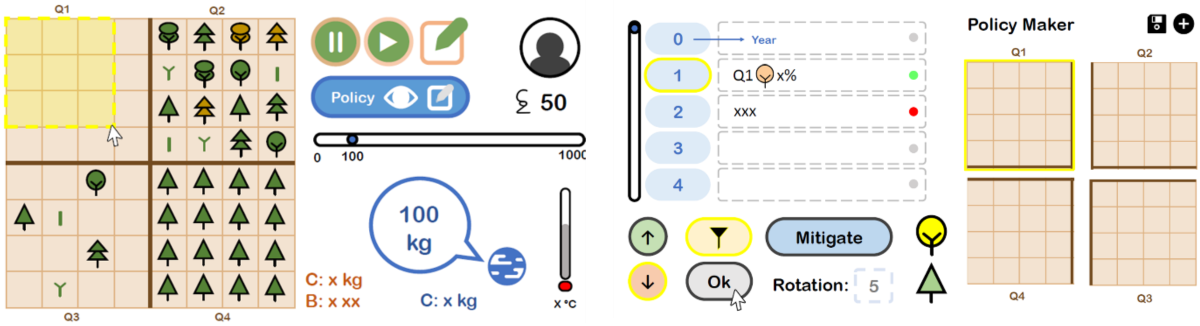


Figure 59. First mock-up of the tool made using MS PowerPoint.

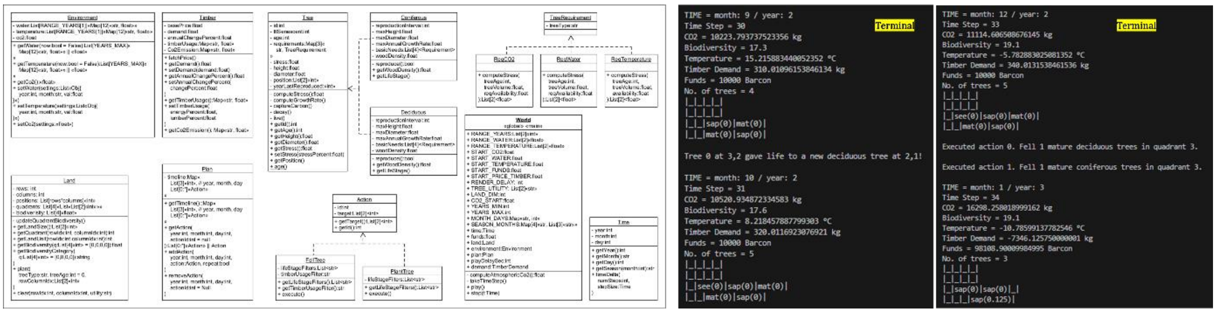


Figure 60. Initial simulation conceptual model and rudimentary printed terminal output of land changing land content and environmental parameter values.

- **(28 Jan 2024 – 03 Feb 2024):** Implementation of the forest growth model part of simulation model v1 is complete. However, all logic is placed within a single World component with no SoC. There are no global variables that store simulation hyperparameters and separate from the rest of the program. At this stage, output is printed on the terminal. There is no UI. Also, the plan is programmed as a list with a nested list for every day in the simulated timeframe.
- **(04 Feb 2024 – 05 Feb 2024):** Forest management actions (plant and fell) have been developed. Time step duration was changed from day to month. The forest management plan is now programmed as an object with `${month}-${year}` keys

mapped to a list of actions only for every month that has at least one planned action. This is more memory efficient.

- **(06 Feb 2024 – 15 Feb 2024):** A UI is developed to complete the early prototype. All simulation processes function as expected. Target setting and user interaction apart from timeline control is yet to be implemented. No alternate income streams. All logic is still in the same single World component although there is a separate file for simulation hyperparameters.

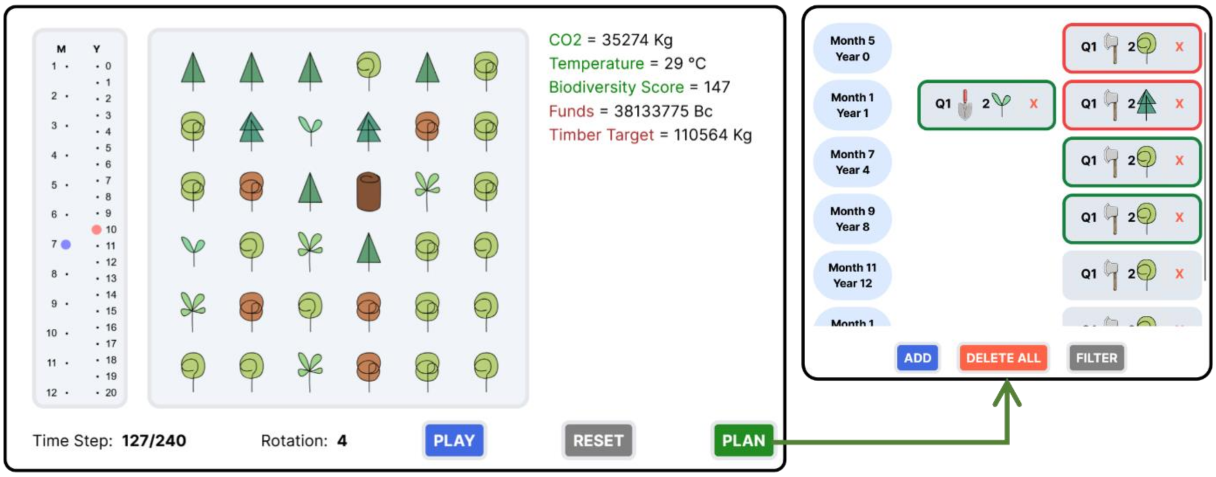


Figure 61. Early web-based partially working prototype.

- **(16 Feb 2024 - 15 May 2024):** The early prototype is carefully analysed for efficiency and scope of improvement. The decision is made to re-implement it, this time, more closely following good SW design principles. The application was simplified to keep only strictly required features. Extensive research was conducted to make better informed simulation model hyperparameter choices and to determine which parts of original conceptual model to discard/retain. Following are key decisions taken during this period.
  - Let time step = 1 year.
  - Introduce other income streams.
  - Drop temperature and water. Focus on CO2 as sole explicitly modelled environmental stressor w.r.t tree growth.
  - Get realistic figures for simulation model hyperparameters.
  - Introduce lumber carbon reservoir.
  - Add plan viewer on home page.
  - Add landing page, help icons, help page.
  - Finalize ideas for challenges.
  - Display income and expenses in its own panel.
  - Display CO2 concentration as an indicator of climate change.
  - Introduce emissions due to fossil fuel usage and a fossil fuels carbon reservoir.
  - UI mock up.

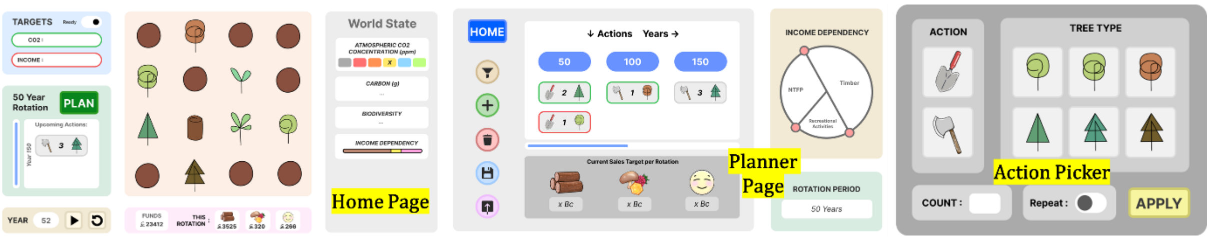


Figure 62. More complete mock-up made using the Figma application.

- **(16 May 2024 - 26 May 2024):** A new GitHub project was created wherein the improved tool idea with a stronger, more practical conceptual model and UI shall be developed in closer adherence to good development practices. This period saw the implementation of a stable carbon cycle. Plant growth model along with the timeline panel, CO2 panel, carbon distribution panel, and biodiversity information panel was implemented. The planner page does not yet exist. The codebase is not very modular, and the simulation model is object oriented.

Figure 63. Output after initial stage of home page implementation using re-defined conceptual model and UI design.

- **(27 May 2024 - 1 June 2024):** Target setters and monitoring is implemented. Forest management action picker UI components and basic features like creation and deletion of actions is implemented.

