School of Computer Science and Statistics

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

Gayathri Girish Nair

Supervisor: Brendan Tangney

Co-supervisor: Silvia Caldararu

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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.

GAYATHRI

GAYATHRI GIRISH NAIR August 16, 2024

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Abstract

Since industrialization, CO_2 levels in the atmosphere has 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, which while informative, 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].

MycroForest is a web-based microworld designed to teach young adults about forest management and CO_2 levels. Learners act as forest owners, creating management plans for planting or felling trees, with consequences reflected in forest composition, atmospheric CO_2 levels, and virtual wealth. Challenges of increasing complexity, such as maximizing income, carbon capture, or both and more, can be set. The tool includes a hybrid tree growth – carbon cycle simulation model, UI components, and input variables. Key challenges included realistic simulation design, user-friendly interface design, and app developing using NextJS, D3.js, Tailwind, and other technologies.

The proposed teaching tool was evaluated at a 2 hour learning session with 10 Transition Year (TY) students on the TAP Bridge2College Programme at Trinity College Dublin (TCD). Feedback was also obtained from educators at the event. Overall, response 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 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 using which, students role-play as a forest owner and execute their own forest management plans while striving to meet challenges set around learning scenarios such that they learn about the importance and difficulty of Sustainable Forest Management (SFM) 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 threatens almost all life on Earth given rising temperatures, ocean acidification, desertification, and frequent extreme weather, which in turn, negatively impacts society by leading to forced human migration, increased mortality, and possibly increased tension between societal factions at varying developmental stages [13]. Such environmental and socio-economic effects also disrupt key industries like agriculture [13], as productivity suffers [12]. Since now 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 an important message at the UN Climate Change Conference COP26 in Nov 2021. Large scale drastic yet necessary changes, however, are unlikely to happen via government efforts alone. It requires a shift in collective mindset and understanding between 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/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 most promisingly, hope. 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 inform more members of this age bracket about the link between forest management and climate change.

So far, worldwide responses to government policies to combat climate change have been lukewarm at best despite several climate negotiations. There is a need to reinforce urgency. It is important to realize that, given the difficult to model, non-linear, and dynamic nature of Earth's climate, unexpected catastrophic changes catching us off guard is a real risk despite best climate modelling efforts. As it stands, 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, 14].

A carbon sink absorbs more carbon than it releases, helping to reduce atmospheric CO2 and mitigate global warming [15]. Enhancing or creating carbon sinks is one of 3 key strategies to combat climate change, alongside reducing greenhouse gas (GHG) emissions and modifying Earth's energy balance. Past efforts to lower GHG emissions have been largely ineffective, and geo-engineering solutions have often been impractical or risky [12]. Thus, focusing on carbon sinks, particularly forests, is a practical approach. Forests, which cover nearly 4 billion hectares and absorb about 30% of global Carbon Dioxide (CO2) emissions [16], are crucial carbon sinks [17, 18]. However, their status is fragile; deforestation can turn forests into carbon sources that release more CO2 (an important GHG [13]) than they absorb [18]. This is because although forest regrowth absorbs carbon quickly, deforestation results in a greater loss of sequestered carbon due to biological processes like heterotrophic activity and burning of biomass by humans [16, 19]. Also, human CO2 emissions exceed what new growth can absorb. Therefore, alongside planting trees, preserving existing forests is essential to addressing climate change [17].

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 3 common models to assess future forest climate mitigation pathways between years 2015 and 2105. In 95% of these scenarios, projections led to increase in global forest carbon stocks under afforestation, shifting harvest patterns, and intensification of forest management. Further, the study found timber prices to increase across all projected scenarios and that expanding forest area/rising timber prices had a greater effect on increasing carbon stocks than volume of wood harvested. This hints at it likely being possible to maintain economic viability of forests while promoting carbon sequestration through forest management strategies and alternate means of income generation [18].

Thus, teaching about the link between forest management and atmospheric CO2 levels while also allowing learners to explore economic viability of forests through timber harvesting and other forest income streams 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, a key indirect influencer of 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, highlight some existing teaching approach aspects that requires strengthening. 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 SFM as a 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 earning potential of a forest, MycroForest garners attention onto the underlying economic "why" that drives deforestation and by extension, climate change.

Increased engagement and attention w.r.t the subject matter has been linked to deeper understanding. Resulting mindfulness often leads to learners making a conscious effort to resolve mental conflict that stems from discrepancies between existing and new notions of a concept to eventually culminate in mental accommodation of novel ideas and improved assimilation of existing knowledge [20]. 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 [21] that facilitates long lasting and deep learning through "learning by doing/making" [22]. Microworlds may be digital or physical, but the former makes is more widely/easily accessible [2]. Thus, MycroForest is a web-based teaching tool that incorporates a microworld comprising a simple model of a forest that learners can interact with through making their own forest management plans and decisions.

In summary, 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. 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 [23]. The resulting web application should be user-friendly with built-in help and support for gradual complexity reveal wherein features are hidden and revealed in stages, allowing learners to master simpler features first to ensure a low entry threshold [9]. The tool should also incorporate a sufficiently realistic simulation of forest growth and the carbon cycle, based on observed natural phenomena and Earth measurements [4].

To promote self-regulated learning, the tool should be engaging and facilitate constructivist learning by allowing users to draft their own forest management plans [20]. They should be able to play the role of a private forest owner, making decisions on tree chopping and planting over multiple years. Further, they should have at least 3 income-earning options from the forest. The app should also allow users to adjust CO2 emissions from fossil fuels and observe long-term effects of their decisions. Hybridizing a microworld with simulation and gaming elements is known to create effective and engaging learning environments. To boost motivation and self-regulated learning, the tool should embrace game-like features such as goal setting and performance monitoring. Learners should be able to set targets (e.g. max CO2 level, min income), with feedback indicating whether or not these are met [20]. Further, exploratory learning is most effective when guided by some structure [9]. So, MycroForest should allow formulation of challenges using the tool that increase the likelihood of specific learning outcomes. For example, one challenge can have learners try to maximize income from forests and another have them try to minimize CO2 concentration. A third challenge can then, combine both goals to effectively teach about inherent trade-offs. Research also shows that learners perform best with graphical feedback supported by limited text instead of just textual feedback [24]. So, MycroForest should prioritize graphical feedback with short explanatory help at hand. E.g., use of dynamic informative icons to reflect land content changes over time could be very user friendly. Forest management actions and income streams should be adjustable via a Graphical User Interface (GUI), and CO2 concentration could be displayed on a color-coded scale indicating expected quality of human life considering climate change effects.

Finally, this project aims to evaluate MycroForest in terms of UX, learning experience, and attitude towards climate change by having Transition Year (TY) students use it during a 2 hour learning session and share feedback. Educator opinions should also be collected and assessed to gauge utility of this application as a teaching tool.

1.3 Referencing

This document uses Numerical referencing with EndNote reference manager.

1.4 Ethics

The tool was used by (N=10) TY students for a period of 2 hours as part of the TAP Bridge2College Programme at TCD 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

Section 1 presents an overview of this project. Section 2 provides details regarding related areas of research and other similar tools. Section 0 explains design decisions, Section 4 describes the implementation approach and Section 5 presents app evaluation methodology and results. Section 6 concludes with a condensed project review.

2 Background

This section reviews similar tools and existing work in forest management, simulation design, education technology, and Human Computer Interaction (HCI). It shall also state how this influenced key design decisions related to MycroForest, the teaching tool developed in this project. Section 0 will describe MycroForest in greater detail.

2.1 Forest Management

Forest management refers to human intervention in forests driven by economic, social, or environmental principles to meet goals like species or resource conservation or protection and maintenance or boosting of forest productivity. Common management actions include felling trees, planting trees, fertilization, building infrastructure (e.g. roads to improve accessibility, irrigation facilities, etc.), administering pesticides or weedicides, culling invasive species, etc [25]. Ecosystem Services (ESs) here, refer to resources or services that a forest grants. ESs may be *provisioning* (e.g. source of resources like wood/timber, food, water), *regulatory* (e.g. climate regulation, water purification, pollination, etc.), *cultural* (e.g. catering towards spiritual beliefs, provision of spaces for recreational activities, etc.), and/or *supporting* services (e.g. carbon sequestration, soil formation, nutrient cycling, etc. which comprise mechanisms that drive other systems crucial for life). Timber sales is the primary source of income from a forest [25]. Thus, given the economic viability and climate change premise of MycroForest, ESs of primary interest are carbon sequestration and timber provisioning.

Planting and felling trees are crucial forest management actions directly linked to timber production [25]. Hence, they are action options for learners in MycroForest. In forestry, management plans are often scheduled per **rotation period**, the time between subsequent plot scale timber harvests. *Clear-felling*, the practice of removing all trees at once, usually at the start/end of a rotation, is a simple forest management strategy. *Thinning*, involving selective tree chopping during a rotation to promote competitive growth, sustained yield, etc. is another [26]. Rotation length is an important choice in a forest management plan [27] because it greatly affects various ESs, especially carbon sequestration. In 2023, E. Z. Baskent and J. Kaspar studied effects of varying rotation lengths on ESs in Turkey's Bürücek forest. Using the ETÇAP DSS model, they found that shorter rotations increased harvest frequency, boosting immediate wood production and economic returns but reducing long-term tree volume and carbon sequestration. Longer rotations typically enhanced carbon sequestration. However, limited felling at longer intervals could increase net carbon storage due to Harvested Wood Products (HWPs) preserving carbon as long as consequent emissions due to deforestation could be compensated by new growth and CO_2 uptake by remaining vegetation [28]. That is, felling few trees at medium to long rotations, primarily for non-burning purposes, could result in lower net GHG emissions compared to natural decay. Baskent and Kaspar observed that some rotation lengths led to better carbon storage than shorter/longer ones such that they expect there to be a forest specific "optimal rotation length for carbon–neutral conditions" [26]. Thus, rotation length is a key input in MycroForest.

Forest management often aims to increase timber production [27] for economic gain, leading to unsustainable deforestation, which contributes to about 20% of all GHG emissions [29]. Wood is either burned for energy or made into long-lasting products. Some consider *energy substitution* (e.g. burning wood instead of fossil fuels) and *product substitution* (e.g. replacing concrete with wood) as climate-friendly due to pound for pound lower GHG emissions [28]. However, some argue that forest loss and its diminishing carbon "sink" status cannot be offset by such substitution [30]. The high demand for wood and its role as a primary income source creates a trade-off between objectives of forest production and carbon sequestration in forest management plans [25]. MycroForest highlights this trade-off and tries to 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 [25] such that owners rely on them for all or a portion of their income for livelihood [24]. As long as funding for ecosystem services like carbon sequestration remains inadequate and unreliable as is largely the case [24, 31], 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 they be managed sustainably. Thus, it is imperative that ideas like Climate Smart Forestry (CSF) which advocates reduction or removal of GHG emissions while maintaining or 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 [24]. Yet another way is to make forests available to the public for recreational use and charge for amenities and/or experiences [32]. 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.

Ultimately however, "no management" is considered as the best forest management strategy involving preserving existing old forests and stopping all deforestation (legal and illegal). Reforestation (turning land that once was a forest back into one) and appropriate afforestation (transforming suitable land into healthy native forest ecosystems) further improves forest carbon storage. 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 5 IPCC reports, refers to this strategy as "proforestation" [27, 29-31]. MycroForest, through 5 challenges that learners try to overcome as part of a learning activity, tries to educate about the need for proforestation.

2.2 Education Technology

Education technology (EduTech) refers to software (SW) designed to facilitate learning, both directly as does e-books, mobile learning apps (e.g. Duolingo, Khan Academy), microworlds, educational games, and indirectly like assessment tools (e.g. Kahoot, Google Forms), learning management systems (e.g. Blackboard, Canvas, Moodle), text editors (MS Word, Google Docs), knowledge organization tools (e.g. Evernote, Notion, Mendeley), synchronous collaboration tools (e.g. Zoom, MS Teams) etc [33]. Depending on design, EduTech tools can be empowering or constraining [34]. When promoting engagement, they have been shown to improve learning depth and persistence [11]. Engagement can be defined as active participation with learning tools, subjects, peers, or faculty, and may also be measured in time, effort, or energy invested [33]. It enhances learning by fostering mindfulness, which promotes conscious effort and development of personally meaningful knowledge. John Dewey, whose ideas inspired constructionism, argued that knowledge is valuable only when personally meaningful [20, 35].

Constructionism is rooted in "learning by making" and promotes self-regulated learning (SRL) by encouraging learners to build their own solutions. It is based on the idea that new understanding is built upon existing knowledge, called constructivism [10]. A microworld here, is a teaching tool based on constructionism which provides a simplified interactive model of some real-world system/idea with objects to think with (OTTW) at its heart [22]. OTTW are constructs that learners manipulate to elicit microworld responses as part of exploratory activities leading to knowledge building. [8, 10] A child's sandbox is a natural microworld where sand and tools (bucket, shovel, etc.) are OTTW and playing with them promotes an intuitive understanding of density and volumes in the child [20]. Logo, Boxer, and SimCalc are early digital microworlds used to teach math/physics [36]. Given advancements in technology (Object Oriented Programming (OOP) languages, improved graphics, web apps) and superior ability of microworlds to model interdependent cause-effect chains common in human/natural systems like economics, disease progression, plant growth, effects of climate change, etc. they are useful in domains beyond just mathematics and physics [36-38].

Facilitating SRL, wherein the learner manages their own learning is central to all microworlds. As per Rieber from 1996, self-regulated learners are *intrinsically motivated* (they find the activity rewarding/enjoyable), *metacognitively active* (they engage in planning/goal-setting), and *behaviourally active* (they tweak the environment to suit own learning styles) [20]. These characteristics parallel the 3 widely accepted components of student engagement (affective/emotional, cognitive, behavioural) [33]. Thus, facilitating SRL promotes learner engagement. This reinforces research suggesting that well-designed Microworlds make for engaging teaching tools [8-10, 22, 36]. The Piagetian Learning Theory (PLT) by Jean Piaget whose ideas inspired the proponent of microworlds, Seymour Papert, and the Flow Theory of Optimal Experience (FTOE) by Mihaly Csikszentmihalyi are 2 popular frameworks that define conditions for SRL [20].

PLT accredits learning to (i) resolution of *epistemic conflicts* between existing mental models and contradicting experiences/observations in the learning environment noticed via deliberate assessment/attempts to understand, known as (ii) *self-reflection*. Conflicts are resolved either through assimilation when the learner understands by placing experiences within existing mental models or through accommodation wherein, they tweak, rebuild, or expand existing mental models to accommodate new ideas in a process referred to as (iii) *self-regulation*. These 3 properties summarize PLT [20].

The flow state refers to the deepest level of engagement. It is known to promote psychological growth and thus, benefit learning. The FTOE framework defines 8 activity components that may induce this state of heightened focus. They are (i) an optimized challenge level, (ii) ability to command complete attention, (iii) clear goals, (iv) clear feedback, (v) provides an absorbing enough experience to free the learner of other worries, (vi) provides a sense of control, (vii) frees the learner of self-consciousness and (viii) distorts sense of time such that learners feel it passing by quicker [20].

Flow state is commonly reported by gamers. Thus, gamification of microworld could improve engagement. This is often achieved by structuring activities around *challenges* that learners try to overcome. But it is hard to determine the right difficulty level where learners are neither bored nor stressed. A solution, as embraced by MycroForest, is to present multiple challenges at different difficulty levels [9, 20, 39].

Many a time, microworlds that try to teach about real world systems comprise a simulation model, as is also the case in 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 when learner is ready" so as not to overwhelm. This is known as *model progression* and is incorporated within MycroForest's challenges. It is also necessary to ensure that such tools entail good UX to avoid learner frustration [9, 20, 38]. MycroForest is carefully designed to grant good UX. 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 with short multimedia explanations leads to better student understanding than graphical or textual feedback alone.</td><td rowspan="2">Most students learn from microworlds only when exploration is part of a structured, carefully designed learning activity.</td><td rowspan="2">Microworld</td></tr>
<tr><td>Learners consistently reported lesser frustration when feedback was graphical rather than textual.</td></tr>
<tr><td>Explanations are most effective when provided intermittently. Tutorials solely before or after learning activities are less effective because they separate explanation from experience.</td><td>Students who discussed the content showed increased learning.</td><td rowspan="3">Game</td></tr>
<tr><td>Instructional support is best provided during the simulation as opposed to earlier because the latter leads to formation of hypotheses that are hard to change even when evidence suggests otherwise.</td><td rowspan="2">Children favored these three game characteristics in a study of student-designed games: (i) storyline quality, (ii) competition, and (iii) appropriate challenge.</td></tr>
<tr><td>Students benefit significantly from simulations that build complexity in stages, allowing time to grasp simpler concepts before progressing to more complex ones.</td></tr>
</table>

Table 1. Observations regarding use of simulations, microworlds, and games as educational tools. [9]

Simulations, microworlds, and games are all useful as interactive educational tools, but combining elements from each, can optimize learning experiences. While simulations visualize complex systems well, the mental model that learners develop can be difficult to evaluate for correctness. In tools like MycroForest, which relies on simulations for correct system behaviour, integrating a microworld approach is beneficial since microworlds produce tangible external artifacts in the form of learner creations that are representative of the learners' internal mental model [9].

Overall, research suggests that hybridization of microworlds with simulation and gaming elements lead to very effective/engaging learning environments. [9, 10, 20, 40]

2.3 Simulation Design

To ensure that forest management plans in MycroForest yield similar carbon flow outcomes as in the real world, the virtual forest must simulate tree growth and the carbon cycle with sufficient realism. A "simulation" here, refers to a "model" (system representation) that can be updated based on simulated conditions to mimic real-world behaviour [41]. Thus, every simulation comprises a conceptual model of some target system. Biological processes like forest growth, carbon storage, nutrient cycling, etc. are often simulated because their complexity, long timeframes, and life support role, makes experimenting with these systems difficult without disrupting critical real-world mechanisms [42]. Of the many simulation paradigms, w.r.t natural systems, Agent Based Simulation (ABS) and Discrete Event Simulation (DES) are 2 popular ones.

2.3.1 Agent Based Simulation (ABS)

ABS is a type of simulation that leverages an Agent Based Model (ABM). ABMs represent a system using independent agents with their own memory and rules that interact with each other and the environment [43].