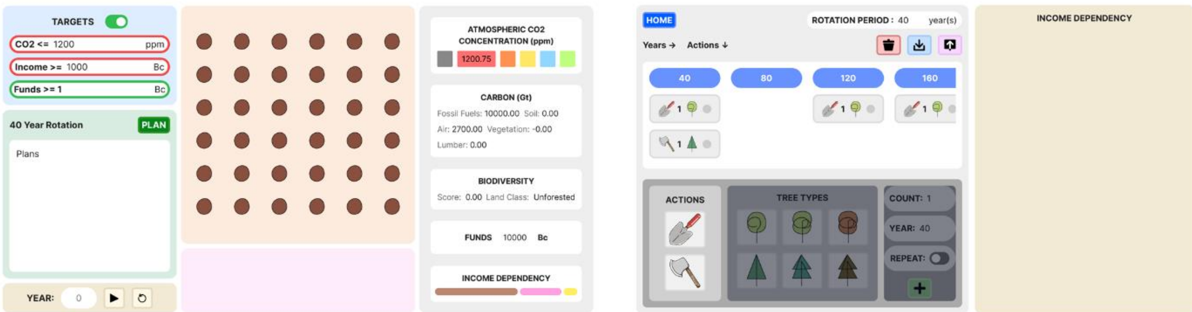


Figure 64. Output of the phase wherein implementation of the planner page had begun.

- **(02 June 2024 – 11 June 2024):** The landing page is added. Other income streams are incorporated into the tool. All home page panels are implemented. It is now possible to hide certain panel to selectively reveal others to enable model progression across challenges. All implemented features are fully functional.

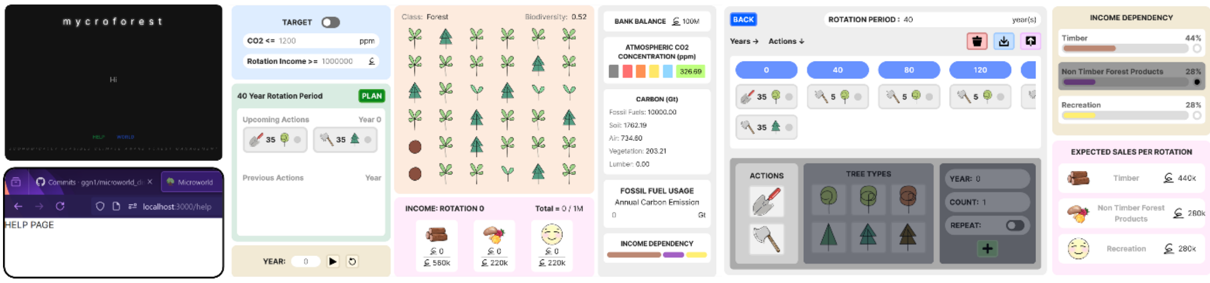


Figure 65. Preliminary complete implementation of all planned features and pages.

- **(12 June 2024 – 18 June 2024):** Simulation model parameters are made more realistic upon further research. User guides in the form of easily accessible help icons and a help page is implemented. A 5 minute [introductory video] is created to quickly familiarize learners at the Bridge to College learning session on 19th June 2024 with MycroForest. The initial form of virtual currency called “Barcon” with a special symbol “S̲” is replaced with the simpler ideas of “coins” with the symbol “🪙” to represent money in the tool. The money viewer panel is implemented. It is made possible to step through the timeline, one year at a time through the addition of single time step buttons.

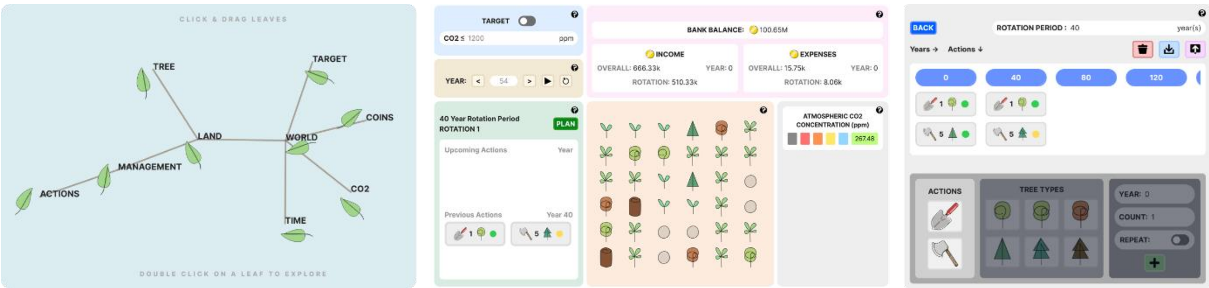


Figure 66. Version of the application that students in the Bridge to College program evaluated. The current implementation is almost identical to this one with only minor changes as per feedback. Students only attempted 2 of the 5 challenges. Hence the image only depicts those features that were visible to the students over the 2 challenges.

- **(20 June 2024 – 27 June 2024):** Age information of trees is added upon hovering over their icons and colour is used to distinguish between seedling and sapling icons of different species. Text and graphics in user help guides is made more simpler and/or comprehensive. Other income stream activation is made binary and not continuous between 0 and 100%. A new option to view income stream based breakdown of "income" and "expenses" on the money viewer is made available. An attempt was made to consider the ocean as an additional regulator of the carbon cycle by introducing water as another carbon reservoir in an attempt to make the model more realistic. This however proved to be extremely challenging given complex chemistry (air-water carbon exchange is complicated given the need to model partial pressure of CO2 in air and water; moreover, carbon is actually present in multiple non-gaseous forms in water that contribute to the carbon cycle [140]) that shall need to be modelled accurately in order to correctly model behaviour that stabilizes the carbon cycle.

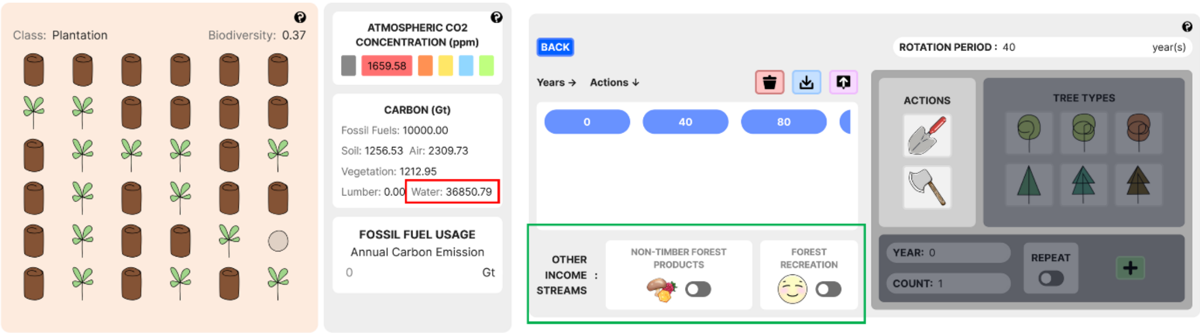


Figure 67. Output showcasing attempt to incorporate the "water" carbon reservoir and the change of income streams from continuous quantitative to binary activation.

- **(28 June 2024 - 1 Aug 2024):** Trying to model this complex relationship through assumptions led to the resulting model being very unstable (atmospheric CO2 levels fluctuated very quickly). Thus, water as a carbon reservoir was dropped given that it only served to further complicate the model with no added value to the tool. Code based was cleaned up to removed unused components. More comments were added to code segments to improve understandability. This marks the end of active development of the application. Focus was shifted toward preparing this document. This stage produced the 1st full draft of this dissertation written report.

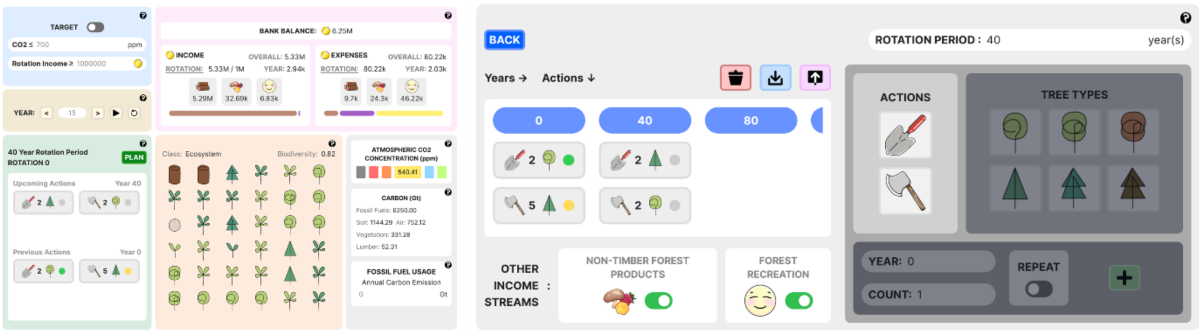


Figure 68. Home and planner pages of the final complete application at the time of submission (challenge 5 view).

- **(3 Aug 2024 - 12 Aug 2024):** This period involves refinement of this document and its submission.

4.1.3 Challenges Faced

Several challenges were faced throughout the course of this project. Following list highlights few of them.

<u>**Complexity Management**</u>

Challenge: A major challenge faced during this project was that of determining an appropriate level of complexity/detail for the tool to capture. During the ideation stage, every idea was entertained. Thus, starting plans were too ambitious for the timeframe. This was expected since the goal was, as advised by the supervisor, to first adopt divergent thinking to begin with the broadest, most creative, model and then follow convergent thinking to then trim down to what can be managed within available time. Given below is a list of concepts that comprised the first idea for MycroForest.

- Entities/mechanisms in the microworld can includes trees, soil, land, time, climate, money. Trees may have properties like species, age, growth rate and tolerance to environmental factors. Trees shall have multiple uses and should capture CO2. They should also affect as well as be affected by biodiversity in the forest. Trees are under stress due to age and living conditions (availability of water, co2, sunlight, soil nutrients). A curve resembling the distribution of availability of resources in the real world shall model availability of resources in the microworld.
- Soil shall be a separate entity and can have properties like acidity, moisture, and texture (compaction, gritty/sandy, etc.) because these factors influence plant growth. Another Land entity should contain trees and the soil. It can also have properties like % of land managed and slope (slope affects forest composition). Land can be divided into 4 quadrants to reflect real word forest estates often being subdivided into plots.
- Time shall be represented at multiple levels (day, month, season, year, decade).
- Climate may be defined by properties like temperature, and moisture/precipitation/humidity that change over the year based on an editable climatogram.
- Apart from income, there can also be costs/expenditure on management actions. Possible sources of income from forests include Timber/wood, NTFPs (animals, plants, fungi), ecosystem service funds, conservation funds, hunting/fishing, eco-tourism, carbon credits, and forest recreation.
- Virtual forests can face biotic (disease, pest, weeds, invasive species) and abiotic (fire, frost, flood, drought) disasters at intervals drawn from some distribution. A Distribution entity can also have properties like spread probability.
- Possible decisions that users can make using the app could be, “How much land to manage?”, “What type of tree to grow?”, and “What management activities to perform and when?”. Possible management actions include “plant”, “fell”, “disaster mitigation”.
- Carbon in the microworld shall move between different reservoirs like air, plants, soil, and fossil fuels.
- World timber demand can be controlled by the user. Timber demand is another target like income of atmospheric CO2 levels that the learner can set and try to meet.

Determining which parts of above ideas to retain in the final teaching tool, was a challenge.

Solution: The solution involved retaining only those elements directly linked to the relationship between afforestation or deforestation, world carbon levels, and income generation from the forest. Research and discussions with the domain expert co-supervisor guided these decisions. Many ideas were dropped, such as disasters, multiple time levels, detailed soil properties, and various income streams. Others were simplified; for example, tree species were abstracted into “coniferous” and “deciduous” categories only instead of individual real-world species like Douglas Fir or Oak. This reduction and simplification ensured the tool remained focused on the core educational goals (illustrating the link between forests and atmospheric CO2 levels and underlying financial motives driving deforestation) without overwhelming or distracting young learners.

Other Income Streams

When looking for income streams other than timber to incorporate within the application to inform learners about there being alternate sources of income from a forest other than just wood sales, hunting/fishing and income from carbon credits were considered.

Hunting/fishing as an income stream was dropped because according to the domain expert/co-supervisor, in the real world, this is often irresponsibly conducted such that biodiversity suffers greatly and eventually leads to decline of forests. Hence, presenting income generation from hunting/fishing permits as sustainable/climate-friendly was deemed inappropriate.

Carbon credits

Precision Loss

Challenge: JavaScript, the primary programming language using which logic of this app was developed, has limited capability for handling floating-point arithmetic and large integers. When working with large numbers on the global scale (e.g. mass of atmosphere = 5.1e+21, amount of carbon in fossil fuels reservoir = 6.25e+18, etc.), errors in computation and NaN values upon performing arithmetic operations, were encountered.

Solution: This challenge was overcome by storing very large or small numbers as Big objects made available by the Big.js JavaScript library. This library allows arbitrary precision computation in JavaScript by representing numbers as objects and providing methods for accurate arithmetic operations using them. In MycroForest's code, variables like `fossilFuelEmission`, `airMass`, `income`, `funds`, and `carbonWeight` are represented by Big objects.

Land Content Icon Transition

Challenge: Land changes over time are to be depicted smoothly to present an animated display of forest composition changes in response to learner management action choices being executed over time. For instance, an icon representing a deciduous tree sapling must soon morph into the icon associated with a mature deciduous tree. Achieving this change using a different icon image for each land content type results in a choppy transition that can lead to poor UX and distract learners from the activity at hand.

Solution: This challenge was overcome by creating icons using SVG `<path>` elements. By changing the "d", "scale", and "fill" properties of these SVG paths, smooth transitions are achieved with the `.transition().duration(50)` functions provided by the D3.js graphics library. This approach allows for fluid morphing of icons, representing different stages of tree growth, and ensures that changes are visually coherent and engaging, thereby improving user experience, and maintaining the focus on the educational content.

<u>Tree Composition</u>

Challenge: In an intermediate version of the tool, it was observed that the land was dominated almost entirely by coniferous trees, regardless of the initial random land composition when left to grow naturally during the warmup period (200 years) before the learner interacts with the forest. This outcome was unrealistic, as validated by a domain expert, because, given the ideal environmental conditions modelled and the initial mix of seedlings comprising both tree species, such dominance is unlikely in the real world. Therefore, the simulation was not suitable for educational purposes.

Solution: The cause of the frequent single-species dominance was identified as the failure to account for an important factor related to tree reproduction: the distance of seed dispersal from the parent tree. Deciduous trees, which produce more widely appealing fruits, have their seeds dispersed further away by animals compared to coniferous trees, which produce less desirable cones. The model at the time did not account for this. So, a new rule was introduced wherein mature deciduous trees were allowed to spawn seedlings either one position away from the parent tree or at few spots that are two positions away. In contrast, coniferous trees can still only spawn seedlings up to one position adjacent to the parent on the land grid. This adjustment gave the shorter-lived deciduous trees a fair chance to compete with the longer-lived coniferous trees, ensuring both species could coexist. This modification is one example of how the model was progressively made more reflective of reality.

<u>Rule Organization</u>

Challenge: Organizing and maintaining a simulation conceptual model with complex and interconnected rules is a significant challenge. When all the information was initially in a single document, it can become overwhelming and difficult to navigate. This complexity led to difficulties in tracking dependencies, understanding the relationships between different topics, and identifying flaws such as missing or cyclic relationships. This also made flaws in logic difficult to detect.

Solution: This challenge was addressed by using Obsidian software to organize the documentation. Obsidian allows for topics to be represented in individual files such that they can be connected through hyperlinks, enabling easy navigation between interconnected topics. This method helped develop a better mental model of the simulation's conceptual framework, making it easier to manage and understand complex interconnections.

Simulation development.

Challenge: Developing a simulation model that is sufficiently realistic to be educationally feasible is a great challenge encountered. This is because capturing complex mechanisms like forest growth and carbon flow can involve an overwhelming no. of decisions to make from conceptual model parameters to implementation tools and logic. It is important to ascertain whether the model is accurate enough to serve the desired educational purpose.

Solution: The solution to ensuring sound simulation design was to follow a simulation development framework that is appropriate for a hybrid simulation model such as leveraged in MycroForest. In 2018, T. Eldabi et. al. adapted the Simulation Lifecycle simulation design and implementation framework first proposed by Brooks and Robinson in 2000 in their work called "Simluation" to work with hybrid simulation approaches [52]. This iterative framework comprising the following 5 stages was adhered to in this project to bring much needed structure to the simulation design.

Stage 1: *Real-World Problem* [52]
The goal is to understand the real-world problem, identify the target system, and pinpoint key components and mechanisms. This stage involves defining the "application area" (broad focus) and "application context" (specific focus). For this project, the application area was "forests and climate change," with the application context being "effects of forest management activities on CO2 levels in the atmosphere."