In biological, ecosystem, and climate modelling, ABMs are popular [43] because such target systems are often composed of discrete entities that independently interact with a shared environment or each other to accomplish individual goals resulting in of composite emergent behaviour [43, 44]. Also, ABMs impose no restrictions regarding no. of attributes or rules per agent which makes them apt for modelling complex systems like forests/ecosystems [45]. Furthermore, research suggests that students using EduTech with ABS outperform others due to better understanding of cause-effect relationships curtesy the "agent perspective" helping learners grasp the idea of individual contributions in a shared environment leading to emergent behaviour [40]. Thus, MycroForest models tree growth and carbon capture using ABS where trees are agents operating in an environment comprising land and multiple carbon reservoirs.

ABMs support varying levels of abstraction as can readily be observed w.r.t plant growth. In population level ABMs, an agents may be individual plants with the ABM capturing forest level behaviour. Individual level ABMs are more nuanced wherein specific plant modules like structural components(e.g. leaves, roots) or more abstract constituents (e.g. carbonate pools) may be agents [45] such that the ABM models growth of a single plant. MycroForest aims to teach about forest level changes under different management plans and not plant biology or growth. Thus, the constituent ABM is a population level one with the forest being a population of tree agents.

Underlying assumptions that influence key mechanisms like tree volume increase or reproduction pattern, can also vary both in approach and level of detail [45]. Following 2 examples of slightly different plant growth ABMs built on empirical and mechanistic approaches respectively, demonstrate this [45].

- **JABOWA** [45, 46]**:** The JABOWA model, an early ABM in plant ecology, simulates forest growth in response to canopy cover changes via sub-routines modelled using *empirical equations* based on simplifying assumptions. E.g. annual growth rate is modelled as $\delta(D^2H) = R \times LA \times \left(1 - \frac{DH}{D_{max} \times H_{max}}\right)$ where tree agent attributes D is Diameter at Breast Height (DBH), H is tree height, D_{max} is maximum DBH, H_{max} is maximum height, and LA is leaf area. R is a constant, and δ indicates volume change. This equation captures growth being proportional to sunlight received ($R \times LA$) and it being inversely proportional to maintenance energy $\left(1 - \frac{DH}{D_{max} \times H_{max}}\right)$. Tree volume ($D^2H$) is simplified and assumed to be akin to that of a cylinder ($\pi r^2 h$). Another assumption is that other growth conditions are optimal. The JABOWA ABM 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). It successfully reproduced ecosystem behaviours such as competition, succession, and vegetation changes at different elevations. This shows that complex systems can be simulated in useful detail with some complexity abstracted away through *simplifying assumptions*.
- **PLATHO** [45, 47]**:** PLATHO is a population-level ABM that simulates plant growth to understand resource allocation through sub-models of processes like photosynthesis, water uptake, and biomass growth. It updates plant and environmental states to meet resource demands (nitrogen, carbon, water, etc.) at different plant organs. Assumptions such as "potential allocation to defensive compounds is inversely correlated to maximal growth rate" and "tree volume ≈ cylinder volume" simplify the model. Prioritization is guided by assumptions like "photosynthesis is less affected by nitrogen deficiency than growth." Given high target system complexity, models like PLATHO incorporate equations, e.g., total carbohydrate demand: $D_{pot} = r_{max} \times W_1 \times \Delta t \times f_T \times f_{Ph}$ where, r_{max} is maximum growth rate, W_1 is amount of living structural biomass, Δt is the time step, f_T is a factor $\in [0, 1]$ that is a function of air temperature, and f_{Ph} is a factor $\in [0, 1]$ that is a function of phenological stage of the plant based on seasonal growth. The PLATHO model tested various hypotheses and predicted responses to different conditions. It

accurately reproduced observations like effects of nitrogen fertilization on biomass gain, validated by comparing simulated and measured apple tree data. Even discrepancies, such as overestimating effect of CO2 on spruce needle compounds, led to further investigation, revealing importance of plant acclimatization to increased CO2 and enhancing understanding.

Mechanistic modelling involves representing some primary system based entirely on knowledge of its underlying structural elements and functional mechanisms. Mathematical equations may or may not be used. Algorithms or functions based on informed assumptions are key drivers of simulation. In *empirical modelling*, systems are represented using high level mathematical expressions based solely on statistical relationships in measured data. The latter is useful when outputs or attribute data of a target system is available, but knowledge about its structure or working is limited [41].

Distinction between JABOWA and PLATHO lies mainly in level of mechanistic detail. JABOWA models plant growth at a higher level with expressions incorporating tree attributes like height, diameter, and leaf area, but not modelling processes like photosynthesis, respiration, and water uptake. Thus, it swaps sub-models in PLATHO for parameters in an equation whose values are data driven. This makes JABOWA more empirical than PLATHO which is more mechanistic due to sub-models representing biochemical processes. This makes PLATHO more realistic and detailed than JABOWA.

With complex target systems as is botany or ecology, there is often a need to intentionally limit level of detail modelled for computational feasibility or to reflect specific simulation purposes. Also, knowledge about underlying mechanisms is likely incomplete. In such situations, distinction between the 2 modelling approaches get blurred. For example, 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 target system's underlying mechanics. Similarly, JABOWA also makes a few mechanistic assumptions to decide on what attributes are to be included in expressions and what modelling characteristics to consider when promoting emergence of appropriately realistic behaviour.

Thus, biology, ecology, and climate change related simulations can require hybrid ABMs combining mechanistic and empirical elements to meet unique needs [41]. Therefore, the ABS within MycroForest models key processes like tree growth and reproduction using algorithms and high-level mathematical expressions incorporating tree and environmental attributes like species, age, size, spatial location, growth rate, environmental stress and aging inspired from JABOWA based on certain mechanistic, informed assumptions or rules inspired from PLATHO 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 approach creates a realistic yet computationally feasible model with smooth UX.

2.3.2 Discrete Event Simulation (DES)

Discrete Event Simulation (DES) is a popular modelling paradigm, especially suited for process flows [48]. It breaks down continuous system behaviour into an ordered sequence of discrete events/processes [43] that makes it possible to simulate slow systems like forest growth in a shorter than real time frame, given that time between events is not simulated and a single event can represent multiple state changes [49]. This ability of DES to hasten slow, real-world processes in simulation is deemed beneficial in forestry related simulation wherein real-time modelling of forest management plan execution is often infeasible due to slow natural timelines [48].

All DEMs comprise entities and a priority queue that manages events [49]. Running a DEM typically involves 3 iterative steps [50]: (i) Execution of *calendar* (a.k.a. schedule, plan, priority queue) *events*. (ii) Execution of activities/*processes* comprising each event which may/may not include stochastic elements/probabilistic execution durations. Uncertainty is often modelled using a probability distribution. (iii) Entity attribute, system state, and statistics updates in response to executed processes.

A use case wherein DES is most popular, is decision making or strategy comparison because human decisions can easily be incorporated as events added to the simulation queue. This accounts for forestry applications of DES that compare management and harvesting strategies, assess various facility layouts, and analyse resource logistics [48]. For instance, Westlund et al. developed an optimization-simulation framework to evaluate wood supply chain performance under varying weather conditions. Their approach combined an optimization model for generating harvest schedules with a DES model for simulating delivery under different weather scenarios [51]. Thus, DES within MycroForest handles execution of forest management actions added by the human user.

The idea of entities generating events comprising a set of instructions to be executed at planned times is very practical w.r.t SW implementation. DES is compatible with OOP because model entities can be implemented as objects with properties capturing entity attributes and methods defining event processes [49].

Furthermore, simulations are built to serve 2 purposes: (i) To analyse/understand some phenomenon/system, or (ii) To provide a training environment that teaches about it. The simulation in MycroForest caters to purpose (ii). 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 [48, 52].

MycroForest aims to allow learners to create and explore effects of different forest management strategies over 300 years on a virtual forest. This presents an ideal use case for DES w.r.t scheduling and execution of management actions as events. It is compatible with the OOP approach used to code the MycroForest simulation model.

2.3.3 Hybrid Simulation

DES is ideal for modelling discrete human decisions/actions over time, while ABS excels at capturing individual agent interactions and emergent behaviour. Thus, for simulating plant growth and carbon capture resulting in forest-level patterns from independent tree – environment interactions, ABS is appropriate. DES is more apt for simulation of discrete user generated actions. Therefore, MycroForest adopts a Hybrid Simulation (HS) approach with ABS to model tree growth and DES to manage timely execution of learner generated forest management actions. HS incorporating elements of more than one simulation paradigm is no uncommon. It is prevalent in health care, supply chain management, manufacturing, and construction. 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" [53]. This reinforces suitability of ABS + DES for MycroForest.

HS is sought after for complexity management because in addition to supporting abstraction of system parts, it also allows problem/system breakdown into smaller parts such that the simulation paradigm most suited to each part may be employed. This helps control accuracy – complexity/performance trade-offs. [54, 55]

A key challenge with HS is compatibility/integration of constituent simulation paradigms. Ensuring interoperability between elements from different simulation approaches can be difficult [54, 55]. To this end, in addition to ABS and DES, MycroForest adhered to a general, Object Oriented (OO) design as shall be discussed in detail 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 [53].

2.3.4 Object Oriented Design

Object-Oriented (OO) software design pattern views systems as collections of interacting *objects* with their own data and functions. The definition of an object is known as a *class*. That is, if `Shirt` were a class, then `Shirt("blue")` and `Shirt("red")` would both be its objects. Object-Oriented Simulation (OOS) applies this concept to modelling, naturally representing many real-world systems [56]. For example, a cell can be modelled as objects representing its components (nucleus, mitochondria, etc.). More abstract concepts like gravity can also be treated as objects.

Given below are 4 ideas known as the 4 pillars of OO design [57, 58].

1. **Abstraction**: This principle emphasizes implementing only essential attributes and functions, providing high-level functionality without exposing underlying details. E.g. it may be 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()`. Following this principle simplifies code, improves efficiency,

and enhances reusability. In MycroForest, the aim is to have trees absorb and release carbon such that their presence/absence affect atmospheric CO2 levels as observed in the real world. Thus, it is sufficient to keep track of carbon stored in a tree. Details about where it is stored and mechanism of carbon allocation between plant organs, is irrelevant. Thus, volume of the tree may be simplified to that of a cylinder and amount of carbon in a tree was abstracted to x% of the mass of that tree.

2. **Encapsulation**: This principle promotes self-contained objects with clear responsibilities, exposing only necessary attributes/methods with others kept private. This fosters modularity/separation of concerns ensuring code flexibility and minimal breakage upon updates. In MycroForest, the function `computeBiodiversityScore()`, accessible only from the `Land` class, encapsulates the biodiversity score calculation which allowed for easy replacement of the method as modifications were confined to a single function when requirements changed from a forest with most old trees being scored highest to one with a certain ratio of young and old trees as observed in nature, being assigned highest biodiversity score.
3. **Inheritance**: OO design supports class hierarchies where child classes inherit properties from parent classes, allowing for customization and extension of functionalities. For example, if `Vehicle` is the parent, then `Car`, `Bus`, and `Truck` may be children who inherit vehicle properties/functions like `colour` and `drive()`while also having unique features. This reduces code duplication. In MycroForest, classes `Timber`, `NTFP`, and `Recreation` are children of the class `IncomeSource` since income may be generated by selling timber, non-timber forest products (NTFPs) or forest recreational activity permits/tickets. `Timber`, `NTFP`, and `Recreation`, all inherit the `sell()` function from `IncomeStream`.
4. **Polymorphism**: This idea states that the same attribute or function may be redefined with a different value. Child classes commonly inherit from the parent and redefine or extend functions. This allows behaviour sharing with minimal resource overhead. E.g., in MycroForest, classes `Timber` and `Recreation` inherit the `sell()` function from the `IncomeStream` class. Selling wood and forest recreation permits involve extra unique computations different from simple selling method and hence both children redefine the `sell()` function.

MycroForest adopts OO design because it naturally mirrors real-world hierarchies while keeping code modular, concise, reusable, and flexible. E.g. MycroForest defines an `Environment` class containing a `Land` object which in turn contains many `Tree` objects. Furthermore, OOS simplifies object communication through function calls and variable access, reducing computational overhead compared to message passing or event-based methods. This flexibility facilitates integration with other simulation paradigms [56].

All simulations need time synchronization, which can be challenging with HS [56]. MycroForest addresses this via a `Simulation` class that coordinates all processes by triggering a time step update that gets propagated through nested objects, advancing all simulated objects in time.

2.3.5 Time Advance

A time advance mechanism here, refers to how progress of time is modelled within the simulation. There are generally 2 ways to implement this [53].

1. **Time Step:** Simulation advances in predefined fixed time steps/intervals (Δt), updating all variables at each step. This is common in ABS.
2. **Next Event:** Rooted in the event worldview of DES, time advances based on event occurrences and not fixed intervals. Most DES implementations adopt this approach.

MycroForest uses the Time Step method with $\Delta t = 1$ year, allowing users to scrub through a timeline GUI to view the world state at any simulated year. This enhances understanding of cause-effect relationships by enabling replayability. Further, fixed, predictable time steps make it easier to measure decision impacts and plan management actions [53]. Actions like tree felling and planting, is typically planned in years because trees can live from 50 to 3000 years, with the oldest living tree, a Great Basin Bristlecone Pine, estimated to be at least 5000 years old [59].

A disadvantage of the time step method is that it limits the simulation's progression rate to $1/\Delta t$, making it impossible to step through faster [53]. In MycroForest, because plant growth varies significantly across time, it is challenging to choose a Δt value. Behaviour can differ greatly depending on whether Δt is 1 month, 1 season, 1 year, or 1 decade. To minimize the influence of Δt on model behavior, it is common to set Δt to be very small such that changes are smoothened [53]. However, this is impractical for MycroForest due to long tree lifespans. A Δt of 1 day would make simulations over 300 years too slow. Simulating 200 to 300 years is necessary to observe long-term forest management effects, as significant changes in carbon levels occur over centuries. Real-world forest management actions are often planned in rotations of 5 to 150 years [26]. Thus, Δt of 1 year was chosen for MycroForest to align with real-world planning, visualize significant changes in tree growth, and cover a long enough timeframe to observe carbon level changes, while keeping simulation time manageable.

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 human-machine communication where usability is a measure of a system's capability for efficient and appropriate task fulfilment [60, 61].

HCI may be uni-modal (single input channel) or multi-modal (multiple input channels). Possible input channels include facial/body movement detection (vision based), voice recognition (audio based) or keyboards/mouse interaction (sensor based). While multi-modal interfaces offer potentially richer experiences, they often require specialized technology (e.g. infrared cameras, haptic devices, etc.) and can be distracting, especially for young learners [61]. MycroForest opts for a simple uni-modal interface using familiar mouse and keyboard interactions for accessibility and ease of use.

HCI can also be grouped as active (user-initiated) or passive (system-initiated). 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 (e.g. sending an email). Passive HCI on the other hand respond to detected non-physical or indirect environmental or user generated queues (e.g. "Hey Siri" voice activation) [62]. MycroForest presents an active HCI. This allows for experiential learning and increased user control, both of which contribute towards a good learning experience [39].

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 [60]. Its intuitiveness makes Norman's Model particularly popular. This model splits the HCI experience into 7 steps organized such that (i) to (iv) comprise an "execution" component and (v) to (vii) comprise the other "evaluation" component. Undesirable HCI is attributed to the "gulf of execution" and the "gulf of evaluation" which define misalignment between "task language" (user's conceptual understanding and possible actions to achieve goals) and "core language" (system's internal processes, responses, etc. and information presentation to users). Other researchers like Abowd and Beale in 1991 extended Norman's ideas by defining 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) [63].

A challenge with Norman's Model, even with Abowd and Beale's UI extension, is its abstraction from a developer's perspective. Thus, it may be advantageous to follow practical guidelines like Jacob Nielsen's usability heuristics, a set of 10 rules to avoid common interface design problems [60]. Furthermore, To address the lack of consensus on a single set of best principles, V. Hinze-Hoare in 2007 conducted a survey of HCI literature and assigned scores to key principles weighted based on proportion of overall citations received. This revealed 8 good HCI principles in decreasing order of weightage: (i) Recoverability (ii) Familiarity (iii) Consistency (iv) Substitutivity (v) Task Migratability (vi) Synthesisability (vii) Predictability (viii) Perceptual Ergonomics. [60]. The first three were most significant and agrees with Nielsen's 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

Multiple existing interactive tools [3-7, 64-68] model forests in the context of growth, climate change, and/or forest management. Broadly, they are either decision making aids for experts like working foresters or teaching tools. 5 such tools are explored here.

<u>Tool 1 – SimForest</u> (Educational Simulation) [66]

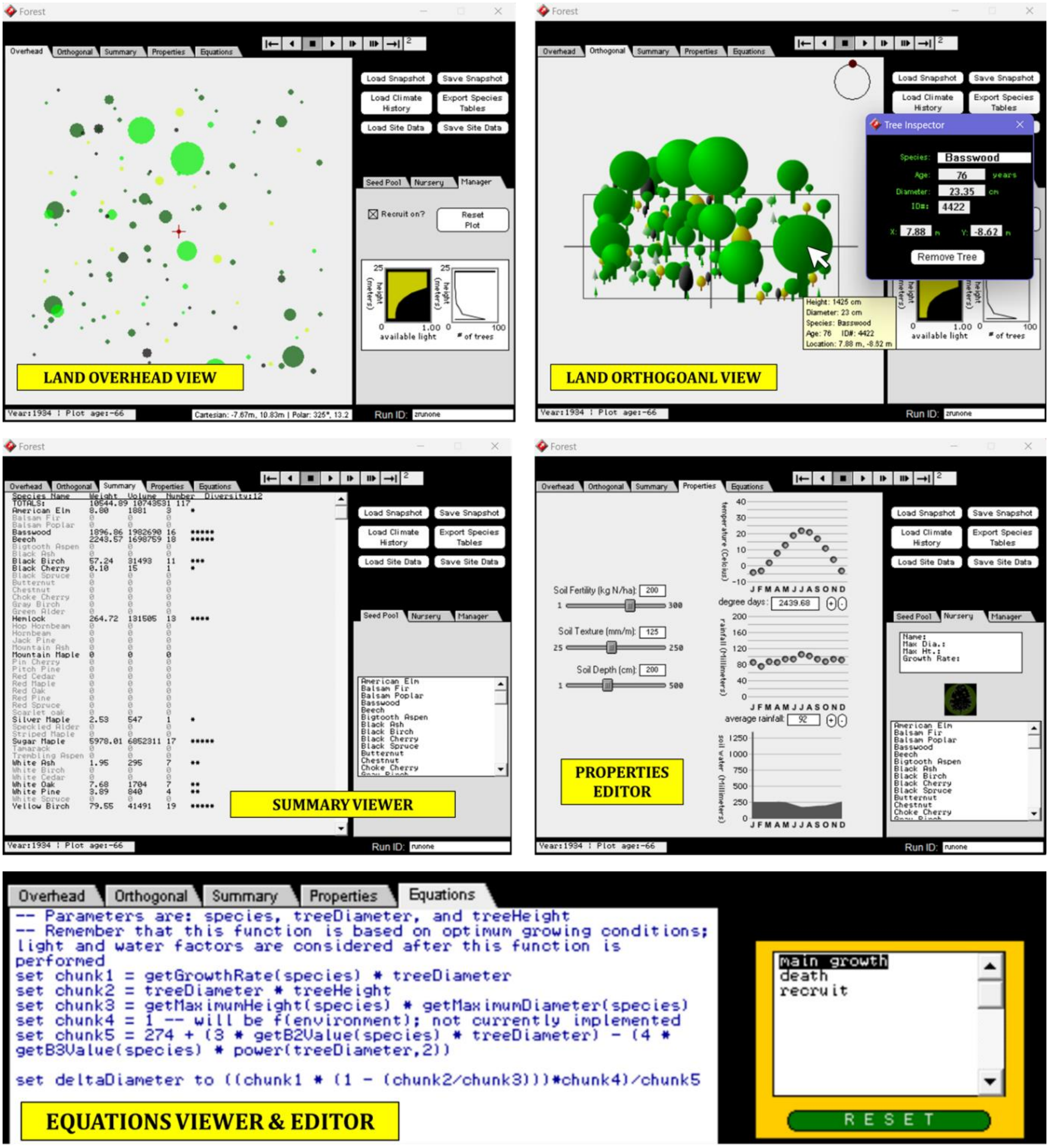

Figure 1. SimForest UI.