Stage 2: *Conceptual Modelling* [52]
This stage involves creating an abstract representation of the target system that captures "objectives, inputs, outputs, content, assumptions, and simplifications of the model". The output of this stage could be a document with model components, mechanisms, and underlying rules that govern their functioning defined in it. This stage also generally involves working closely with a domain expert to validate model designs. In this project, multiple versions of a "world rules" document was produces with the conceptual model defined. This was discussed with the domain expert co-supervisor to ensure soundness of ideas. The latest version of the conceptual model is presented in section 3.4.1.

Stage 3: *Computer Modelling* [52]
Now, the conceptual model is translated into a computational model. This involves coding the model, integrating different modelling paradigms, if necessary (e.g., discrete-event simulation, agent-based modelling, and object oriented design in case of this project.), and preparing the model for experimentation. Section 3.5 describes current technical design.

Stage 4: *Verification and Validation* [52]
This stage involves experimentation (e.g. model hyperparameter tuning) and investigation (e.g. running simulations under known conditions to see if expected resulting behaviour is obtained) to evaluate model performance. Stages 2, 3, and 4 are iteratively repeated until the model is found to be realistic enough for specific use cases. In order to validate the simulation model within MycroForest, forest management plans that result in known behaviour was implemented to evaluate if resulting state updates in the microworld matches observed effects of adopted management plan in the real world. For example, one validation exercise was to set up 4 scenarios as follows in MycroForest.

(i) **Scenario:** Chop as many trees as possible in rotations that are 10 years long. Replace all chopped ones with coniferous tree seedlings to create a plantation. **Result:** Overall profit = 123.05 M coins. CO2 concentration remained ≤ 1040 ppm. Avg. no. of old growth or senescent trees at the end of each rotation = 0 trees. Mean biodiversity score at the end of each rotation = 0.46.
(ii) **Scenario:** Same scenario as in (i) except that rotation length is 40 years. **Result:** Overall profit = 119.61 M coins. CO2 concentration remained ≤ 800 ppm. Avg. no. of old growth or senescent trees at the end of each rotation = 0.29 trees. Mean biodiversity score at the end of each rotation = 0.5.
(iii) **Scenario:** Same scenario as in (ii) except that chopped trees are replaced using equal no. of coniferous and deciduous trees. **Result:** Overall profit = 101.32 M coins. CO2 concentration remained below 830 ppm. Avg. no. of old growth or senescent trees at the end of each rotation = 0.29 trees. Mean biodiversity score at the end of each rotation = 0.84.
(iv) **Scenario:** No management. **Result:** Overall profit = 0 M coins. CO2 concentration remained ≤ 495 ppm. Avg. no. of old growth or senescent trees at the end of each rotation = 9.43 trees. Mean biodiversity score at the end of each rotation = 0.78.

Above results reproduced the following known observations [25, 26, 29], which suggests that MycroForest's simulation model is appropriately realistic.

- Older forests diminish as rotation lengths get shorter.
- Longer rotation length promotes old-growth forests, enhances biodiversity, and improves carbon sequestration, but income from wood may be lesser.
- Short rotation lengths result in higher wood harvests but reduces forest biodiversity and carbon sequestration.
- Mixed age and species forests support greater biodiversity.
- Best management strategy for carbon sequestration is "no management".
- Preserving older trees is necessary to sequester more carbon.

Stage 5: *Solution and Implementation* [52]
This stage involves incorporating the developed simulation model into some specific solution. Here, this solution is the MycroForest web-based teaching tool. The developed simulation (simulation model + input parameters) was incorporated into the rest of the web-application (UI components, app pages).

5 Testing and Evaluation

This section describes the testing and evaluation of MycroForest as carried out by transition year students (target user base) in the Bridge to College learning session. Further, feedback regarding the app from teaching faculty and a domain expert is also discussed.

5.1 Pilot Testing

Before evaluation at the Bridge2College learning session, MycroForest was first reviewed by 2 educators who were to lead the learning activity, as well as the supervisor of this project. The purpose of this review was to assess readiness and suitability of the application for a valuable interactive learning experience.

During the first educator evaluation of the application on 14 June 2024, the app was considered promising and potentially suitable for the learning activity given few UI adaptations and complexity management through careful design of learning challenges. Figure 69 shows the version of MycroForest first displayed to the facilitators.

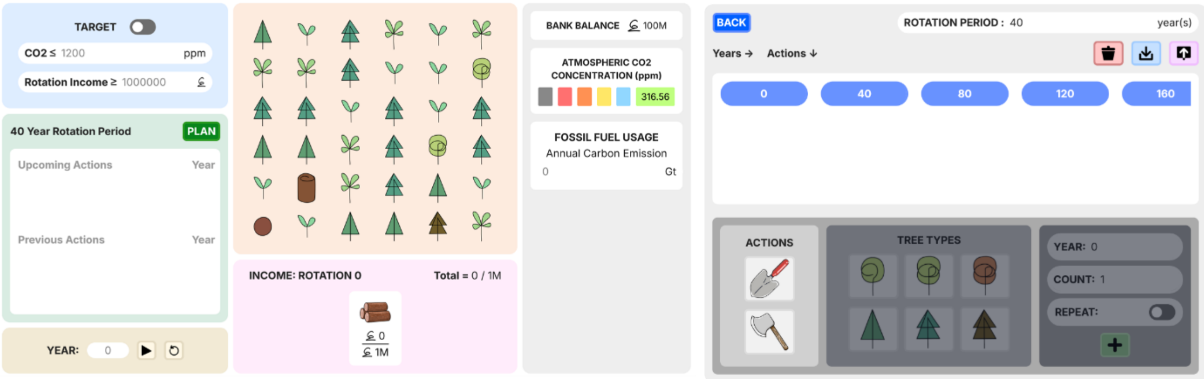


Figure 69. Version of MycroForest first presented to facilitators.

Figure 70 shoes the 3 challenges initially proposed by the author of this document as learning activities for students.

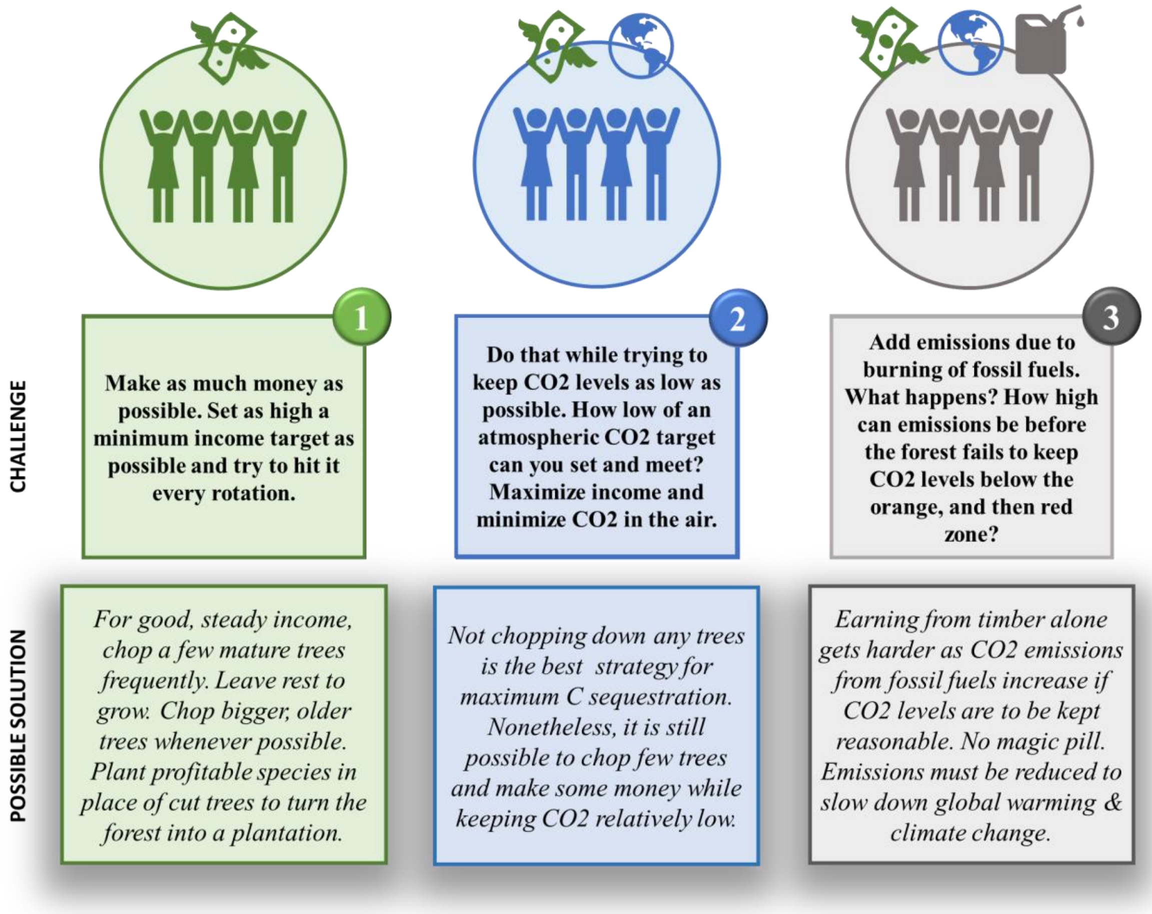
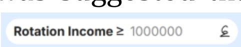


Figure 70. Initial challenges proposed for Bridge to college learning activity.