SimForest is a Java-based software for inquiry-based learning that simulates forest growth under various environmental conditions (soil fertility, texture, depth, water, temperature, rainfall). The forest can grow naturally, or learners can plant trees from a selection of 30 species. Users can play/pause the simulation and move forwards or backwards in time at different speeds, with both overhead and orthogonal views available. Clicking on a tree shows its properties (species, age, diameter, ID, position) and allows for deletion. Learners can edit tree properties and environmental conditions. A summary tab displays weight, volume, and number of trees per species, and an equations tab shows editable growth, death, and reproduction mechanisms. Further, the tool comes in 2 versions based on learner control over simulation variables. The black box model limits access, while the glass box model allows learners to edit nearly all parameters and equations. The glass box model also enables tree cutting and core sample analysis. The tool also allows saving and reloading of world snapshots.

Pros	Cons
Rich set of manipulatable controls.	No big cons.
General forest growth simulation. Multiple learning scenarios may be developed.	Does not consider CO_2 levels.
Clean user-friendly UI.	
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. Needs download/set up. OS, Java, or Swing related compatibility issues possible.
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).	
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.

SimForest's detailed simulation model is based on allometric equations. MycroForest assumes most growth conditions modelled by SimForest as ideal, focusing on just carbon availability. SimForest emphasizes tree or environment parameter editing, not forest management. In contrast, MycroForest allows creation of land management plans involving actions like chopping and planting trees, while not permitting unrealistic actions like editing species, age, or height of grown trees. Like SimForest, MycroForest allows system state to be saved and reloaded for easy sharing of world settings and reproduction of past results. MycroForest also has timeline controls as in SimForest, enabling forwards/backwards motion in time and playing/pausing of the simulation.

<u>**Tool 2 – Foster Forest**</u> (Decision Support Simulation) [3]

Foster Forest embraces the Companion Modelling (ComMod) approach. It is a simulation adapted to be a Role Playing Game (RPG) aimed at experts like forest managers, community forest federation members, etc. 5 participants, a mayor, public forester, protected area manager, and 2 private landowners make social, economic, and ecological decisions to manage ES availability. A facilitator is also required to computerise participant decisions and must be a Foster Forest expert who can adapt source code to implement creative strategies. All participant roles manage budget and avoid negative impacts of ecological factors like overgrazing. Some roles have more exclusive objectives (e.g. mayor maintains water quality and upholds aesthetic value of forests, public forester focuses on timber harvests, protected area manager promotes old growth conservation and shares information about carbon storage).

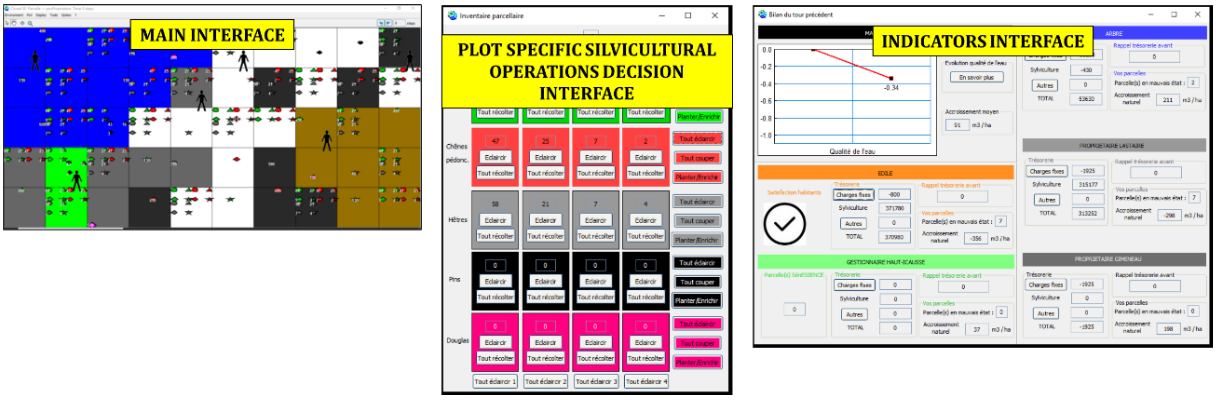

Table 3. Foster Forest UI – The main interface displays the 50 land plots simulated. Different views (owner view, eligibility for conservation plan view, etc.) can be selected to be overlayed on these plots. The above main interface image shows the ownership view coded per participant. The indicators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

The simulation is built using the CORMAS platform upon an Agent Based Model (ABM) composed of spatial (land plots owned by participants), semi-autonomous (participant roles), and physical entities (trees). The participatory experience comprises 5 steps starting with a pre-simulation questionnaire that asks about climate change views, followed by a user-guide briefing session before the main activity with multiple rounds is conducted. The session ends with a post-simulation questionnaire and collective debriefing session.

The simulation progresses in 10-year timesteps comprising 2 periods. During the action period, the facilitator shares climate projections, timber, and carbon prices. Players then discuss and present forest management strategies involving tree planting/removal, hunting, trading plots, and execution of sustainability efforts like old growth protection. In the next computerised update phase, the facilitator inputs player decisions into the tool, which simulates forest growth, calculates successive ABM entity states, and updates values like participant income/expenses and changes in social/ecological parameters (e.g. carbon storage, soil fertility, etc.). The facilitator concludes this phase by providing an overview of new parameter values and climate changes.

Pros	Cons
Participants enjoyed the ComMod wherein decisions followed group discussions.	Participants must be familiar with the domain. Not for the lay man.
	Participants found the UI too mathematical and hard to relate to.
	Tool requires extensive introductory training and user guides.
Tool is **realistic** with well a designed ABM.	Participants cannot interact with the tool directly. They rely on a facilitator.
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.
Tool is very **flexible** and supports a rich variety of scenarios. Participants can come up with creative strategies not severely limited by tool capabilities.	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.

Design decisions in MycroForest inspired by Foster Forest include the following.

- Using an ABM approach for forest growth and carbon flow.

- Implementing carbon reservoirs similar to Foster Forest's plot carbon storage.
- Tracking participant income and expenses related to forest management actions.
- Featuring more than one tree species with varying growth rates and wood prices.
- Implementing younger trees to be more sensitive to environmental factors.
- Allowing only mature trees to reproduce, with natural regeneration needing nearby mature trees.
- Incorporating tool use and debriefing sessions for effective pedagogy.
- Conducting group activities where students collaboratively design management plans, inspired by the ComMod approach.

The ABM in MycroForest is simpler than in Foster Forest, omitting details like soil fertility and tree competition due to project scope constraints, primarily time. This simpler model effectively links forest management practices with atmospheric CO2 levels, making it suitable for educational purposes w.r.t getting young learners to think about the role of forests in mitigating rapid climate change. Unlike Foster Forest, MycroForest is a web application, making it more accessible with minimal setup. Its user-friendly, aesthetically pleasing design includes easily digestible guidance. MycroForest is also a microworld accessible to non-experts and young users, requiring only a standard browser, a desktop or laptop, and a stable internet connection.

<u>Tool 3 – MineSet</u> (Educational Game) [4, 65]

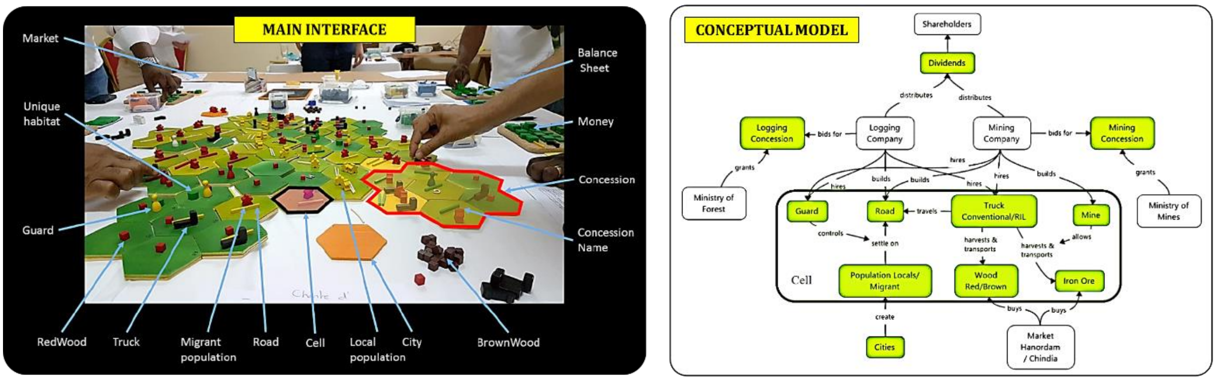

Figure 2. MineSet interface (left) and conceptual model (right). [4]

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 land use strategies effects of which are measured in terms of forest cover, biodiversity, and volumes traded. The underlying model captures 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. tested the game online with Forestry graduate students via Zoom, noting high engagement, effective learning, and development of realistic strategies. Participants indicated a need for a fully digital version of this game or similar ones as widely accessible and transformative learning tools [65].

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.
Implements model progression to slowly 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.

Like Mine Set, MycroForest prioritizes capturing causal links between system components over producing accurate real-life outcomes. This focus suits learning tools aimed at understanding management activities and environmental impacts rather than plant growth or carbon transformations. A simpler model makes the tool faster and more user-friendly. MineSet uses indicators such as landscape composition and species diversity, with a maximum value approach to categorize changes into mentally trackable categories. MycroForest mirrors this approach with range-limiting and color-coded categories for atmospheric CO_2 levels and biodiversity scores, enhancing the impact and clarity of these indicators. The idea that "learning begins when the game is over", is central to teaching tools like MycroForest and Mine Set where focus is on encouraging discussion around sustainable resource management. After playing the game Mine Set participants reported learning about (i) the system, (ii) themselves, and (iii) peers, thanks in large part to frequent group discussions. This reinforces the decision to have students use MycroForest in groups and interleave challenges with debriefing sessions.

Tool 4 – About That Forest (Educational Game) [5]

About That Forest is a multiplayer RPG where learners, as forest dwellers, draft, and vote on policies for tree harvesting or non-timber product sales. Players can also plant trees and monitor other players. Poor forest health leads to floods affecting the entire community. The game is available on mobile devices, browsers, and PC.

Pros	Cons
Underlying code allows for easily modifiable settings.	No big cons.
ComMod.	Underlying model and research not openly available.
Engaging.	
Competition in addition to cooperation.	
Multiple economic drivers of exploitation.	Atmospheric CO_2 levels is not a modelled indicator.
Widely accessible.	
Appeals to a wide age group and range of starting knowledge levels.	

Table 6. About That Forest – Pros and cons.

This tool highlights the economic drivers behind forest exploitation and the "tragedy of the commons," where profit-driven decisions lead to resource overuse and ecosystem collapse. MycroForest, like About That Forest, focuses on the economic viability of forest management and includes non-timber products as secondary revenue. MycroForest's click-through introduction on the landing page is inspired from About That Forest's text based introduction. Furthermore, About That Forest presents land as a grid with each cell possibly containing a tree whose icon changes to reflect its growth over time. This makes for a simple and informative display of land composition change. MycroForest thus, also adopts this visualization approach. Both About That Forest and MycroForest have one main indicator of climate change which 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 3. Forest Kids UI elements.

Forest Kids is a Unity 3D-based educational game for young children available on mobile (Android, iOS) and web. Players explore 4 forest types (boreal, tropical, temperate, arid) with a team of digital children and an alien, learning about flora, fauna, and forest ESs. The game has timed mini-games (picture matching, match 3, and spot the plant/animal) that earn points and add species to the player's collection, motivating continued exploration. It includes fun facts and lessons on the water cycle, greenhouse effect, days, and seasons. Interaction is primarily point-and-click/drag, with no planning or constructionist elements. The game is more explanatory than experiential.

Pros	Cons
Age appropriate for children.	No learning through making.
Visually very attractive.	Facts presented during matching and memory games are random and lack connection. This can make them hard to learn.
Great user experience with smooth interactions.	
Motivating mini games.	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 the facts as I focused more on memorizing tile symbols to get the matches right before the timer runs out to score maximum points.
Very informative and covers different topics related to forest biodiversity and Earth's climate.	
In-app help is well placed and provided in small, easy to absorb chunks.	
Text in the game is supported by audio readouts to make it easier to absorb for children.	
Facts are repeated from time to time but not too frequently. This may promote information persistence in memory.	

Table 7. Forest Kids – Pros and cons.

A key lesson from this tool is that games in educational tools should not distract learners. Unlike Forest Kids, MycroForest has no score or point system. Instead, competition is introduced by having students work in teams and compare strategies, aiming for the lowest CO2 levels or highest income. This approach ties the competitive activity back to forest management, reducing the chance of learners entering gamer's "twitch" mode. Similar to Forest Kids, MycroForest is age-appropriate for young adults and features custom artwork to enhance aesthetic appeal and improve user experience.

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 harmed by this. Another driver for prevalence of simulations in forestry is associated speed up of natural and ecological processes which makes it possible to appreciate the true gravity of the consequences of decisions made over time. These qualities make tools like MycroForest attractive for educational purposes. Also, all forest management related tools (Foster Forest, Mine Set, About That Forest) include timber harvesting as a primary revenue source and so, MycroForest follows suit. Another important lesson from reviewed tools is that good UX and a pleasing UI are crucial for user engagement. Thus, MycroForest adheres to HCI best practices.

Table 8 compares aforementioned tools (table columns) against each other w.r.t certain qualities (table rows). MycroForest, the resulting product, has been added to this table to analyse whether it possesses all qualities originally deemed desirable. Following points describe qualities.

- **Realistic:** Models the real world sufficiently well such that environment responses to forest management actions mirror real world observations.
- **Engaging:** Users find it engaging.
- **Easily Accessible:** Is widely accessible with minimal set up required.
- **For Youth:** Youth understand and use it with ease. They find it informative.
- **Team:** Facilitates decision-making that is satisfying to do collaboratively.
- **Solo:** Provides a rewarding experience for individual learners.
- **Focused Aim:** Does not try to do too many things at once. Focuses on few specific key ideas (e.g. forest management actions and atmospheric CO2 levels, forest management actions and economic gains/losses).
- **Forest Management:** Allows learners to make forest management decisions.
- **Forest As Carbon Sink:** Highlight role of forests as important carbon sinks.
- **Financial Motive:** Draws attention to financial motives that drive forest exploitation.
- **Low Entry Threshold:** Fairly easy to start using without getting overwhelmed.
- **Easy To Use UI:** Has good UX and a simple, easily navigable, not frustrating UI.
- **Sufficient Built-In Help:** Contains user-friendly, comprehensive, built-in user guides.

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 caveats)*

Many apps are scientifically accurate or realistic regarding plant growth models. This is true for decision-making aids like Foster Forest aimed at experts and simple explanatory tools like Forest Kids. MycroForest, however, uses a simplified conceptual model, assuming ideal growing conditions except for CO2 and generalizing plant species to coniferous or deciduous. This simplification is acceptable as MycroForest focuses on teaching the causal links between forest management and atmospheric carbon levels. Other tools like Mine Set, About That Forest, and SimForest also abstract plant growth details to emphasize broader behaviours or interactions. Of these, SimForest is likely the most detailed, considering more environmental factors like temperature, light availability, soil depth, and water capacity.

MycroForeset and SimForest do not have 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, a facilitator, and special SW downloads. Mine Set is a physical board game that needs setup and is best played in person. SimForest requires downloading and installing, which can cause compatibility issues. Therefore, compared to web-based or mobile applications like About That Forest and MycroForest, tools like FosterForest, Mine Set, and SimForest are less accessible.

Overall, MycroForest meets all intended criteria w.r.t this project. It is a sufficiently realistic, engaging, and accessible web-based teaching tool aimed at the youth. Although there is no multiplayer mode, both team and solo learning activities can be structured around it. Unlike many tools that try to do multiple things at once, MycroForest focuses exclusively on forest management, its effect on atmospheric CO2, and impact of financial motives. This app is built to be easy to get started and use with ample built-in help.

2.6 Summary

Research for this project involved a review of fields like forest management, education technology, simulation design, and human computer interaction, as well as analysis of 5 interactive tools with similar elements as MycroForest, the proposed teaching tool.

Key forest ecosystem services and management strategies were analysed, recognizing carbon sequestration and timber provisioning as crucial for MycroForest, which aims to educate about economic viability of climate-conscious forest management. The tool includes tree planting and felling as key actions affecting both timber production and CO2 levels, thereby influencing carbon sequestration. Rotation period was identified as a critical decision factor in forest management within MycroForest. While halting deforestation and promoting afforestation and reforestation are essential to combat climate change, forest owners often depend on forest income. MycroForest offers alternative income streams and presents challenges to inform about the importance of proforestation and reduced resource usage w.r.t slowing down rapid climate change.

Exploring education technology showed that microworlds are effective teaching tools due to their support for self-regulated learning rooted in constructionism, which promotes deep, persistent, and engaging learning. MycroForest, a simulation-as-microworld, incorporates gaming concepts and offers target setting, model progression, and challenges at various difficulty levels. This blend of simulation, microworld, and game elements has been linked to enhanced usability and learning effectiveness.

MycroForest needs to model tree growth, the carbon cycle, and effect forest management plans created by learners. So, different simulation paradigms were studied. A hybrid simulation approach was adopted. MycroForest uses ABS to model tree growth and carbon transfer with 1 year time step time advancement while DES is used to incorporate forest management decisions taken by learners. Ensuring interoperability between different simulation approaches is difficult. MycroForest manages this through adoption of object oriented design which also upkeeps software quality.

Research suggests that good human computer interaction is key to effective education. To this end, MycroForest presents an active, unimodal, and thereby less distracting, pleasing UI that tries to incorporate best practices based on known good HCI principles like Norman’s model and Jacob Nielsen's usability heuristics.

Examining 5 similar tools informed the design of features in MycroForest, like timeline controls, forest representation, and climate change indicators. It also suggested elements to avoid, like distracting gamification, unrealistic updates, and a steep learning curve. The result is a realistic, engaging, and accessible web-based tool that offers a rewarding individual or group learning experience focused on forest management, atmospheric CO2, and underlying financial motivations, tailored for young adults.

3 Design

This section describes the scope of this project, pedagogical approach adopted, current UI, HCI best practices application, system architecture and technical details.

3.1 Scope

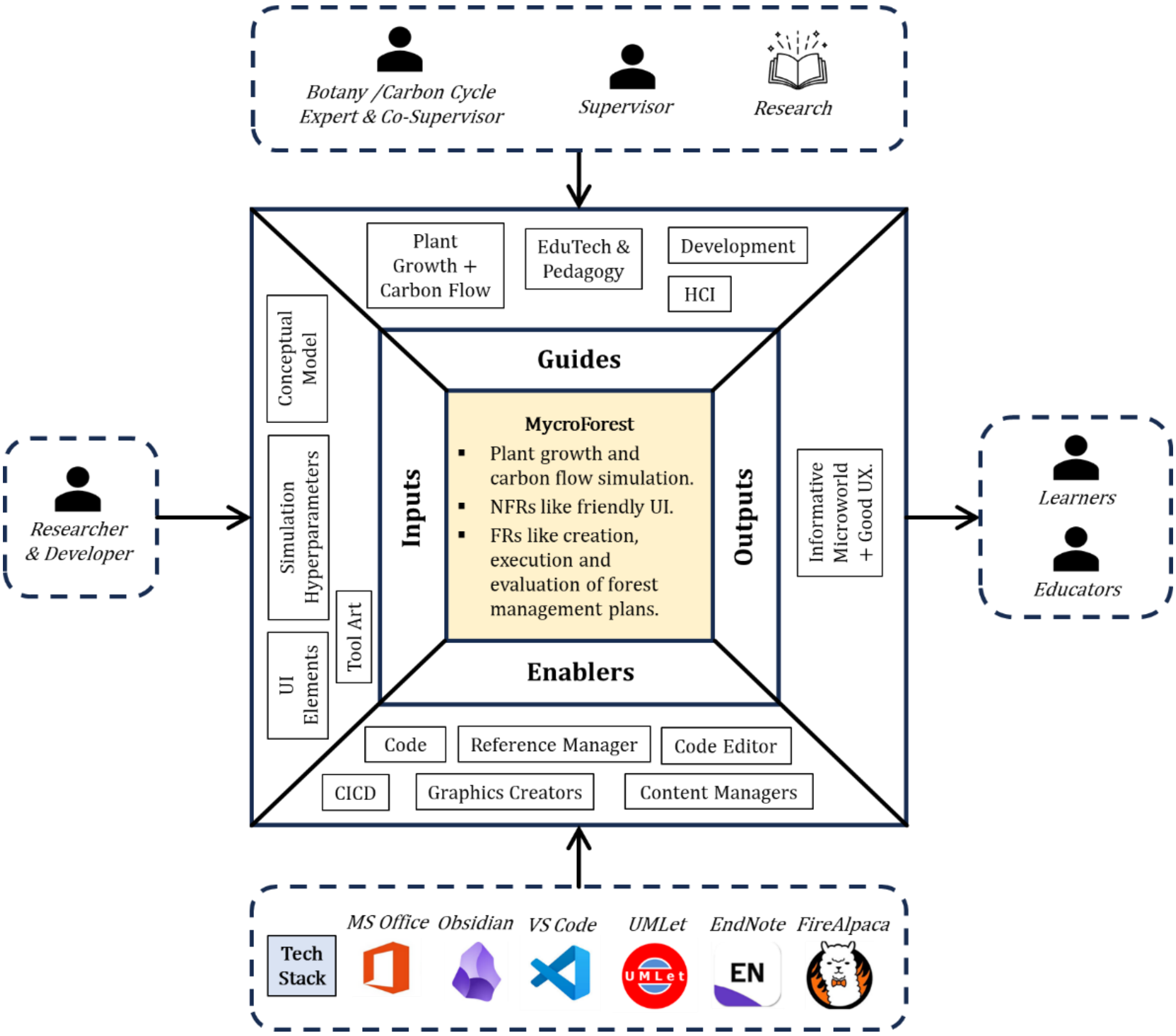

Figure 4. Scope diagram [69] with core focus in the middle.

Deliverable Name [70]**:** MycroForest.

Project Justification [70]**:** Project objectives are as follows.

- Research EduTech, simulations/microworlds, forest management, and climate change to develop a user-friendly tool that informs youth about the role of forests as carbon sinks and economic factors driving resource exploitation through SRL.
- Evaluate the tool w.r.t educational value, learner engagement, and usability based on feedback from students and faculty who use it at the Bridge2College program.

Scope Statement [70]**:** MycroForest is designed for learners to explore climate-aware forest management by creating and executing their own management plans and analysing its impact on a virtual forest environment. It will not model biochemical processes like photosynthesis but will illustrate realistic cause-and-effect relationships between management actions and carbon levels as is sufficient for the associated educational purpose. Users will have limited access to plant growth or environmental parameters, focusing instead, on management actions like planting/harvesting.

- **In Scope:** MycroForest provides a virtual forest that evolves based on a hybrid simulation model where learners can create, execute, and analyse management plans and means of income generation via non-timber products or visitor permits. The UI shall adhere to HCI and data visualization best practices.
- **Out of Scope:** Due to time constraints and the interdisciplinary nature of the project, forest growth and carbon flow models are simplified and not biochemically accurate. They focus on variables affecting the carbon cycle using high-level averages from real-world data and assume other conditions to be ideal (e.g. factors like sunlight, temperature, and soil nutrients are not explicitly modelled since do not directly influence the simplified carbon cycle). Since the primary focus is forest management, learners may only update model hyperparameters via management plans and cannot alter values like max tree height, soil carbon release rate, etc. directly. These values are pre-defined based on research and expert opinions from Dr. Silvia Caldararu.

FRs & NFRs: Below are functional and non-functional requirements prioritised using the MoSCoW scale wherein priority categorization = Must > Should > Could > Would [71].

#	*FUNCTIONAL REQUIREMENT (FR)*	*PRIORITY*
1	System shall allow creation, editing, and deletion of forest management plan actions.	MUST
1.1	System shall enable users to make following decisions regarding each forest management action: (i) Action type = Plant / Fell. (ii) Tree type affected = Age, Species. (iii) No. of trees affected. (iv) Action execution time. (v) 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 about action execution status (full/partial success, 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 CO2 in air in a color-coded manner where colors stand for expected quality of human life at that CO2 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 some 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 income and expenses breakup among 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 a web application with wide accessibility needing minimal set up. It should work well on at least Firefox, Chrome, Edge, Brave, and Opera browsers on modern PCs/laptops.	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

Table 10. MycroForest - Non Functional Requirements (NFRs)

Key People & Technologies

The project team included a researcher/developer (author), Dr. Brendan Tangney – a Computer Science professor at TCD specialized in Educational Technology as supervisor, and Dr. Silvia Caldararu – a Botany, Climate Change, as well as Carbon Cycle expert as co-supervisor. Key tools used were MS Word, MS Excel, MS PowerPoint, Obsidian, FireAlpaca, VS Code, UMLet, and EndNote. MS Word was used for this writeup, MS Excel for organizing tables and spreadsheets, and MS PowerPoint for creation of figures. Obsidian helped manage interlinked personal files, UMLet enabled UML diagram creation, FireAlpaca was used for creating artwork for MycroForest, EndNote managed research references, and Visual Studio Code served as code editor.

Working With Domain Experts

Throughout 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, an expert in Education Technology reviewed UI and learning activity designs to ensure an engaging and appropriately challenging experience for young adults. Periodic meetings with him allowed discussion of project artifacts as part of the Agile workflow's analysis phase. He was always available at times of need and skilfully identified whenever research/development was off-track as well as advised refocusing on priorities. Below are few specific examples of his valuable contributions.

- Initially the option to add management actions within a rotation period was excluded, assuming it to be too complex/confusing. However, Dr. Tangney suggested that allowing management actions, during intermediate years would be both interesting and intuitive for learners. This was recognized and implemented. It later led to learners discovering the management strategy of thinning for themselves.
- He noted an inconsistency in an early version of the application where both the total bank balance and money-related target were labelled as "funds." This violated Jacob Nielson's Usability Heuristics rule (iv) and could cause confusion. Thus, UI was edited by renaming the income target setter and bank balance more distinctly.
- During Bridge2College learning session discussions, 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 recommended designing challenges that allow learners to use target-setting features to compete in groups. This inspired the idea of having student teams compete to achieve higher income targets or lower CO2 levels. Based on healthy enthusiasm observed at student discussions, this made the activity more enjoyable.

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 carefully reviewed the plant growth and carbon flow model to ensure sound simulation design and reflection of reality. She also shared feedback regarding the UI. Below are few specific examples of her contribution.

- The initial carbon flow model excluded soil carbon, focusing only on air, vegetation, and fossil fuels. Dr. Caldararu recommended including soil, emphasizing its critical role in regulating atmospheric carbon levels.
- She also recommended exploring different wood uses which affects amount of carbon released. This led to incorporating harvested wood use for energy production v/s as lumber, thereby considering how HWPs can lock away carbon and increase net carbon sequestration if not burned and new growth replaced felled trees.
- Initially, hunting/fishing was another income stream. Dr. Caldararu advised that this may take away from the SFM learning outcome, as this income stream is often abused causing forest biodiversity loss, adversely affecting forest resilience. Thus, it was decided not to present hunting/fishing as a climate-friendly income source.

- Dr. Caldararu suggested implementing a "developer mode" to track key variables like "carbon absorbed", "tree life stage", etc. such that it may be saved and visualized for fault diagnosis. This feature was implemented. Individual tree data (stress, carbon absorbed, life stage, etc.) and environment data (carbon per reservoir, atmospheric CO2 concentration, etc.) can be recorded and saved as CSV files to later be visualized using Python libraries like pandas, NumPy, and matplotlib. This made error detection faster. Figure 5 shows screenshots of this dev mode, including activation in the utils.js file, data saving using the button on the timeline, and data visualization.

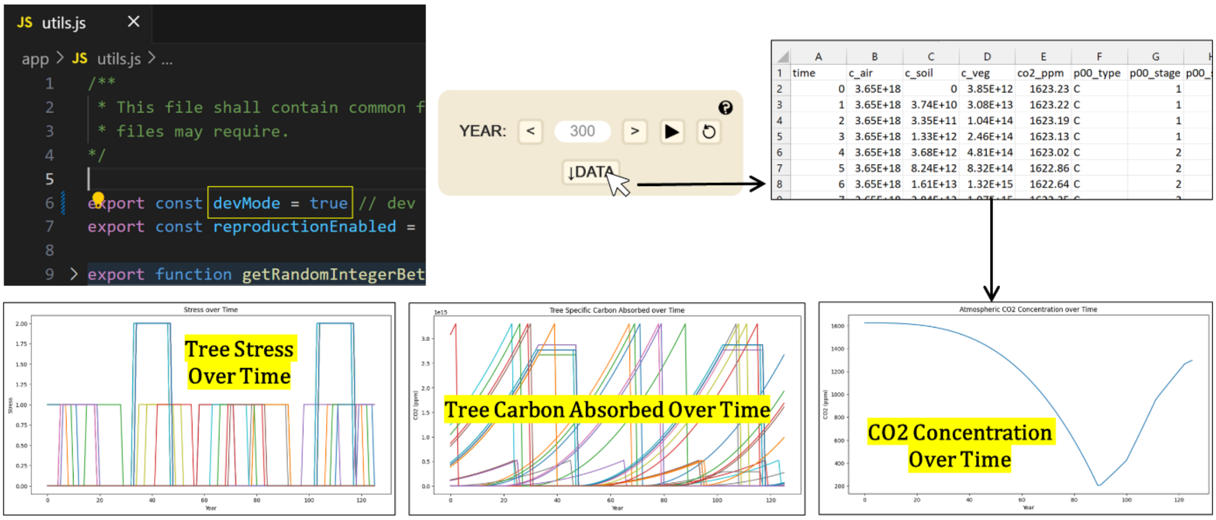

Figure 5. Dev mode.

3.2 Pedagogical Approach

As discussed in section 2.2, hybridization of microworlds, simulations, and game theory in EduTech improves learning. Well-designed simulations offer informative, relatable representations of real-world systems. Microworlds present many ways to interact with and manipulate model parameters. Exploration of a microworld providing timely and appropriate types of feedback is an absorbing experience. Ability to build virtual constructs in the microworld invokes a sense of control. Gamification through target setting, multiple challenges, and model progression keeps learners appropriately stimulated. Finally, a narrative can add fantasy/role-play which frees learners of other worries and self-consciousness. Thus, skilful hybridization leads to learning environments that agree with frameworks like FTOE and therefore, likely better caters towards SRL than does any approach (simulation, microworld, game) on its own.

All microworlds contain interactive OTTW. They support learning by allowing variable manipulation or facilitating outcome exploration. By this definition, each panel on the world and planner page in MycroForest is an OTTW. The planner page includes OTTW for forest plan and income stream management, while the world page features panels for target setting, time navigation, and fossil fuel usage. All other panels on the world page are also OTTW due to their role in graphically reflecting internal state changes.

Table 11 below, summarizes main EduTech ideas from section 2.2. Following paragraphs explain how MycroForest design elements and intended learning activity tries to adhere to identified pedagogy best practices w.r.t a gamified simulation-as-microworld.

Piagetian Learning Theory (PLT)	**Good Practices (GP)**
(i) Epistemic conflict.	(i) Structure learning activities around challenges for gamification.
(ii) Self-reflection.	(ii) Multiple challenges with varying difficulty improves likelihood of learners finding an optimal difficulty level.
(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 11. Pedagogy best practices.

Land plot content icons are updated per simulation timestep with a 100 millisecond delay, reflecting changes w.r.t time and planned forest management actions. Action execution status appears colour coded in the plan viewer as well as planner. The monel panel gets updated with virtual money earned/spent. Colours and a number get updated to reflect atmospheric CO_2 concentration changes. Green/red colour indicates Achieved/failed status of targets. Finally, text box entries turn red to indicate erroneous input. Feedback within MycroForest is primarily graphical. Both a dedicated help page and short multimedia (text + image) user guides upon clicking easily accessible ❓ symbols associated with each world/planner page panel is also available. All these features cater towards GP (v), PLT (ii), and FTOE (ii, iv, vi).

Further, Good UX is essential to prevent frustration (GP (iv)) that impedes learning. Research was conducted on HCI best practices. Principles from Norman's Model, Task-Core Language Mapping, and Jacob Nielsen's Usability Heuristics was applied alongside data visualization knowledge to enhance usability. Simplifying assumptions w.r.t the simulation model also helped ensure a fast and smooth UX.

This teaching tool may be used by students in the presence of a qualified facilitator as mid-activity guidance promotes correct learning. The learning activity can also be split into short parts, each having a slightly different goal/theme with group discussions held in-between so that learners may interact with tutors and peers, which also allows tutors to ensure correctness of learner mental models. This activity structure aligns with GP (vii, viii), PLT (ii, iii), and FTOE (ii, iv, v). Furthermore, learners may compete in teams to develop forest management strategies that meet specific goals which can later be analysed and discussed amongst all and the facilitator. This can be motivating and enjoyable, thereby satisfying GP (i) and FTOE (ii, v, viii). Also, MycroForest allows learners to set maximum air CO_2 concentration and minimum rotation income targets with colours green or red indicating success or failure respectively. This facilitates self-evaluation/monitoring and thus, aligns with FTOE (i, iii, iv, vi) and PLT (ii).

Ensuring learning from microworlds requires structure. This can be achieved by presenting challenges with specific goals, which guides the thought process and adds gamification to maintain motivation. MycroForest includes 5 challenges with increasing difficulty. The interface displays only those UI elements, controls, and use guide material essential for each challenge, hiding others to aid model progression. This approach aligns with GP (i, ii, iii, vii), FTOE (i, ii), and PLT (i). Table 12 summarizes implemented challenges. To switch between them, facilitators are to press Ctrl + Alt + 1, 2, 3, 4, or 5.

	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 a profitable resource. This motivates deforestation. # Generally, forest management activities are performed in rounds.	# Plan to 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 sequester carbon. # Mature/older trees are imperative to keeping atmospheric CO2 conc. low. # Mature trees absorb more carbon as they grow. But older trees store more CO2. # Chopping bigger old trees releases more CO2 at once than chopping smaller young ones. # Clear felling is a bad strategy. # Thinning is a better idea. # Best strategy is no management.	# 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 conc. ideal.	Challenge 2 Features + Money Viewer	# It is impossible to keep CO2 levels in a safe range without lowering profit margins.	# Set CO2 and income targets. # Tweak plan and see if targets are achieved. # Report lowest CO2 + highest Income combination achieved.
Challenge 4	How long before fossil fuel usage leads to critical CO2 levels (red)? How to delay this?	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 emissions to current global level of 10 GtC. Count years before CO2 level is critical and the entire forest dies. # Tweak plans to see if 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 as profitable or reliable as timber. # There is a need for more ways to earn from a forest without felling trees. # Income streams like forest recreation requires building infrastructure and thus large initial 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 12. Learning activity challenges implemented in MycroForest.