While the educators appreciated the possibility for multiple learning activities to be built around the tool, they also pointed out that aforementioned challenges, although not considering other income streams, may still be too complex for a 2 hour learning session. They needed to be simplified. Other suggestions were UI related as follows.

(i) The colour of the circle icon representing empty land  was similar to that of a dead tree . This could be confusing to learners. Thus, the colour of the empty land icon was to be changed. – This was implemented prior to the learning session.

(ii) At the time, virtual money in the microworld was a represented using a fictional currency called Barcon . It was deemed that this can be hard to relate to and might distract learners. Hence, it was suggested that the notion of a currency be swapped for a simple, general, universally relatable idea of coins  to represent money. – This was implemented prior to the learning session.

(iii) It was suggested that the viewer not be shown the income per rotation target setter 

as it is more interactive for the learners to try and manually note down incomes per rotation and compare those values against that of peers. Also, learners may initially be only interested in overall income. Thus, the income per rotation target setter, for starting challenges can be too complex and distracting a feature. – The rotation income target was hidden in the challenges that students tackled.

(iv) There were no buttons to step through the timeline one year at a time. It was possible to achieve this by typing subsequent years into the text box. But this can be cumbersome. Hence, the need for single step buttons in the timeline was pointed out by the supervisor. – These were added prior to the learning session.

(v) At the time, it was not possible to view information about the trees upon on hovering over their icons in the land plot. This was a feature that was to be implemented but was not prioritised. An educator pointed out that this feature is important as it can save users time needed to look up reference material to determine tree type and thus should be implemented before the learning session. – This feature was implemented before the learning session.

(vi) Similarly, at this point, only the help page was implemented. The readily accessible help "?" icons were not. It was suggested that the more accessible version of help ("?" icons) be implemented soon before the learning session. – This was implemented before the learning session.

(vii) Lastly, at this stage, it was not possible to add management actions (plant/fell) in the years between start of rotation periods. It was suggested that learners be granted this freedom as this is more intuitive and reflective of the real world wherein although management actions are often planned in rotations and executed at the start of each rotation, forest owners may still choose to perform certain actions in between rotations. Thus, it was suggested that learners be able to do the same. – This feature was implemented before the learning session.

All suggestions above were addressed. The challenges were simplified. They were updated and broken down into 5 challenges inspired from storytelling principles as described in section 3.2. Of these challenges, given the 2 hour time limitation, the transition year students, as part of the Bridge2College workshop, only undertook the first 2 challenges.

	Goal	**Active Features**
Challenge 1	Maximize income from the forest.	Timeline, Land, Money Viewer, Plan Viewer, Planner, Timber Income Stream
Challenge 2	Keep atmospheric CO2 concentration at as desirable a value as possible.	Challenge 1 Features + CO2 Target Setter + CO2 Scale - Money Viewer

Table 22. Challenges undertaken by transition year students at the Bridge2College workshop.

After all suggestions were addressed, the lead educator took another look at the application on 18 June 2024, a day prior to the Bridge2College workshop at which it was approved for use at the learning session.

Prior to showcasing the tool to the educators, it was tested by friends and family (4 people). All of them reported the tool to be a valuable experience. Suggestions for improvement were as follows.

(viii) Initially, the landing page did not have text reading “CLICK” that prompts the learner to click on the “Hi” text to start the introduction. 3 of the 4 testers did not understand without verbal assistance that they had to click this text. This is what led to the inclusion of the “CLICK” text on the landing page.

(ix) Another issue with the introduction was that users (4/4) were inclined to press the “H” or “W” keys at the dialogue that explained about this causing navigation to the “Help” and “World” pages respectively. Pressing these keys amidst the introduction would mean that the learners don’t finish the introduction containing valuable information about the application. Hence, a feature was added that prevents navigation and asks the learner to complete the brief click through introduction (if this is the first time they’re taking it) before navigating to other pages.

(x) Help was not as detailed at the time. All users expressed the need for more details in the help such as different stages of tress and age range of each stage. Help was made more extensive soon after.

5.2 Bridge2College Workshop

The Bridge2College workshop is a venture by Trinity College Dublin (TCD) which invites transition year students to explore and learn about a variety of subjects through several short learning sessions over multiple days. Students sign up for sessions that they would like to attend. This presents young adults the change to discover the subject area they may choose to pursue as part of higher studies or their career.

Figure 71. Students interacting with MycroForest at the Bridge2College learning session.

The teaching tool proposed in this work was presented at a 2 hour learning session aimed at students (N = 10) interested in Computer Science where they discovered the possibility of interdisciplinary (software engineering, forestry, botany, teaching, climate change) application of Computer Science skills through the example of MycroForest. Additionally, using the application, they also had the opportunity to learn about forestry, sustainable forest management, and the importance of forests in slowing down climate change. As part of the learning activity described below, the students attempted the 2 challenges in teams and tried to outcompete each other in highest income earned (challenge 1) and lowest atmospheric CO2 level achieved (challenge 2).

Learning Activity:

1. Introduction (short welcome and explanation by educators + MycroForest 5 minute introductory video).
2. Challenge 1 – Maximize income.
3. Discussion.
4. Challenge 2 – Maximize carbon capture.
5. Discussion.
6. Presentation by the user regarding the development journey of MycroForest with some under-the-hood implementation and development approach details that students may find interesting given their inclination towards Computer Science.
7. Questionnaire – UIUX (PSSUQ), educational experience, attitude towards climate change.

5.3 Usability Evaluation

Usability is a critical quality measure of any software application. The most informative of education technology will impart no knowledge if learners find it difficult to use. Thus, this section discusses methodology and results of the usability evaluation of MycroForest conducted at the Bridge2College learning session.

Usability is generally assessed based on 3 factors as given below [141, 142].

1. **Effectiveness:** Degree of task completion achieved by users of the evaluated SW.
2. **Efficiency:** Resources (e.g. time, effort) needed to complete a task.
3. **Satisfaction:** Perceived usability. This is a subjective measure of how easy it is to use the evaluated SW. [142]

The System Usability Scale (SUS) and the Post Study Usability Questionnaire (PSSUQ) are 2 popular tools (questionnaire formats) used to evaluate usability of education technology [142].

5.3.1 System Usability Scale (SUS)

[141]

SUS is a short (10 question) questionnaire that provides a quick overview of the subjective usability of a SW application. SUS responses are collected in the Likert scale format wherein a score of 1 and 5 on a five point scale indicates strongly disagree and strongly agree respectively with other numbers indicating intermediary responses (2 = disagree, 3 = neither agree not disagree, 3 = agree).

Questions in SUS were carefully picked and organized. The questions in SUS are formulated based on those among 50 questionnaire items that led to most extreme responses in an experiment with 20 people. This is appropriate as Likert Scale responses are considered to best fitting as a means of recording responses if corresponding questions provoke extreme expression of attitude. Moreover, SUS structures positive (common response is agreement) and negative (common response is disagreement) responses in an alternating fashion to encourage responders to really think before answering.

Final SUS score (inclusive range = 0 to 100) is calculated as the sum of scores associated with each question (inclusive range = 0 to 4) multiplied by 2.5 such that odd numbered questions are scored as scale position – 1 and even numbered questions are scored as 5 – scale position.

Overall, SUS is deemed an excellence choice for a quick and broad usability assessment.

5.3.2 Post-Study Usability Questionnaire (PSSUQ)

[142]

PSSUQ is another popular usability assessment format. There is both a long (19 questions) and short (16 questions) version of this. Unlike SUS which primarily focuses on measuring satisfaction [141], PSSUQ covers all 3 aspects of usability (effectiveness, efficiency, satisfaction). This framework also expects answers in the Likert Scale format wherein it is possible to respond to each question using an integer in the inclusive range of 1 to 7 such that 7 represents most disagreement and 1 indicates most agreement.