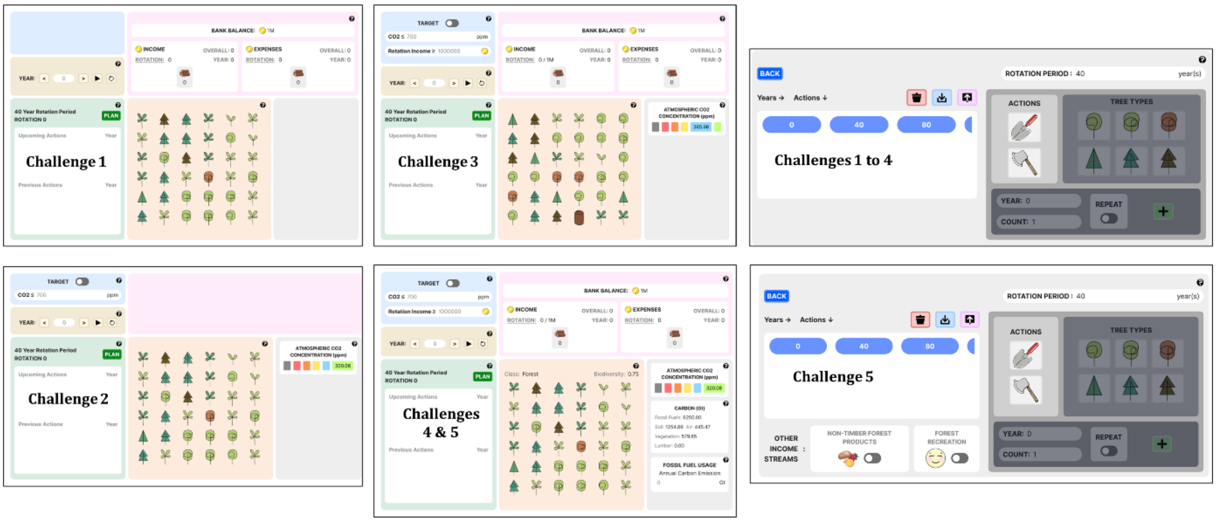

Figure 6. UI gradual feature reveal over 5 challenges.

Implementing problem-based, reflective, and inquiry-based learning via supportive class climate, peer interactions, and teacher-learner relationships enhances retention of learned values and information [11]. MycroForest supports these conditions with target setting, immediate feedback, and challenges coupled with discussion opportunities.

Lastly, research suggests that young learners appreciate a good story/premise for the learning activity (GP (ix), FTOE (vii)). Hence, the landing page incorporates an interactive exercise to spark interest followed by a quick click-through introduction that welcomes the learner with a narrative, setting the scene for the activities to follow.

Challenges in MycroForest are inspired by the Hero's Journey storytelling framework introduced by Joseph Campbell, a professor of literature at Sarah Lawrence College, in his work "The Hero with a Thousand Faces". Unlike traditional storytelling, wherein the audience follows a character, MycroForest allows learners to experience the journey themselves, as a hero who embarks on an adventure, faces trials, encounters a crisis, and ultimately returns home transformed, with new insights [72, 73]. In MycroForest, the learner is the hero, and presented microworld is the special world. The landing page and introduction serve as call to adventure. Faculty and peers assist, as learners navigate the tool. Challenges 1 to 3 are smaller trials, while 4 and 5 present a crisis by introducing all app features, including anthropogenic fossil fuel emissions. Learners would realize that balancing high income from timber with low CO2 levels requires compromise. The goal is for them to understand that albeit less profitable, SFM is possible with low carbon emissions and limited deforestation. The experience aims to increase awareness of forestry practices, the role of forests in CO2 control, and the need to reduce carbon emissions, potentially inspiring learners to be more climate-responsible and further explore SFM.

Please find an image Mapping the Hero's journey framework to the learner's UX in MycroForest in Appendices 8.3.

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 upon mouse hover with the cursor acting 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.

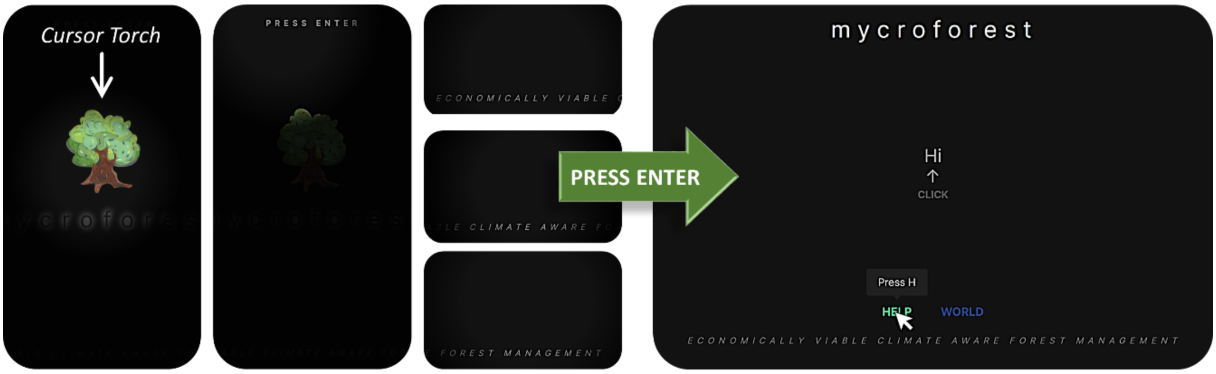

Figure 7. Landing page. Left: Interactive mouse cursor torch reveal content. Right: Introductory content that is revealed upon pressing the "Enter" key.

Clicking on “Hi” begins a dialogue which progressively introduces the learner to the app. The first time a user starts this click-through session, they must complete it. Attempting to move to other pages mid-way, causes a message to appear – “Your enthusiasm is much appreciated, but I’m not done yet. Please continue clicking. I promise this won’t take long”. When the learner clicks on the text, it fades to reveal the next dialogue until the last one is reached. Each dialogue serves a purpose. E.g. the dialogue “The forest is healthy and fairly large. I’d say it’s a good size for a first time forest owner like yourself.” suggests to the learner that they will be assuming the role of a forest owner.

Please find the full dialogue in Appendices 8.4.

Help Page

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 opens a pop-up window with text and images describing that component and how to interact with it. Each leaf shaped node may be dragged such that the others follow in a fluid motion. This adds an element of fun such that learners may to stay and explore topics.

Figure 8. Help page with interactive graph. Double clicking a leaf node reveals pop-up text and graphics explaining significance and use of associated microworld component.

World Page

Pressing "W" 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.

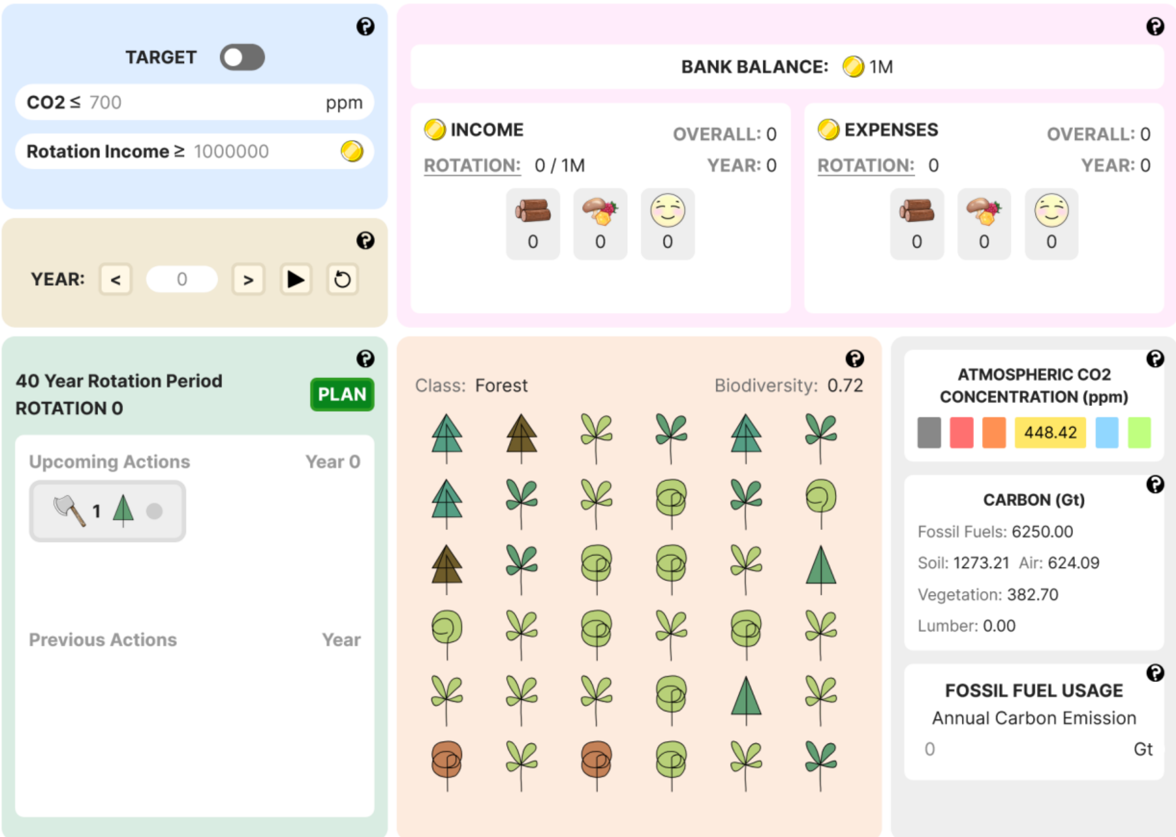

Figure 9. World page. This is the tool's main GUI.

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 which may either contain a tree or be empty. Hovering over land content reveals its type at the bottom of the plot.

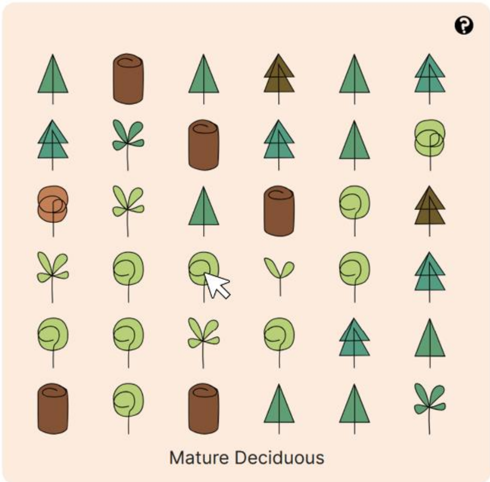

Figure 10. Land plot with mouse over interaction.

Timeline

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

Figure 11. Timeline controls.

Clicking the PLAY BUTTON runs the simulation. The number displayed changes to reflect each new timestep. Once clicked, the play button changes to a PAUSE BUTTON. Clicking the pause button halts 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.

In the TEXTBOX, learners may type in any year within simulation range (0 to 300 years) and the microworld jumps to it. Upon entering some input, the play/pause and reset buttons change to a CONFIRM BUTTON and CANCEL BUTTON. Clicking the confirm button applies the year change 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.

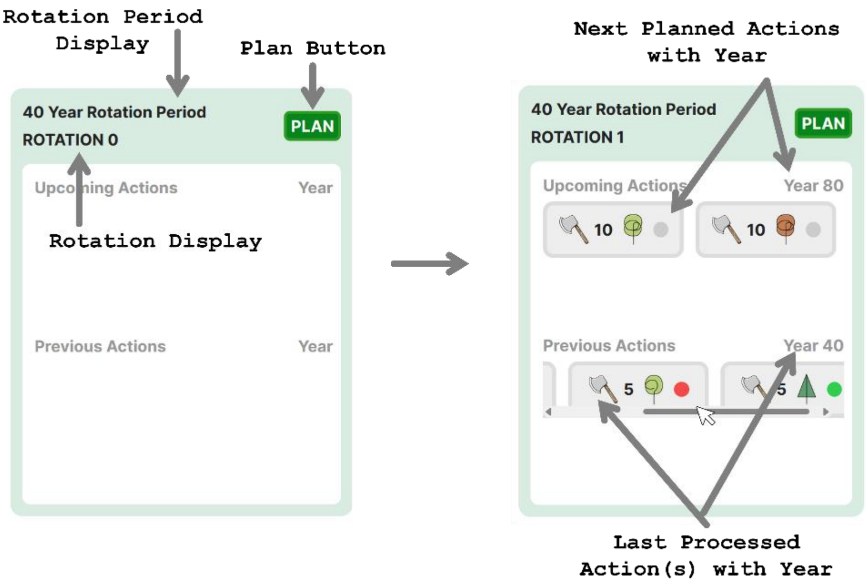

Figure 12. Plan viewer interactions.

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. EXPENSES refer to coins the learner has spent overall, this year, and this rotation.

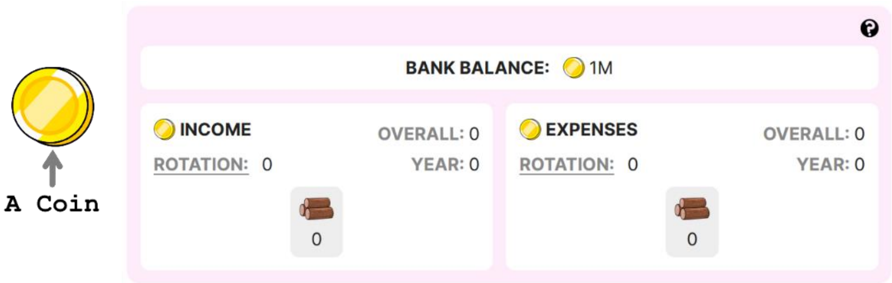

Figure 13. Money panel overview.

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.

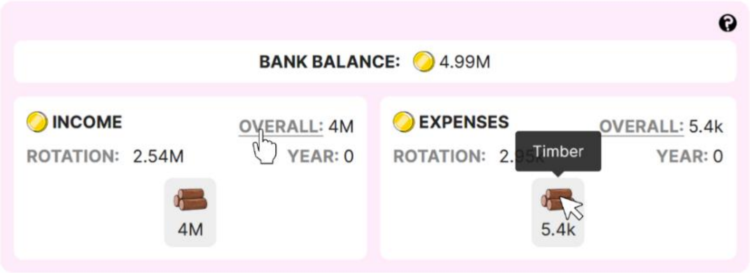

Figure 14. Money panel interaction.

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.

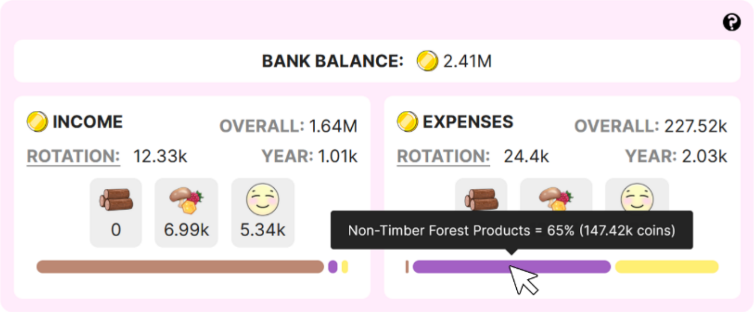

Figure 15. Income stream breakup.

CO2 Scale

Natural processes like respiration and human activities such as burning wood or fossil fuels release carbon into the atmosphere, mainly as CO_2. In the microworld, CO_2 concentration is displayed on an easy-to-read scale, with each band labelled to indicate expected quality of life at that CO_2 level upon considering climate change. Current CO_2 levels during the simulation are shown in the ATMOSPHERIC CO2 CONCENTRATION panel. Hovering over each tile reveals band range and associated quality of life label.

Figure 16. CO2 concentration display panel.

Targets

Learners may set targets. The TARGET panel displays and facilitates this.

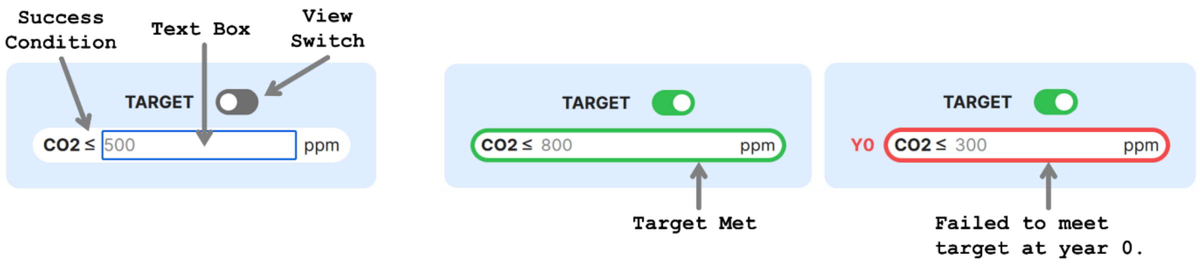

Figure 17. Target panel interaction.

Learners can set a minimum CO2 concentration in the TEXTBOX, below which levels must not drop. The VIEW switch can be toggled on/off. When on, the target panel shows whether target is met, with a green border for success and a red border for failure. The first year of failure is also noted (e.g., Y2 for Year 2). Similarly, target income value can be set, indicating min income per rotation. If target is not met, the rotation where the failure first occurred is displayed with the notation "R" followed by the rotation number.

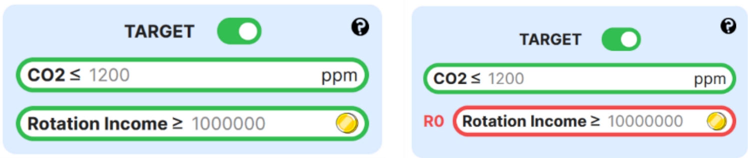

Figure 18. Income target met and failed display.

Fossil Fuel Usage

The FOSSIL FUEL EMISSIONS panel both displays and allows learners to set amount of carbon released into the atmosphere annually due to humans burning fossil fuels. By, default, this is 0 GtC but, can be changed by typing any positive whole number.

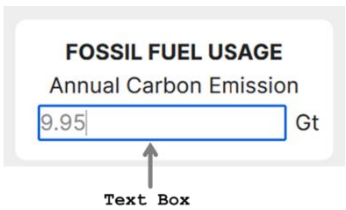

Figure 19. Fossil fuel emissions panel.

Carbon Composition Display

The carbon panel displays exact amount of carbon in each reservoir throughout the simulation. There are 5 carbon reservoirs. Amount of carbon is expressed in Gigatonnes (Gt) of Carbon (1 Gt = 10^{12} kgs).