Another advantage that PSSUQ presents over SUS is that its score can be expressed in terms of 3 subscales (questions 1 to 6 = system usefulness, 7 to 12 = information quality, questions 13 to 15 = interface quality) in addition to an overall usability score. This, more detailed breakdown, makes it easier to identify key areas of improvement. Calculation scores for multiple questions in the PSSUQ evaluation framework simply involves computing the average of all scores corresponding to each question $\left(\frac{\sum scores}{no.\ of\ questions}\right)$.

In 2023, P. Vlachogianni and N. Tselios conducted a thorough literature review and statistically analysed perceived usability evaluation of EduTech using the PSSUQ evaluation framework. The identified the following [142].

(xi) No significant correlation observed between avg. PSSUQ score and participant age.

(xii) No significant correlation observed between avg. PSSUQ score and subject studied.

(xiii) Mean PSSUQ scores assigned by students pursuing higher education were significantly lower than those of primary/secondary education.

(xiv) Based on the Pearson correlation coefficient associated with 58 surveys, there was no statistically significant relationship between the number of participants and the PSSUQ score. For example, it was observed that 12 participants produced equivalent results to a larger sample size in 90% of studied cases.

Overall, PSSUQ is a well-rounded choice of evaluation framework if one is interested in detailed feedback about a system that points out more specific areas requiring improvement.

5.3.3 Adopted Questionnaire

PSSUQ has been shown to be effective with small sample sizes [142] as was the case with students available for the learning session (N = 10). It is also favoured over SUS if the objective is to obtain more detailed feedback regarding usability of the application across all usability metrics (effectiveness, efficiency, satisfaction). Furthermore, observing the questions from both frameworks, some questions in the SUS list are likely to appear inapplicable w.r.t MycroForest or just vague as far as the young users are concerned. Consider the evaluation item "I think that I would like to use this system frequently". This is not directly applicable to MycroForest as this is not a tool that students are likely to use very frequently for some day to day activity for extended periods of time. Other evaluation items from SUS like "I found the various functions in this system were well integrated" and "I thought there was too much inconsistency in this system", are both likely to cause some confusion because trying to identify features that may be considered as a "system function" and judging whether it was "integrated well" as well as interpreting what "inconsistency" might mean w.r.t to a web based learning application, are both challenging tasks that might lead to young learners answering these questions without much thought. Evaluation items in the PSSUQ form have simpler wording and is more straightforward.

Thus, the questionnaire that was used to evaluate MycroForest at the Bridge2College program uses questions and the response format of the PSSUQ evaluation framework. Although its pros outweigh its cons, one disadvantage of the PSSUQ framework is that it is longer (up to 19 questions) than SUS (10 questions) [142]. To mitigate corresponding ill effects like responder fatigue, the shorter version of PSSUQ with 16 questions was considered when creating the post-activity questionnaire for the Bridge2College learning session.

Neither the SUS nor the PSSUQ frameworks have open ended questions. Adding such questions can present learners with the opportunity to freely express their more unique thoughts or suggestions regarding the application. Such direct suggests can provide useful directions for application improvement. Further, although the PSSUQ framework addresses evaluation of general SW usability metrics, it is known that no generalized framework can evalute context-specific metrics associated with a system [141]. Here, value of the tool as a learning aid, is the context-specific metric. It is important to have a few more questions in the questionnaire that try to evaluate effectiveness of the application at teaching valuation ideas to the students and to gauge whether a microworld based tool that is expected to be engaging, was truly so, or not. Additionally, given that the tool tries to raise awareness about climate change, it would also be interesting to note differences in attitude of learners towards this before and after the learning activity. Thus, 10 questions were added to the MycroForest evaluation questionnaire in addition to the 16 questions from PSSUQ to comprise a total of 26 questions. Two of these are open ended questions that allow learners to express their subjective thoughts more freely. All responses were anonymous. No personally identifying data (contact details, name, school details, etc.) were collected from learners.

Please find a PSSUQ template with questions used in the MycroForest questionnaire here. The 10 added questions (questions 17 to 26) regarding educational experience and attitude towards climate change are listed below.

17. This system made me think about responsible forest management and the important role that forests play in keeping atmospheric CO2 levels in check. (Response type = Likert scale from 1 to 7.)
18. I feel like I learned something valuable using this system. (Response type = Likert scale from 1 to 7.)
19. Tools like MycroForest makes learning engaging. (Response type = Likert scale from 1 to 7.)
20. I think a lesson using this tool will be a valuable use of time at school. (Response type = Likert scale from 1 to 7.)
21. What did you like best about this tool? (Response type = Open ended.)
22. How do you think this tool can be improved to further enhance your learning or user experience? (Response type = Open ended.)
23. If you come into possession of a forest, what will you do? (Response type = Open ended.)
24. Please state your one key takeaway from this experience. (Response type = Open ended.)
25. On a scale of 1 to 10, how concerned were you about climate change before this learning activity. (Response type = Likert scale from 1 to 10.)
26. One a scale of 1 to 10, how concerned are you about climate change after this learning activity. (Response type = Likert scale from 1 to 10.)

Please find the complete questionnaire presented to learners at the Bridge2College workshop here.

5.4 User and Educator Feedback

Questions in the MycroForest evaluation form are related to 3 main areas of interest. These are "general usability" (questions 1 to 16 from PSSUQ along with questions 21 and 22), "educational value" (questions 17 to 20 along with questions 23 and 24), and "attitude towards climate change" (questions 25 and 26), which shall henceforth be colour coded in this section using the colours "yellow", "blue", and "green" respectively.

Responses to each category of questions by the 10 learners who used the tool as part of the Bridge2College workshop is summarized within the 3 tables below. Please find question wise distribution of responses for all evaluation items here.

#	PSSUQ Analysis	PSSUQ Overall Score	PSSUQ System Usefulness Score	PSSUQ Information Quality Score	PSSUQ Interface Quality Score	21. What did you like best about this tool?	22. How do you think this tool can be improved to further enhance your learning or user experience?
1	Individual Scores →	3.3	4.0	2.7	2.7	It was fun	Nothing
2		2.1	2.0	2.2	2.0	simple and quick	different scenarios
3		1.6	1.2	2.5	1.0	Tree	More tree
4		4.2	3.7	4.2	5.3	Deforestation	Idk
5		1.6	1.8	1.7	1.3	How easy it was to use	Manage money
6		1.4	1.3	1.7	1.3	The simplicity	Add timing for the trees being planted etc
7		1.6	1.3	2.2	1.3	How clearly it showed us how forestry affects CO2 emissions	No error messages came up
8		2.3	2.8	2.0	1.7	it was good, very useful	I do not know
9		1.7	1.3	2.0	1.7	It was easy to use and very informative	Make it more clear how the years and rotation period work
10		1.8	1.3	2.3	1.7	The idea of how forestry model worked	The information page is hard to find
	Average Score →	2.2	2.1	2.3	2.0		

Table 23. Learner Evaluation - Usability related responses.

#	Educational Value Score		23. If you come into possession of a forest, what will you do?	24. Please state your one key takeaway from this experience.
1	Individual Scores →	2.0	Balance CO2 with money	Lower CO2 more air in the atmosphere
2		1.8	manage it accordingly	the effect trees have
3		1.0	Not deforestation	Trees
4		5.8	Chop it down and make some money then buy a yacht	Thumbs up.
5		1.0	Manage the forest	Climate change

#		Score		
6		1.5	Research for a good plan to keep co2 low enough and make money at the same time	Comp science can mix with forestry
7		1.0	Manage the CO2 emissions	The most sustainable way to manage a forest doesn't necessarily affect profits
8		1.0	try to find the perfect middle ground and think about our world	.
9		1.5	Plan and manage it to make money while keeping C02 levels low	That it is important to manage forestry beforehand in order to do what’s best for the environment
10		1.0	Think about my life decisions	Forest are important
	Average Score →	1.8		

Table 24. Learner Evaluation - Educational value related responses.

#	25. One a scale of 1 to 10, how concerned were you about climate change before this learning activity.	26. One a scale of 1 to 10, how concerned are you about climate change after this learning activity.
1	8	8
2	8	8
3	10	10
4	1	1
5	8	8
6	6	3
7	9	10
8	7	9
9	7	8
10	8	7

Table 25. Learner Evaluation - Attitude towards climate change related responses.