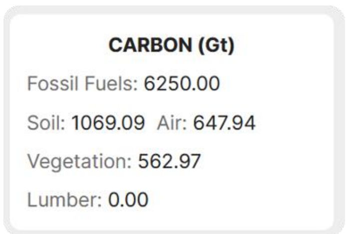

Figure 20. Carbon distribution panel.

Planner Page

The world page contains a "PLAN" button leading to the planner page. The MANAGEMENT ACTION PLANNER here, allows forest management plan creation involving planting or felling trees and activation of other income streams. The "BACK" button returns the learner to the world page.

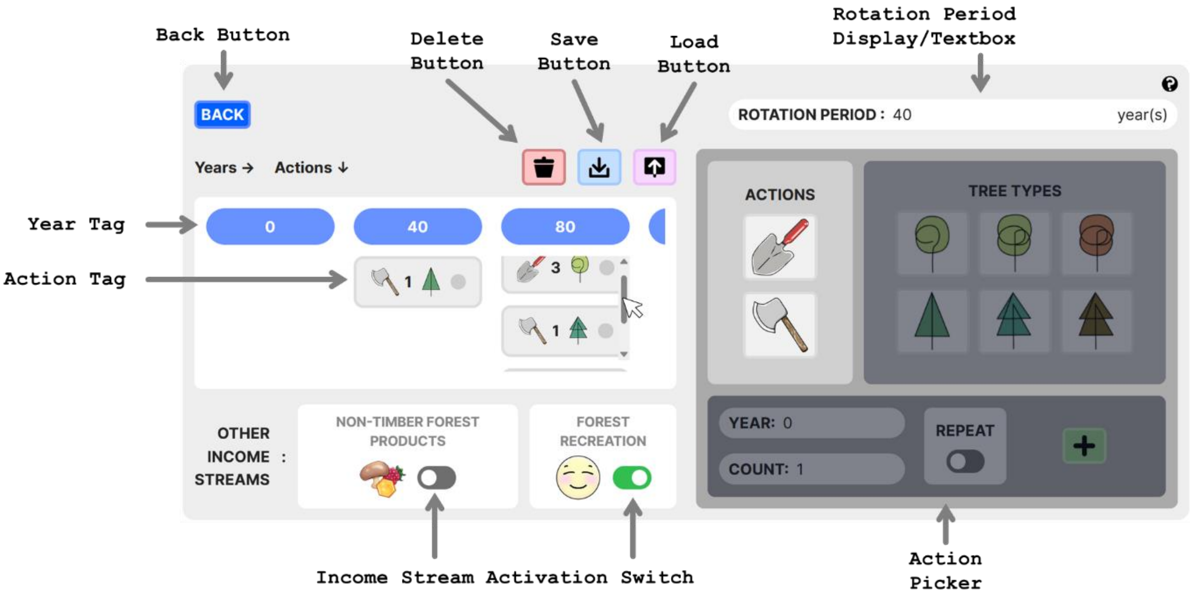

Figure 21. Planner page that contains a GUI that facilitates forest management plan creation.

There are 2 possible management actions: (i) **Felling:** Only mature, old growth, or senescent trees may be felled. Depending on size of the tree, it can cost up to 3000 coins to fell it. Income fetched from the felled tree will depend on its wood density and size. Nevertheless, felling a tree always generates some income from timber sales. (ii) **Planting**: Irrespective of tree life stage chosen from action picker, planted trees start out as seedlings. Planting incurs a fixed cost of 277 coins.

To add actions, first, action type must be selected. Then, tree type (species and age) and finally, maximum no. of trees to be affected and the year when this action is to be executed. If invalid numbers are entered into text boxes, that change is not applied and text turns red. If REPEAT switch is on, picked action will be performed every rotation starting that planned year. Finally, 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 $\geq$ 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 rotation period value update.

Blue year tags represent years at the beginning of each rotation as per set rotation period. The view frame is horizontally scrollable. ACTION TAGS added using the ACTION PICKER will appear under their corresponding year tags such that under each year tag, they are vertically scrollable in case of view frame overflow. Clicking an action tag, selects it. Clicking a selected tag, deselects it. Multiple tags may be selected at once. Selected actions can be deleted by clicking the DELETE BUTTON. Double clicking this button deletes all planned actions. Clicking the SAVE BUTTON saves current system state along with learner decisions. The UPLOAD BUTTON allows saved state loading.

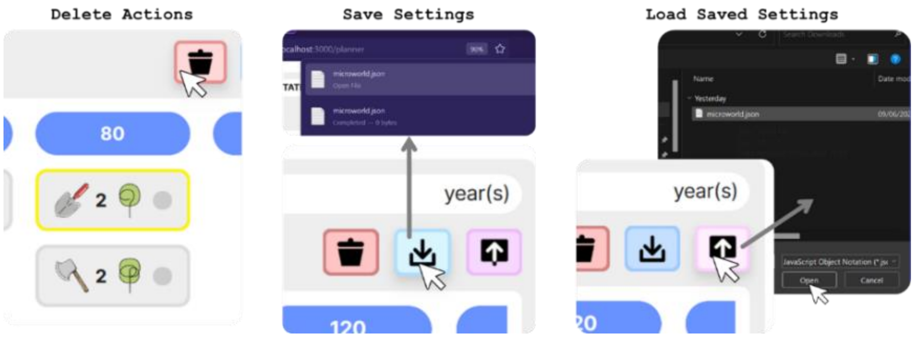

Figure 22. Management action planner. Delete actions and save or load plans interaction.

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.

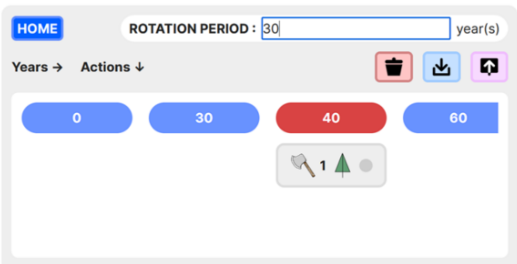

Figure 23. Within rotation action coloration difference.

Action tags display information about corresponding actions and their execution. If an action was successful for all planned no. of trees, then status is green. If it was only possible to execute it for a fraction of originally specified no. of trees, then status is yellow. A red status indicates that the action could not be executed at all. Actions may not get executed for some trees if the specified tree type does not exist on land at the planned moment, or if there are insufficient coins to fund the action.

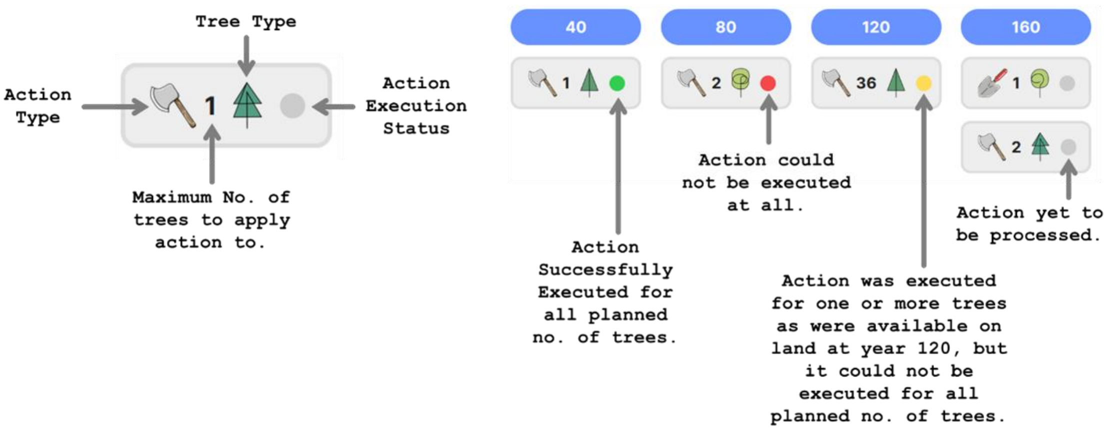

Figure 24. Significance of action tags.

Income can be generated via the TIMBER INCOME STREAM by selling wood from felled trees. When the fell action is successful, harvested timber is sold and gets used. Learners may also harvest and sell other forest resources like honey, mushrooms, and berries through the NTFP INCOME STREAM or open the forest up for public recreational use and earn through visitor permit/ticket sales via the RECREATION INCOME STREAM. Switching on the corresponding switch activates each income stream.

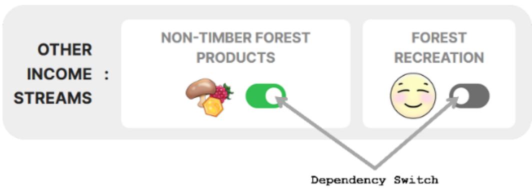

Figure 25. Other active and inactive income streams.

3.3.2 HCI Principles

Table 13 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 without irrelevant information.
(ii) Intention formation.		(ii) Speak the user's language.
(iii) Action sequence specification.	(ii) *Performance* – System interprets user actions correctly and responds appropriately.	(iii) Minimize memory load.
		(iv) Maintain consistency.
(iv) Action execution.		(v) Provide timely and apt feedback.
(v) System state perception.	(iii) *Presentation* – System presents updated state.	(vi) Clearly mark exits.
(vi) System state interpretation.		(vii) Incorporate shortcuts for expert users.
	(iv) *Observation* – Users update mental model based on presented changes.	(viii) Display good error messages.
(vii) System state evaluation.		(ix) Design to prevent errors.
		(x) Ensure help is readily available.

Table 13. HCI principles summary.

Norman's Model & Task - Core Language Mapping: *ARTICULATION* → MycroForest incorporates Norman's Model. It allows CO2 and income ***goal*** setting. Learning activity challenges guide learner ***intentions***. Users interact through forest management plan development. The management action planner offers an action picker and plan viewer, simplifying the creation and immediate viewing of plans. This aligns with Norman's Model ***principle (iii)*** by making it easy to view or edit plans. Further, MycroForest allows learners to trigger ***action execution*** and step through plans easily using the timeline's play, pause and step buttons. *PERFORMANCE + PRESENTATION* → Land plot, money viewer, CO2 panel, carbon panel and targets panel all reflect **system state** changes after each timestep so that users may ***perceive*** all relevant plan consequences. MycroForest strives to cause-effect interpretation easy. *OBSERVATION* → Thus, an option to pause and replay the simulation or jump to specific points in time is provided to help investigate plan effects on the virtual forest. Furter, starting forests and plans may be saved/reloaded. Action execution status is also presented. Land content change is graphically displayed and animated as the simulation runs to facilitate change detection. All these factors hope to support ***learner interpretation*** of the system. Lastly, and CO2 panels use colour to indicate condition idealness, helping learners ***evaluate*** system state.

Jacob Nielsen's Usability Heuristics: Role of text in MycroForest is largely explanatory only as the UI on main pages (world/planner page) is graphics heavy. The learner only encounters text paragraphs when learning to use the tool via either ❓ icons or the help page. ***Language*** of text is kept ***simple*** for easy comprehension by youth. Icons depict ***familiar***, largely unambiguous items (e.g. axe = fell a tree, chopped logs = timber, plus = add, dustbin = delete, etc.). Stylized tree icons encode information like species and life stage. Interactive elements are common (buttons, text boxes, switches, scrollbars, hover, click, double-click, keypress) and likely familiar to learners. The planner page plan viewer displays world page actions and action execution status on the world page gets reflected on the planner page, improving decision consequence monitoring/evaluation. World settings (plan, targets, initial forest composition, active income streams, management actions) can be saved and reloaded. Learners can thus worry less about keeping plans in ***memory*** and focus on interpreting results. All terms in MycroForest mean the same thing on every page. Display language (graphics and text) is kept ***consistent***. The tool provides immediate ***feedback*** upon time update and action execution by with state changes reflected on the UI. 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. No shortcuts are implemented. ***Erroneous*** text box inputs are met with text turning red or a red border indicating this. Further, there are measures in place to ***prevent errors***. E.g. it is not possible to load the planner page without having navigated there from the world page. This prevents state corruption. Comprehensive built in ***help*** is available in bite sized chunks to inform but not overwhelm.

3.3.3 Data Visualization

Note: Below content is based on knowledge from lectures and material put together by Prof. John Dingliana for the CS7DS4/CSU44056 – Data Visualization module undertaken by this author at TCD as part of the MSc. Computer Science (2023 – 24) course.

Centuries of research suggests that sight is the most important human sense [74]. Thus, data visualization is integral to SW design. Content presentation greatly influences mental model of a system and rate at which viewers develop the right understanding.

What?

In MycroForest the simulation model is, the dataset. Dataset type is temporal as system state changes over time. The model is visible to the learner via displayed system state variables and thus this is ***what*** is visualized. Different data types benefit from different visualization methods. Broadly, data may 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), or ordinal (ordered; e.g. small, medium, large). Table 14 identifies key data attributes in MycroForest that are to be visualized and their types.

Data:	Years	Tree Type	Tree Age	Tree Position	Income
Description:	Current year in simulation.	Coniferous or deciduous.	Age of the tree.	Tree (x, y) position on land.	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.	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.	Success, partial success, 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 14. Visualized data attributes and their types.

Why?

Data visualizations serve 2 purposes: explanatory or exploratory. Explanatory visualizations convey a known data story, while exploratory visualizations present all data for the viewer to investigate. In MycroForest, since the model is based on informed research and resembles a known system, ***purpose*** of data visualization is ***explanatory***. Task abstraction is a 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 viewers may perform (verbs) on certain target potions or characteristics (nouns) of visualized data. Following are 3 action – target task abstraction examples (actions are blue, targets are magenta).

- Prospective business owners might analyse consumer trends regarding their product and consume information as they discover key customer bases. They may produce own data about striking features in the dataset. E.g. annotating customers by derived age categories might reveal that most of them are millennials.
- Doctors may search a brain scan to look up and confirm shape of the frontal lobe, locate the hippocampus, browse for known neural activation paths, or explore to look for unexpected abnormalities.
- An air crash investigator might query flight data to compare it with data from past crashes to identify similarities. They may summarise instrument readings from normal flights by plotting distributions and extracting extremes like min and max values to see if crash related values are outliers.

Similarly, using MycroForest, learners may produce forest management plans and compare results 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, forest income, biodiversity score, etc. Learners may explore different strategies as they browse through varying values for other settings like rotation period length and activation of income streams to locate plans that achieve goals like carbon sequestration maximization, income generation maximization, etc. In the process, they learn about challenges and best SFM practices.

How?

Visualizing data involves selecting suitable encoding channels, which refer to graphical element characteristics. There are 8 channels: position, shape, size, brightness, colour, orientation, texture, and motion. They can be selective (easy to distinguish), associative (support grouping), ordinal (show order), or quantitative (allow quantification). Range of a channel refers to no. of distinct data point types that it supports. Multiple encoding channels can be used in the same visualization. Some combinations, like position + colour, offer better visual separability than others, like using multiple hues of the same colour. Once chosen, encoding channels are incorporated into visualization idioms which are essentially types of graphs (e.g. scatter plot, line plot, pie chart, etc.). Idioms may also show changes, facilitate selection, and exploration. Multiple idioms may be combined through juxtaposing, partitioning, or superimposing. Further, they also handle complexity by incorporating 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” well enough to inform without distracting or overwhelming the viewer.

Following paragraphs justify some data visualization choices in MycroForest.

Most data attributes in MycroForest get updated as the simulation runs. This change is captured through animation via the motion encoding channel. Land content icons, action tags, and all numbers (money, CO2, carbon, etc.) get updated per time step.

The **land plot** visualizes Tree Age and Tree Type. Trees can live up to 100 years and remain on land longer after death. To avoid overwhelming the viewer, trees are grouped into 6 age categories, with precise details revealed on hover. Biodiversity score ranges from 0 to 1 and is categorized into “Unforested,” “Plantation,” “Forest,” or “Ecosystem” for better differentiation. Figure 26 shows how both colour and shape were varied to distinguish between tree type – life stage groups. Dead trees use the same symbol for both species since behaviour after death is same regardless of species. The land grid in MycroForest (6 rows by 6 columns) fits a scatter plot idiom which encodes tree positions. Changes over time are animated using the motion channel.

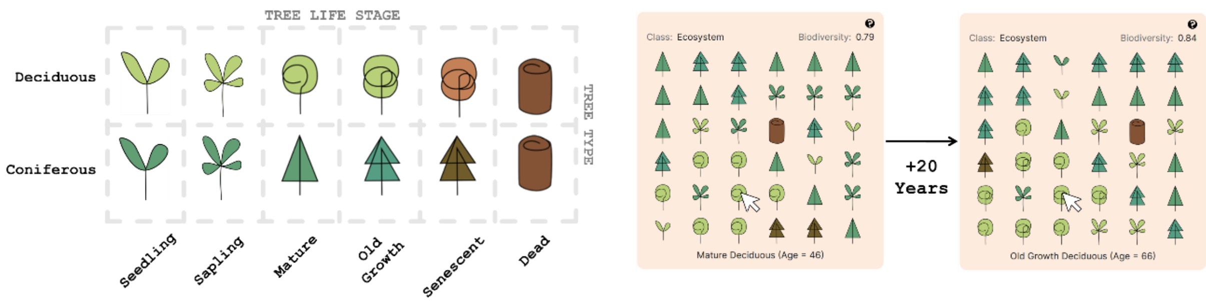

Figure 26. Land plot visualization that leverages colour, shape, position, and motion encoding channels.

The **money viewer** shows Income, Expenses, Total Money, and Is Income Stream Active, with numbers limited to 2 decimal points as greater precision does not add educational value. There are 3 income streams (Timber, NTFP, Recreation) and 2 figures (income, expenses) that change over time, creating high data complexity. Total bank balance and overall figures are shown in text, but data is grouped into 3 time-based levels (overall, this year, this rotation) for concise clarity. Only active income stream figures are displayed. A stacked bar chart is used to show stream wise contributed proportion. Hovering over bars reveal details like stream name and specific value of coins. When there is more than 1 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. All these figures get updated per timestep. Thus, the money panel uses 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 leveraged to manage complexity.

Figure 27. Money panel visualization that leverages colour, size, position, and motion encoding channels.

The **planner** and **plan viewer** visualize forest management plans by learners. Management actions comprise 5 data attributes (Action Type, Action Tree Affected, Action Num Trees Affected, Is Action Successful, Action Year). There are 2400 possible actions. Complexity stemming from high dimensionality was reduced as follows.

- Encode 4 action attributes into one symbol, using colour to indicate execution status (red = failed, amber = partially successful, green = successful).

- Only years marking start of a rotation (blue) or ones within a rotation (red) with planned actions are shown in the Planner. Learners see few years at a time and may scroll to view others that overflow the viewer window. Yellow implies "selected".
- The plan viewer shows only upcoming/last processed action tags, separated using position (top/bottom). Clicking on the PLAN button opens the planner with details.

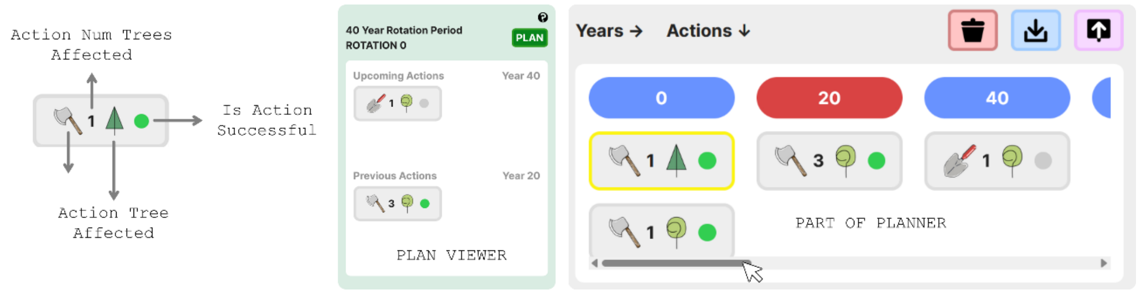

Figure 28. Management plans visualized using position, colour, and motion (content changes over time) channels.

<u>CO2 concentrations</u> are continuous and quantitative with a wide range. To enhance interpretability, they were categorized by impact on human life due to climate change and color-coded. Only current value is displayed and updated each timestep. Hovering over a colour reveals its category, saving space by eliminating the need for a legend.

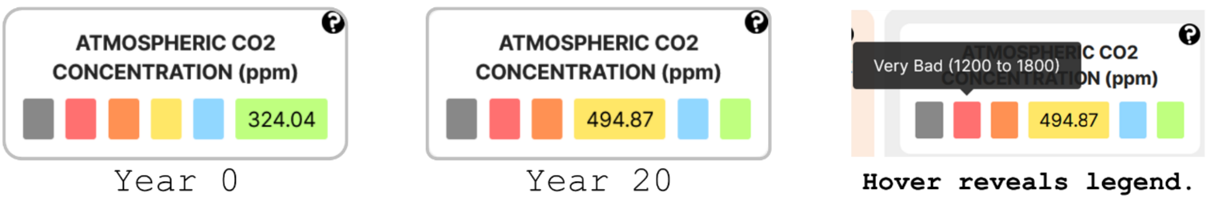

Figure 29. Colour and motion (updates over time) encoding channels used in the CO2 panel.

Another notable display design decision is the use of red and green colours to indicate whether <u>targets</u> have been achieved (green) or not (red). Lastly, the decision was made to use a toggleable switch component to capture attributes like "Is Serious Mode", "Is Income Stream Active" and "Is Action Repeated" whose values, the learner can set. These components are implemented to have a distinctly separate colour and shape in ON and OFF positions which encodes their categorical binary nature well.

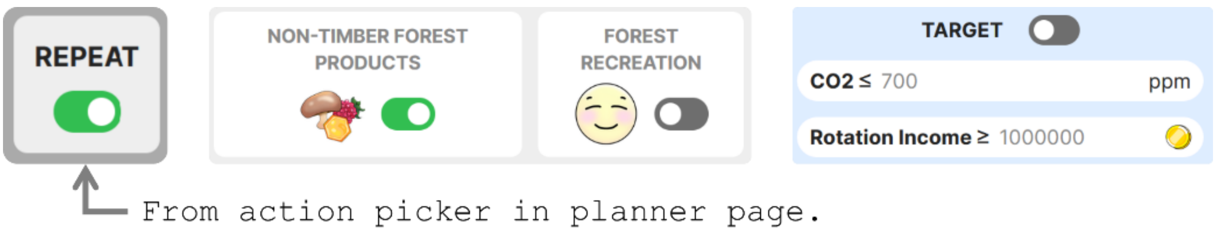

Figure 30. Use of switches.

Overall, encoding channels used were colour, position, size, and motion, with position + colour being the most common combination. This is also evident in the world and planner page; wherein related graphical elements were separated by coloured panels for best 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 31.

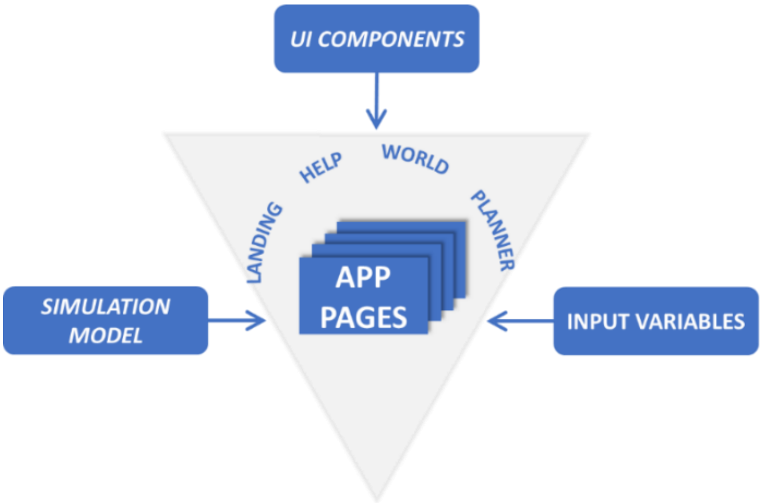

Figure 31. MycroForest App Structure

3.4.1 Simulation Model

This section outlines the conceptual model behind the simulation and the research that inspired it. Assumptions and abstractions simplify the model for a smoother, more focused learning experience, avoiding slow computation and poor UX. Model parameters are set to realistic values based on research.

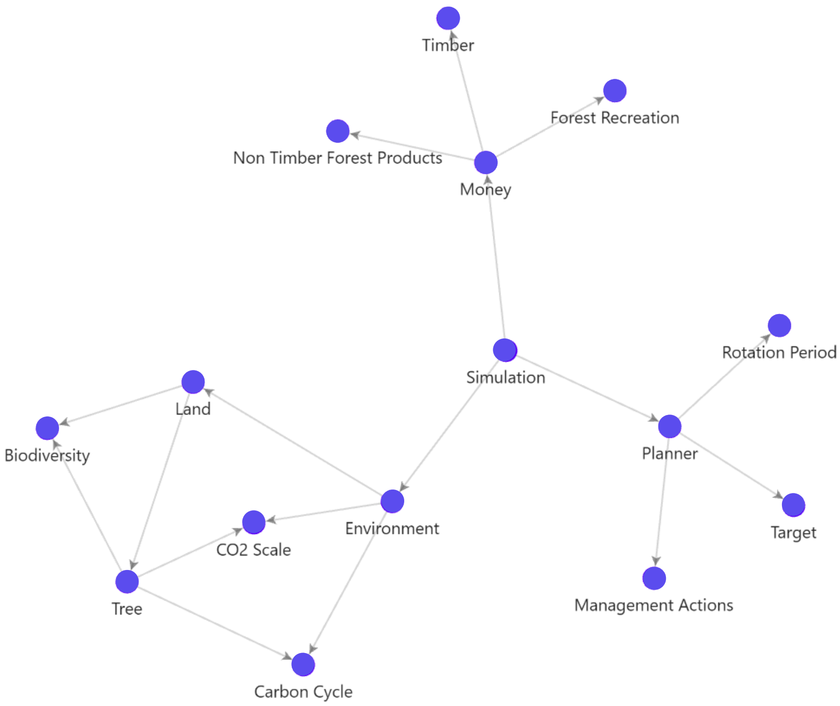

Figure 32. Graph representation of simulation model entities. Click on a node to navigate to its explanation.

Figure 32 is a graphical representation of the simulation conceptual model. Each node represents a key idea or component as explained below.

Simulation

Simulation is the master component that manages all others. It coordinates all world elements and initializes the microworld which contains an Environment, and a Planner that keeps track of user generated forest management plans. The simulation also triggers state update of all world components, refreshes the UI to reflect changes, and tracks forest resources and Money flow. (*Back To Graph*)

Environment

The environment comprises the atmosphere, Land, and carbon reservoirs. 5 reservoirs are modelled as follows between which carbon moves in a simplified Carbon Cycle.

1. **Soil**: Soil holds carbon as organic material or minerals [75].
2. **Fossil Fuels**: About 5 to 10,000 gigatonnes (Gt) of CO2 in the lithosphere is stored as fossil fuels [75], which are remains of dead organisms from Earth's distant past that upon been buried deep underground and exposed to great pressure as well as temperature over time, has turned into energy dense oil, solids (coal), and gas.
3. **Atmosphere:** The mass of the atmosphere is about 5.1e+21g [76]. 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) was computed as $\frac{mass_{CO2}}{mass_{air}}$ ×1e+6 [77, 78]. The CO2 Scale groups air CO2 concentrations into categories based on impact on human quality of life after considering associated climatic conditions.
4. **Vegetation**: Plants sequester carbon dioxide (CO2) from the atmosphere by removing it and storing it in solid or liquid form [79].
5. **Lumber**: This man-made reservoir includes all wood preserved in use (like furniture or construction) rather than burned. Preserving wood significantly slows its breakdown and re-entry into the carbon cycle through natural decay [80, 81].

At simulation creation, carbon reservoirs must be initialized. Earth's carbon amounts are estimated at 800 GtC in air, 2300 GtC in soil, 550 GtC in vegetation, and 10,000 GtC in fossil fuels [75]. To support plant growth in the microworld, air carbon was scaled down to 500 GtC. Thus, amount in other reservoirs were also scaled to maintain a ratio same as on Earth, ensuring that the simulation is realistic enough for a teaching tool. At first, all carbon in soil and vegetation is assumed to be in air, as the microworld starts with no plants. Plants then capture and store carbon in themselves and the soil as they grow. Table 15 summarizes this carbon distribution. (*Back To Graph*)

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 15. Carbon distribution among reservoirs. GtC = Gigatonnes of Carbon and gC = Grams of Carbon.

CO2 Scale

Atmospheric CO_2 concentration is measured in Parts Per Million (ppm), indicating the number of CO_2 parts per million parts of air. PPM is a standard concentration measure, like a percentage [78]. In the microworld, CO_2 concentration is organized into a labelled and color-coded scale, reflecting expected human quality of life after considering climate change effects. Another scale classifies photosynthetic efficiency at different CO_2 levels.

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

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

Figure 33. Quality of human life and photosynthetic efficiency associated with atmospheric CO2 concentration. Please find knowledge that informed design of above scale in Appendices 8.5.

In the CO_2 concentration–quality of life scale, levels $<$ 200 ppm or $>$ 1800 ppm are unliveable since photosynthesis struggles $<$ 200 ppm [82] and global warming causes inhospitable climate $>$ 1800 ppm [83]. The tolerable CO_2 range in the microworld (200–700 ppm [84]) is likely broader than on Earth because MycroForest exaggerates CO_2 changes by scaling up carbon absorption and release to simulate global forests with just 36 trees. CO_2 levels between 700 and 1200 ppm are considered bad as it nears the tipping point from beyond which, recovery is difficult [14, 84]. (*Back To Graph*)

Carbon Cycle

The carbon cycle refers to movement of the carbon element between its various states and locations on Earth. Most of it is bound to rock in the lithosphere, with the rest found in the ocean, soil, atmosphere, living organisms, and as fossil fuels deep underground. Any location where carbon is found in large quantities is called a carbon reservoir. Carbon moves between these reservoirs through the slow and fast carbon cycles [75].

- **Slow Carbon Cycle** [75]**:** Carbon moves between air, water, and rock slowly over 100 to 200 million years. Air bound carbon dissolves in water and rains down as a weak carbonic acid, slowly reacting with rock to chemically weather them. Ions (calcium, magnesium, carbon, etc.) so released, 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 is compressed over time to produce rock like limestone. Lastly, volcanic activity returns some carbon from deep inside earth into the atmosphere to complete the cycle.
- **Fast Carbon Cycle** [75]**:** This cycle primarily concerns the biosphere or life on earth and is fast enough to be visible in a human lifetime. Plants and phytoplankton absorb CO_2 from the atmosphere and turn it into sugar through photosynthesis, a chemical reaction. When carbohydrates so produced are broken down to for energy either by producers themselves or other organisms that directly/indirectly consume them, CO_2 and other carbon compounds are released back into the air through respiration. Carbon in life is also released into the soil and air when dead organisms decay.

Undisturbed, both cycles maintain amount of carbon in each reservoir at about the same range. Activities like burning fossil fuels quickly moves large quantities of carbon from the slow to fast cycle and disrupts carbon balance. Land use changes and deforestation reduce carbon sequestration ability of the biosphere and soil, aggravating the carbon saturation problem, causing ocean acidification, global warming, and consequently, climate change [75]. MycroForest models key elements of the fast carbon cycle and ignores the slow one as effects of the latter is small within simulated 300 years.

Following paragraphs explain how MycroForest models carbon transfer between the 5 reservoirs considered (air, soil, vegetation, lumber, fossil fuels).

Tree Growth & Decay

In MycroForest, vegetation refers to trees which both absorb and emit carbon. This transfer mechanism is slightly different in the growth, biomass maintenance, and decay phases of a tree's existence as follows.

- **Growth**: Plants absorb CO2 from air for photosynthesis, meaning 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 biomass. Let a tree have grown in volume by $\Delta Volume_{tree}\ m^3$ with density $Density_{tree}\ g/m^3$. Then, the tree's weight should have increased by $\Delta Mass_{tree} = Diameter_{tree} \times \Delta Volume_{tree}$. Of the total weight of a tree, around 50% is dry weight [85]. Thus, $\Delta Mass_{tree}^{dry} = 0.5 \times \Delta Mass_{tree}$. About 47.5% of a tree's dry weight, is carbon [85]. So, $Carbon_{tree}^{absorb} = 0.457 \times \Delta Mass_{tree}^{dry}$. This absorbed carbon gets added to total 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 height and diameter increases, a tree also needs to replace biomass lost due to damage or shedding [46]. Carbon in this replaced biomass is referred to here, as maintenance carbon. Maintenance carbon is subtracted from air and added to soil ($Carbon_{air} = Carbon_{air} - Carbon_{tree}^{maintain}$ and $Carbon_{soil} = Carbon_{soil} + Carbon_{tree}^{maintain}$) without vegetation reservoir levels changing because the amount of carbon in biomass lost to soil is assumed to be the same as that absorbed from air to replenish it. Let volume of replaced biomass = 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 microworld settings chosen through trial and error as it was not possible to find real-world figures for this. As before, $\Delta Mass_{tree}^{maintain} = Density_{tree} \times \Delta Volume_{tree}$, $\Delta Mass_{tree}^{maintainDry} = 0.5 \times \Delta Mass_{tree}^{maintain}$, and $Carbon_{tree}^{maintain} = 0.475 \times \Delta Mass_{tree}^{maintainDry}$.
- **Decay**: As trees decay, carbon stored in them re-enters air and soil from vegetation. If a tree has died and remains on land, about 15% of carbon stored in it is released into air and soil each year [86]. Thus, in the microworld, decayed volume per timestep =

15% of tree volume at time of death. Let annual amount of carbon lost to decay be fixed at $Carbon_{tree}^{decay} = 0.15 \times Carbon_{tree}^{t}$ where t = time right before tree death. Thus, weight of dead tree lost to decay would be $Mass_{tree}^{decay} = \frac{Carbon_{tree}^{decay}}{0.475}$ and consequently, volume would be $Volume_{tree}^{decay} = \frac{Mass_{tree}^{decay}}{Density_{tree}}$. Thus, after each year, volume of a dead tree that remains in soil, changes as $Volume_{tree} = Volume_{tree} - Volume_{tree}^{decay}$. Of the amount of carbon decayed each year, around 35% ends up in the soil with the rest getting released back into air [87]. So, $Carbon_{soil} = Carbon_{soil} + \left(0.35 \times Carbon_{tree}^{decay}\right)$ and $Carbon_{air} = Carbon_{air} + \left(0.65 \times Carbon_{tree}^{decay}\right)$.

Soil Release

Soil naturally releases a portion of stored carbon into air through processes like microorganism respiration. Of the around 2300 Gt of carbon in soil, about 60 Gt is lost annually [75]. Thus, in MycroForest, annual soil release is set to $\frac{60}{2300} \times 100 \approx 30\%$ of soil carbon, such that $Carbon_{soil}^{release} = 0.03 \times Carbon_{soil}$ per timestep with $Carbon_{soil} = Carbon_{soil} - Carbon_{soil}^{release}$ and $Carbon_{air} = Carbon_{air} + Carbon_{soil}^{release}$.

Timber Usage

Harvested wood has various uses. It can be burned for heat/power, used in construction, or made into products like paper. This, in MycroForest, uses are broadly categorized into "energy" (for burning) or "lumber" (for preservation). About 50% of globally harvested wood is used for energy [88]. Given that, mass of carbon is computed from mass of harvested timber multiplied by dry weight % and carbon % as previously seen. Here, $Carbon_{timber}^{energy} = 0.5 \times Carbon_{timber}$ and $Carbon_{timber}^{lumber} = 0.5 \times Carbon_{timber}$. It is assumed that all carbon in burned wood re-enters air and that all of it in lumber gets preserved. Using harvested wood adds carbon to both lumber and air reservoirs. $Carbon_{lumber} = Carbon_{lumber} + Carbon_{timber}^{lumber}$ and $Carbon_{air} = Carbon_{air} + Carbon_{timber}^{energy}$. Timber is obtained when a tree is felled. When chopped, around 25% of the tree (roots = 21.3% [89] + the stump + some foliage) is assumed to remain in soil while the rest is harvested. Thus, $Carbon_{timber} = 0.475 \times 0.5 \times Mass_{timber}$ where $Mass_{timber} = 0.75 \times Mass_{harvestedTree}$.