The following paragraphs present feedback regarding the usability, and educational value of MycroForest from educators at the Bridge2College learning session.

Lead Educator: “The Mycroforest application is an effective and engaging learning tool for students. Students found it easy to navigate and use after a brief explanation and demonstration. The learners were very interested in and engaged with the scenarios presented and were keen to meet the goals we asked them to meet. The tool has layered detail such that it can be adapted to whatever time is available for a workshop or session - while we used the tool for a couple of hours, I could easily design much longer learning activities using Mycroforest and would enthusiastically do so given the chance. The group discussions that took place after student interaction with the app were very interesting and made it clear that the learning outcomes had been met or exceeded, despite the fact that most students had no prior knowledge of forest ecosystems, the forestry industry, or the associated impacts on atmospheric CO2. I would happily utilise Mycroforest as a learning tool again.”

Educator 2: "I found the students really engaged with the app as the UI and overall web design was quite user friendly and easy to follow. The scale of the simulation allowed the students to get an introduction to forestry and its importance, while also allowing them to imagine its effects on a much bigger, realistic scale. I found the students responding well when they thought of it as a game with goals to reach each time. Through turning a rather complex subject into an interactive activity, the students could easily grasp the concept of forestry, perhaps more so than reading/learning in a traditional classroom setting."

Educator 3: "I think the forestry app is an amazing learning tool for all ages. It is extremely interactive and provides you with knowledge while still being fun. The students found it very easy to understand how the app works and really enjoyed the challenges that were set! I'm confident that the students understood by the end of the session the overall teaching of the effects of deforestation on our world, and what that could mean for their future."

The following paragraphs present feedback from the co-supervisor of this project, Dr. Silvia Caldararu who is a Domain Expert (Botany, Climate Change, Forests).

"MycroForest tackles a concept that is critical but rarely explained to the lay public and especially to young learners. We frequently talk about forests as climate solutions but without explaining both how long that takes and what it looks like and what the financial trade-offs are. MycroForest achieves a good balance of complexity and clarity, allowing the learner to quickly grasp what is going on but giving sufficient depth to reflect he real world situation. I was very impressed that learners naturally came up with real-world land management strategies, despite these not being explained, planned or prescribed in any way."

"There are two main issues that I think could be further improved in potential future iterations, although I want to stress that these do not take away from MycroForest being an excellent learning tool as it is. The first is that of spatial scale – the setup is for managing a forest, yet the learner is shown the global atmospheric CO2 concentration, which is impacted by many other things and larger areas of land. We discussed this multiple times during development and the current implementation was the best we could come up with. Second, there is the implication that making money and reducing CO2 levels are somehow equivalent goals. In the face of the global climate crisis, one might argue that reducing CO2 overshadows all else, and especially for young learners who are very aware of the crisis we are facing and frequently active in the activism space, the way we phrase the problem is crucial."

Additionally, the author of this document had noted down few ideas from learner discussions at the end of each challenge during the Bridge2College learning session as showcased in Figure 72.

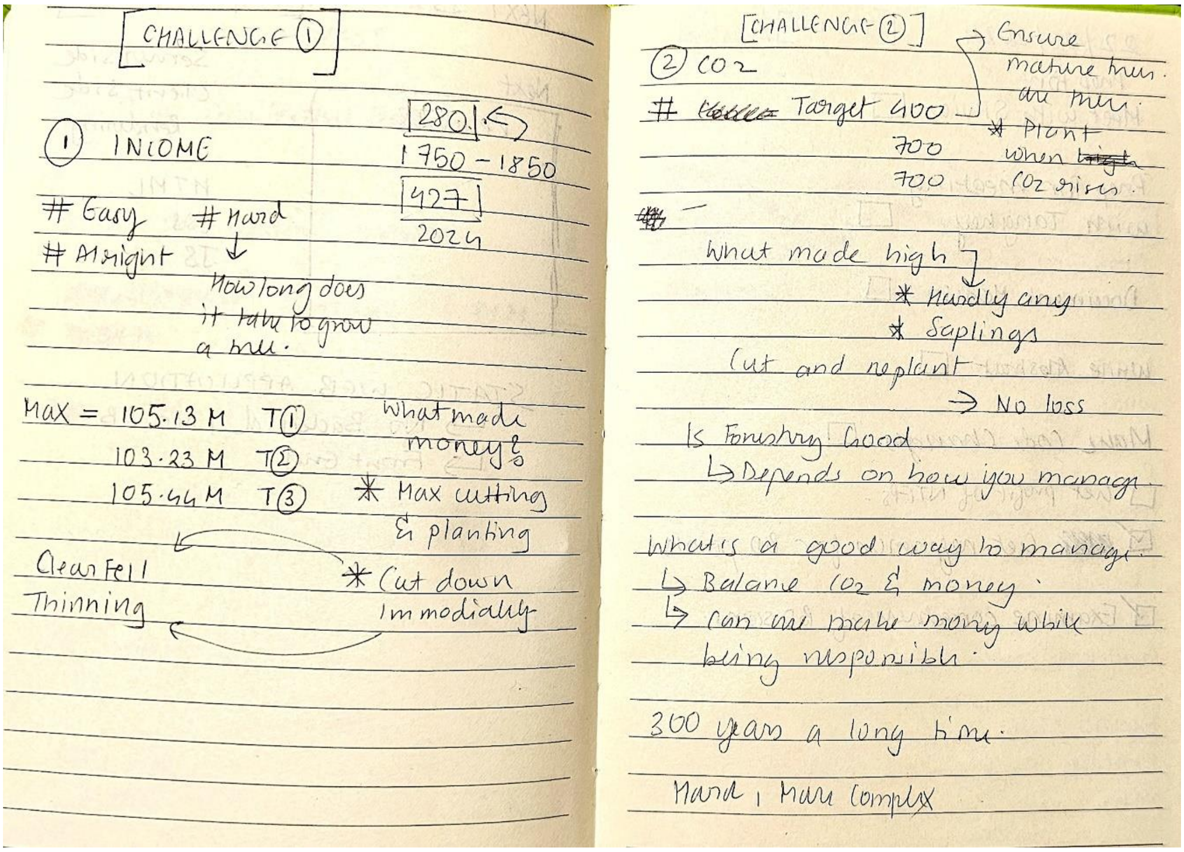


Figure 72. Bridge2College - Learner discussion notes.

5.4.1 Findings

Based on responses from the above section **Error! Reference source not found.**, learner f eedback on MycroForest is largely positive. Average usability scores range between 2 and 2.3 on the 7 point PSSUQ scale. On average, all 3 usability subcategories of system usefulness, information quality, and interface quality received similarly good ratings. This suggests that most learners found the tool highly usable across the board given that 1 = most usable and 7 = least usable. Average education value related score is also most positive at 1.8 meaning that most students found the experience of using MycroForest, educationally rewarding.

Considering individual usability and educational value ratings, it can be observed that only 3 of 10 individuals ever reported a negative score (> 4). Following figure displays the distribution of scores for questions that received at least one negative response. From these responses, it can be gathered that the biggest area for improvement w.r.t MycroForest is regarding error messages. It appears most learners would have liked to receive more error messages to steer them towards correct behaviour upon incorrect inputs or order of inputs. It is unclear as to what actions triggered the conditions that sparked the need for error conditions. Thus, MycroForest will benefit from being subject to more testing by new users who then report discovered errors or undesirable behaviour such that error messages may be displayed under those circumstances. The other most significant undesirable characteristic of the application was 20% of learners find it difficult or just about manageable to find “help” information. Efforts have been made through re-organization of information after this evaluation to try and address this issue. Further testing is required to analyse effectiveness of this.

Figure 73. Evaluation items that received at least one negative score.

Only 1 individual disliked the UI. Further, it is interesting to note that a negative score for all the questions 13, 14, 17, 18, and 20 is assigned by the same single individual only.

This learner also reported least concern about climate change (level of concern = 1/10) both before and after having used the tool. This, along with open ended answers like "Deforestation" was what they best liked about the application and that if they come into procession of a forest, the primary course of action would be to "chop it down and make some money to buy …", etc. hints at the possibility that the response may have been biased or perhaps the student was unwilling to fully commit to the activity. Of course, there is also the possibility that the tool and learning activity failed to sufficiently promote or inform this learner about the importance of sustainable forest management. This is however less likely given that all other learners found the learning experience valuable such that their concern regarding climate change either rose (for 3/10 learners) or remained at the same high level (for 4/10 people at ≥ 8).

This also points towards a third possibility that perhaps the learning activity is more impactful and appreciated by those learners who are already concerned about climate change to begin with (concern > 5), but not nearly as much for individual who are not concerned about climate change initially. Once again, these warrants testing with a greater sample size. Also, it is estimated that continuing through to challenges 3, 4, and 5, may help stress the importance of sustainable forest management and dangers of ignoring climate change further. Due to a shortage of time, the Bridge2College learners did not get a chance to reach challenge 4 as described in Table 11 wherein fossil fuel emissions due to anthropogenic activities present a climate "crisis" w.r.t atmospheric CO2 levels rising rapidly.

Furthermore, it is interesting to note that the remaining 2 learners reported a drop in concern regarding climate change after using the app compared to prior to this (concern levels dropped from 8 to 7 and 6 to 3 respectively). Once again, this is expected to be due to their only having been time for 2 challenges wherein emissions due to human activity that actively moves carbon from the slow carbon cycle to the fast one through burning of fossil fuels, is not yet considered. Also, it may be that these students left the experience more hopeful about the future and with greater confidence in the positive role that sustainable forest management can play in mitigating rapid climate change. The key takeaway reported by one of these students were "that it is important to manage forestry beforehand in order to do what's best for the environment". Given a forest, this student reported that they would "try to find the perfect middle ground and think about our world". The other student also reported that if they owned a forest, they would "research for a good plan to keep co2 low enough and make money at the same time". Both these responses point towards a willingness to make climate conscious decisions. The willingness to take action in the right direction with limited concern or hope for the future is referred to as "positive reappraisal" and is considered to be among most effective crisis coping mechanisms [2]. Positive reappraisal is important to motivate action against climate change, especially since a large portion of the youth report feelings of helplessness and despair in the matter, a.k.a. climate change anxiety [2, 13].

Educator feedback was very positive. All 3 educators feel that students were engaged in the activity and that learning outcomes were met. Educator 2 points out how the activity being very interactive, likely contributed to the learners having learnt concepts perhaps deeper than what they may grasp through traditional non-interactive explanatory classroom setting. This is consistent with existing research [8, 10, 19, 35, 48] that report well defined microworlds leading to more effective learning through promotion of learner engagement when compared to classic explanatory teaching.

Further, all 3 educators report that students seem to greatly appreciate and even "enjoy" the added element of gamification through challenges and were keen to meet "goals". This shows that the decision to facilitate goal setting via target setters was a sound approach and further lends validates existing work like [4, 9, 19, 60, 64] that support the idea that non-distracting gamification with clear goals can motivate learners using an EduTech platform and serve to provide structure to learning activities involving a microworld.

The lead educator as well as educator 2 greatly appreciate the "layers of complexity" or "scale" that the tool presents, thereby making it suitable for multiple learning activities. Educator 3 also sees potential for this tool to be adapted for use across a wider age group. All 3 educators reported that learners found the tool "easy" to use/understand after a brief introduction even though many students were unfamiliar with forestry.

Also, it is worth noting that the lead educator reports discussions "after" tool usage to be interesting and particularly indicative of achievement of learning objectives. This parallels the notion that in case of tools like MycroForest, "learning begins when the game is over" [4]. This further highlights the importance of learning activities being followed by debriefing or discussion sessions.

Feedback from the domain expert ("MycroForest tackles a concept that is critical but rarely explained …") recognizes motivation of this project as relevant. She merits MycroForest on giving learners a glimpse at realistic forestry practices (management activities planned in rotations) and realistic long timescales over which forests grow and therefore forest based natural climate solutions operate. In learner discussions, multiple students pointed out about how 300 years (timeframe of simulation) is a "long time". Discussions regarding this with educators and peers seemed to leave learners with a better understanding of true time scales over which natural climate solutions operate. This may have left learners more aware of the need for early and consistent forest management efforts to maximize the role of forests as carbon sinks.

The domain expert was most impressed with how students were able to come up with 2 real world forest management strategies, clear-felling, and thinning, entirely on their own using the tool with no prior knowledge about them or instructions from educators. Further, students also correctly recognized that while clear-felling can be profitable, it is likely the worst strategy when the goal is to maximize carbon capture. Another notable outcome was that students in the discussion session correctly recognized the need for preservation of older growth and mature trees to prevent rapid rise of CO_2. This perfectly captures the key sustainable forest management principle of old growth protection.

Lastly, the expert also shares 2 limitations of the application. She mentions how there is a discrepancy in figures w.r.t the scale of the forest presented to the learner. This stems form how a virtual forest of maximum 36 trees influence Earth scale carbon figures reported in the microworld. The decision was made to present the users with at most 36 individual trees as this allows for intuitive application of management actions while still being mentally trackable. Carbon and environmental figures like volume of atmosphere is implemented on global scale because real-world figures are more readily available on a global scale. Carbon absorption and release by individual trees were scaled by a factor of 2.5e+8 so that 36 trees may be able to significantly influence world CO_2 levels. While this does not significantly disrupt learning as the expert clarified, it does present a slightly distorted view of how much carbon a single tree might absorb. A part of the user guide which reads "Please note that the virtual forest presented does not reflect any single real-world forest, it is a simplified, abstract representation of all forests on Earth." within MycroForest, as well as an educator in the beginning of the learning session, informs users of this abstract nature of the virtual forest.

The second limitation of MycroForest that the expert rightly points out is that although MycroForest responds to a profit focused management plan with increased levels of CO_2 in the atmosphere as it should, given that challenges draw attention to income generation from forests (to showcase trade-off between ecosystem service and production related objectives), learners may get the impression that goals of carbon sequestration and that of income generation from the forest is of equal importance. This is more likely if learners only attempt challenges 1, 2, and 3 (Bridge2Forest learning session students attempted challenges 1 and 2 only). In reality, given the pressing need to address climate change immediately, the objective of carbon capture takes clear precedence over income generation. This limitation was compensated for in discussion sessions where educators reminded learners of the need for a climate-first approach to forest management.

5.4.2 Instruments Used

The 2 hour learning session as part of the Bridge2College workshop by TCD took place in a university owned learning hub equipped with modern desktop computers complete with working keyboards and mouses as well as a stable internet connection. Learners accessed MycroForest through the Google Chrome web browser. Since the tool was built to be easily accessible as a web application, no other equipment was required to interact with MycroForest. A wall projector was also leveraged to display the introductory user guide video and computer science related presentation about how MycroForest was developed.

5.5 Development Success

This section states how successful, development of MycroForest was w.r.t set of features that were to be implemented (FRs and NFRs as described in section 3.1) and the planned project timeline.

Of the 12 NFRs 11 can be considered to be completely satisfied with NFR 9 (the tool shall make available, sufficient amounts of easily findable built-in help) with fairly high MoSCoW priority of SHOULD, was possibly only partially satisfied, given that 3 learners reported a less than great level of ease regarding being able to find necessary information.

All but one FR was implemented. FR 11 (System shall allow users to sign-up and log-in to persist information) was not implemented as the choice was later made to keep the application static given that increased development complexity associated with implementing sign-up or log in was not seen as a worthwhile endeavor within the timeframe of this project given that the educational value this would add is not great (group activities can be performed through structuring of learning activities that way, and does not strictly require built-in multi-learner support in the application). It was for this reason, that this feature was assigned lowest priority. It was seen as a good feature to have, but not currently strictly necessary. This is a good feature to strive to develop as an extension of this project. Further, some additional features not in the list of FRs such as the ability to add management actions between rotations and the option to view a breakdown of overall, per rotation, as well as per year income/expenses for each income stream was introduced.

Regarding development timeline, all planned key activities apart from development and testing of a low-fidelity prototype was executed, albeit in a slightly different order or for varying stretches of time, than in which they were planned. It was possible to develop and refine a working, viable, teaching tool in time for the Bridge2College program. Enough time was allocated for research required to make sufficiently informed decisions and it was also possible to prepare and refine this document within allotted project time.

5.6 Summary

TO DO.

6 Conclusion

TO DO.

6.1 Recap

TO DO.

6.2 Limitations

TO DO.

6.3 Future Work

TO DO.

6.4 Personal Reflection

TO DO.

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8 Appendices

8.1 Survey Instruments Used

The questionnaire used to gather feedback from learners was created and distributed as a Google Form. Google Forms was chosen because it is simple to use and automatically runs basic analytics on results like creation of response frequency distribution charts. Online questionnaires are also easier to distribute via links accessible on any PC or smart phone connected to the internet.

8.2 Use of GenAI in this Work

TO DO.