Unlike in the microworld, in reality, all carbon in burned wood does not re-enter the atmosphere (some wood may be turned to ash etc.), but most of it, still does and hence this is a sound assumption. Also, it is assumed that wood used for lumber is preserved responsibly to maximize lifespan such that carbon in it is not released in the simulated timeframe. In reality, carbon stored in HWPs is not as straightforward. Amount of carbon sequestered depends on several factors at wood production, use, and end of life stages. In the production phase, carbon in wood varies depending on tree type. Hardwood from deciduous trees is denser and preferred for durability which often leads over-harvesting and thereby, more carbon released than preserved. In the use phase, wood products keep some carbon from re-entering the fast carbon cycle until it decays. At this stage, best course of action is to recycle into secondary wood products and extend its life. Another, less desirable option is to burn it to produce greener energy compared to that produced by burning fossil fuels. These are, however, ideal scenarios. Unfortunately, a lot of harvested wood ends up in landfills before end of life and rot quickly to release CO2 as well as more potent GHGs like methane (CH4). Also, processing of wood using toxic substances like CCA or ACQ to increase lifespan often does more harm than good [80]. Nevertheless, in MycroForest the assumption that lumber carbon does not re-enter the cycle, is sound because if responsibly produced and used, wood can indeed lock away carbon out of the fast carbon cycle for centuries [81].

Fossil Fuel Usage

Normally fossil fuel carbon enters air very slowly over millennia via the slow carbon cycle. But since the industrial age, humans have burned 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 Gt of CO2 ≈ 10 Gt of carbon was added into the atmosphere this way [75, 90]. In MycroForest, carbon added to air due to fossil fuel usage is $Carbon_{fossilFuels} = Carbon_{fossilFuels} - Carbon^{release}_{fossilFuels}$ and $Carbon_{air} = Carbon_{air} + Carbon^{release}_{fossilFuels}$. Learners can edit $Carbon^{release}_{fossilFuel}$. (*Back To Graph*)

Land

Land in MycroForest, represented as a 6×6 grid amounts to a total of 36 spots. Each spot may host 1 live Tree. Here, "36" spots is an arbitrary choice deemed small enough to be visually tracked yet big enough for management plans to yield varying results. Assuming trees are grown in rows with 25 ft between them, 1 acre could support 83 trees (tree spacing and distance calculator). Thus, 36 trees would occupy 0.43 acres = 1740.15 m^2. Thus, land in the microworld is assumed to span 1740 m^2. Although too small to represent a real forest (mean size of private forest in Ireland ≈ 80,000 m^2 [91]), given only at most 36 trees, scaling real world forest figures to suit land of size 1740 m^2 should help map real-world figures to the MycroForest more accurately. Further, land content determines Biodiversity which in turn, influences tree growth rate, trees' ability to recover from stress, and earnings from some income streams.

Spot Availability

In the microworld, a tree can only grow if a suitable spot is available, which means: (i) There are no trees in the spot, or (ii) There is just 1 dead tree in the spot such that it has decayed to the point where $Height^{max}_{tree} = 0.5 \times Height^{max}_{tree}$. The value of 0.5 is arbitrary, but this rule emulates how in nature, new growth arises from remains of a dead tree while it is still decaying.

Initialization

At the start, the simulated world is populated with seedlings based on a predefined species mix: 60% coniferous and 40% deciduous. Initially, 92% of the space is free, with 8% occupied by seedlings—2 coniferous, 1 deciduous, and 33 empty spots. This setup reflects the forest composition in Ireland [92] but may change as the forest evolves over. After 200 years, the resulting forest becomes the starting point for players, with initial seedling placement random, allowing for different forests with each browser refresh. Learners can save and reload specific forests. (*Back To Graph*)

Tree

In MycroForest, trees are categorized as either "deciduous" or "coniferous", representing a simplified version of Earth's diverse species. Deciduous trees, such as oak and maple, shed leaves in winter or produce fleshy fruits and flowers. Coniferous trees, like cedar and spruce, are evergreen, reproduce via cones, and have needle-like leaves. The classification was chosen over others like "hardwood" and "softwood" because it the presents cleanest separation. The latter can be misleading (there exists "hardwood" species with soft wood and vice versa) [93]. Category properties assume values averaged over multiple species and are not therefore based on any single tree / species.

Table 16 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 [94, 95], more long lived [96], have softer wood [93, 97], mature slower [98] and reproduce less often [99] compared to deciduous trees.

Coniferous	Deciduous
Maximum height = 70 m. [94]	Maximum height = 40 m. [95]
Reproduction interval = 2.5 years. [100]	Reproduction interval = 1 year.
Wood density = 6e+5 g/m^3 [97]	Wood density = 7e+5 g/m^3 [97]
Evergreen. Does not shed leaves seasonally. Thus, % of carbon lost and replenished per year in addition to growth (maintenance carbon %) = 1%. [93]	Sheds all leaves in autumn and regrows them in spring. Thus, maintenance carbon is assumed to be = 40%. [93]
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 16. Difference between coniferous and deciduous trees.

As seedlings, trees of both species have same height = 0.2 m since real data with species wise seedling size differences was not found [101]. Developed tree age groupings as in Figure 34 was based on informed assumptions (aforementioned sources).

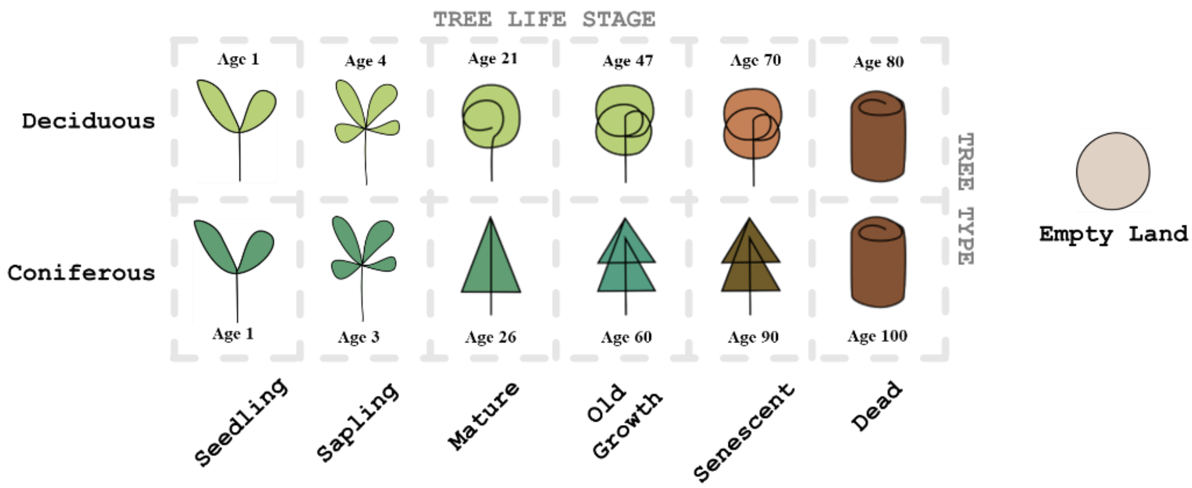

Figure 34. Possible land content with ages.

Trees are modelled to live and die as in the real world. When 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 stress negatively effects growth [102], but certain conditions like high biodiversity can help reduce impact of stress. Trees may recover from environmental stress when conditions are favourable [103]. Following passages explain design of each such key mechanism in MycroForest.

Stress

Modelling tree mortality as a consequence of stress as in MycroForest, is a common approach. The growth model in MycroForest incorporates real world observations regarding effects of stress on tree vigour [102, 104]: 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. Plants experience increased stress when resources (CO2, water, heat, etc.) are either too abundant or too scarce. Under favourable conditions, trees recover from stress. The Tree Decline Recovery Seesaw model in [103] captures the tree vigour – stress relationship well.

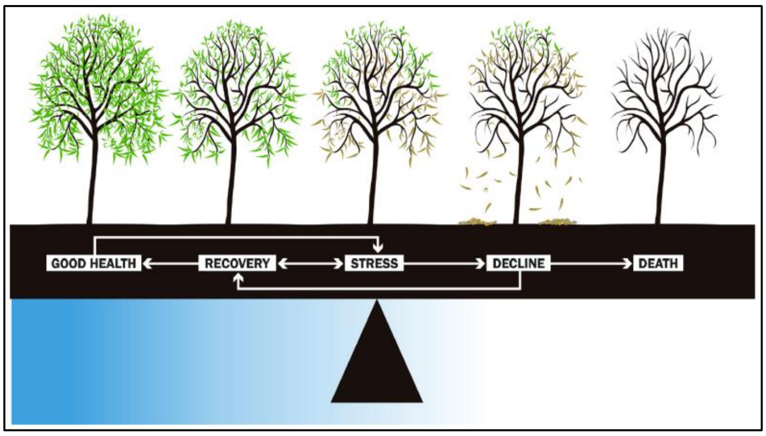

Figure 35. The Tree Decline Recovery Seesaw model illustrating how health of a drought stressed tree shifts between varying stages. Physical changes like leaf re-growth and loss indicates recovery and decline respectively. [103]

In MycroForest, trees have a "stress" property. They die only when $Stress_{tree} \geq 1$. Living trees are under stress due to environmental conditions (air $CO2$ level) and time (age).

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

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

In the microworld, only CO2 is explicitly modelled as an environmental stressor due to its strong link with climate change. Realistically, plants face many other stressors like pests, temperature fluctuations, competition, etc [105]. Modelling these is out of scope. This would add complexity without much educational value and thus was omitted. CO2-related stress is calculated based on each tree's tolerance for CO2 availability, with premature trees (seedlings, saplings) being more vulnerable than mature ones.

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

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

Table 17 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 17. Tolerance of trees to CO2 availability.

Aging stress peaks when a tree hits max age. It increases by $Factor_{stress}^{age} = 0.01$ every year after a tree enters the senescent stage, capturing old-ager related health decline.

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

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

When conditions are favourable, trees recover from past stress. Healthier plants recover faster. Rate of recovery is determined by a $Factor_{stress}^{recover} = 0.2$ that was arbitrarily chosen based on the informed assumption that recovery is generally gradual [103].

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

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

Living

After accounting for stress, if a tree is alive, the following life processes occur.

- **Recovery:** The tree may recover from stress as mentioned previously.

- **Growth**: Tree growth includes both new mass gain and maintenance volume gain. Maintenance volume replenishes biomass lost from natural shedding (self-pruning) or damage. It is computed as an arbitrary fixed % of tree volume, $Volume_{tree}^{maintain} = Volume_{tree} \times Factor_{volMaintain}$. 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 lose very little biomass this way. In the real world, tree height is limited by various factors, but diameter typically continues to grow, albeit more slowly after maturation [106, 107]. This ongoing growth, called "secondary growth," [108] is modelled in MycroForest. For simplicity, tree volume is treated as cylindrical. Here, "growth volume," " growth height," and " growth diameter" refer to new growth, while "new volume," "new diameter," and "new height" represent sum of old values plus new growth.

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

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

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

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

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

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

Once the tree reaches 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 under increased stress, but greater biodiversity enhances forest resilience. The biodiversity stress reduction factor $Factor_{stress}^{bRed}$ mitigates negative impact of stress on growth [109].

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

Max annual growth height is based on tree age at start of its mature stage and max height. Max growth diameter computed based on max growth height using the relationship $Diameter_{cm} = Height_m^{3/2}$ where height is in meters and diameter is in centimetres [110]. Thus, given $Diameter_m = \frac{Height_m^{3/2}}{100}$, max amount that the tree can grow by under primary growth per timestep can be computed as $Height_{tree}^{growthMax} = \frac{Height_{tree}^{max}}{Age\ at\ the\ beginning\ of\ "mature"\ lifestage}$, $Diameter_{tree}^{growthMax} = \frac{\left(Height_{tree}^{growthMax}\right)^{3/2}}{100}$.

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 if there is a free spot adjacent to it and the tree is either mature or old growth with $Stress_{tree} \leq Factor_{stress}^{reproduce}$ where it is assumed that $Factor_{stress}^{reproduce} = 0.5$.

  $$RprIvl^{deciduous} = 1\ year \qquad RprIvl^{coniferous} = 2.5\ years$$

  Most conifers reproduce through cones or wind dispersion, while many deciduous trees produce fruits that attract animals, who then spread the seeds farther from the parent tree. This biotic dispersal often leads to wider seed spread [93]. Thus, deciduous trees may spawn seedlings in 2 more spots, 2 steps away from the parent in addition to immediately adjacent positions as can coniferous trees (Figure 36).

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 36. Positions around a parent tree where new seedlings may spawn.

- **Death & Decay**: Naturally over time or when felled, trees die as $Stress_{tree} = 1$. Once dead, they decay as mentioned in Carbon Cycle. (*Back To Graph*)

Biodiversity

Biodiversity refers to variety of life forms in a forest and is a key indicator of its health. Higher biodiversity enhances forest resilience through increased genetic variability, which aids in adaptation, greater tree diversity, reduced risk of complete die-out from species-specific threats, and stronger ecosystem functions like nutrient cycling [111, 112]. Biodiversity figures computed in MycroForest are Score B, Category B_{cat}, and Stress Reduction Factor $Factor_{stress}^{bRed}$. Mixed forests with trees of varying ages are healthiest. They host rich biodiversity. Even dead wood contributes towards increased biodiversity (fungi, insects, etc) [111-115]. Thus, in MycroForest, biodiversity score considers species $B_{species}$ and age B_{age} composition of the forest.

Based on research, for $B_{species}$, 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.

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 37, Figure 38, and Figure 39, present tree age composition of an old growth forest in Vienansalo Wilderness, Eastern Fennoscandia [115].

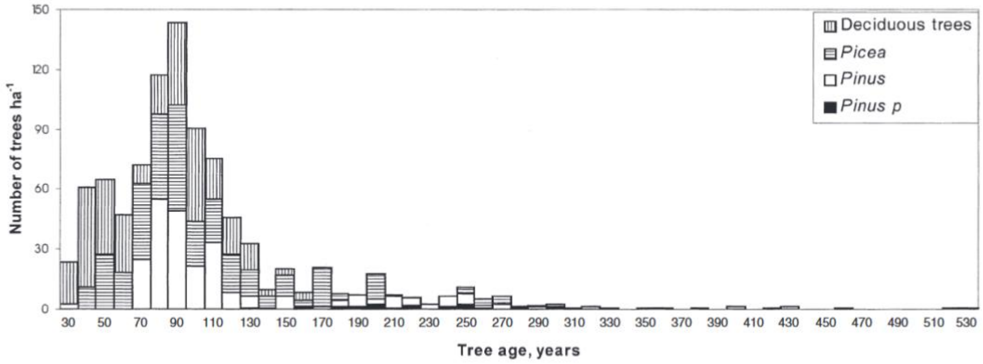

Figure 37. Distribution of no. of mature trees by age per hectare based on data from an old growth forest in Vienansalo Wilderness, Eastern Fennoscandia [115].

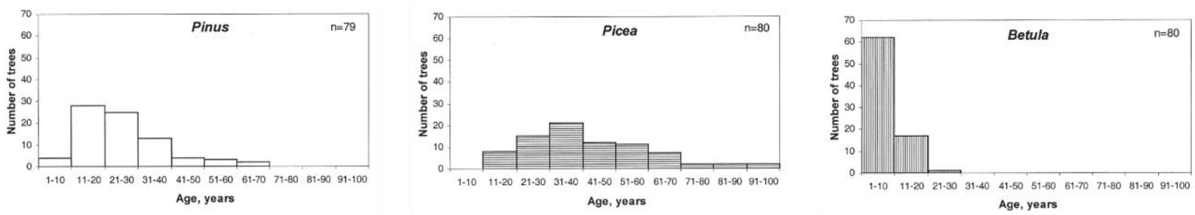

Figure 38. No. of seedlings and saplings per hectare based on data from an old growth forest in Vienansalo Wilderness, Eastern Fennoscandia [115].

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 39. No. of dead tree stumps per hectare based on data from an old growth forest in Vienansalo Wilderness, Eastern Fennoscandia [115].

Since age of oldest and youngest trees in this forest differs from that in the microworld, to mimic age composition of the real forest, there was a need to map age group ranges in the microworld to corresponding ranges in the real forest. Scaling was done to obtain Table 18 by computing $y = \frac{(x-a)\times(d-c)}{b-a} + c$ where x = number on original scale, y = corresponding number on new scale, a and b = min and max value on original scale respectively and, c and d = the min and max value on 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 18. Mapping of tree ages in the microworld to those observed in a real forest.

Based on tree age groupings from Table 18 and approx. tree per hectare counts from Figure 37, Figure 38, and Figure 39, an approx. ideal age composition as in Table 19 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 19. Ideal proportion of each tree age category.

Calculating B_{age} involves computing the following for each age groupings (seedlingSapling, mature, oldGrowthSenescent, dead).

- Current proportion of trees of this age group, $Prop_{ageGroup} = \frac{TreeCount_{ageGroup}}{36} \times 100$ where $TreeCount_{ageGroup}$ is no. of trees in this age group.
- Maximum possible error $Error_{ageGroup}^{max} = max\left(\left(100 - Prop_{ageGroup}^{ideal}\right), \left(Prop_{ageGroup}^{ideal} - 0\right)\right)$ where $Prop_{ageGroup}^{ideal}$ is ideal proportion of trees of this age group.
- 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 $B = \frac{B_{species} + B_{age}}{2}$.

Given knowledge that ecosystems are more biodiverse than new forests or plantations [111] and that biodiversity is proportional to forest resilience, land categorization and biodiversity based stress reduction values in Table 20 were formulated. (*Back To Graph*)

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 20. Mapping between biodiversity score range, land category, and biodiversity stress reduction factor.

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 by 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 activate other income streams. (*Back To Graph*)

Management Action

Management actions are actions that affect the forest which learners may opt to execute. Creating a new management action involves selecting the action type, type of tree (species, age) to which the action is to apply, no. of trees to be affected, year in which the action is to be executed and whether the action is to be repeated every rotation. There are 2 types of management actions: Felling and Planting. Both felling and planting a tree involves paying a fee. If funds are insufficient, the action fails. When a tree is felled, 25% of it (roots = 21.3% [114] + stump + some foliage) remains in the soil to decay, while 75% is harvested and added to timber stock, with half sold for energy [88] and the other half for lumber. Planting is only possible if a free spot adjacent to the parent tree is available, in which case, a new seedling is added on land. ***Note:*** Trees can reproduce naturally or be planted by learners. Even without intervention, if a mature or old-growth tree is present, a new seedling may sprout in an adjacent free spot. (*Back To Graph*)

Target

The microworld allows 2 target types: CO2 Level and Income per Rotation. If the CO2 level exceeds the set target during the simulation, the year this first occurs will be displayed next to the corresponding text field. If the plan fails to generate enough income to meet the set value in any rotation, the rotation where this first happens will be shown next to the text field. Successfully meeting a target, results in a green border around the text field, while a failure is indicated by a red border. (*Back To Graph*)

Rotation Period

In MycroForest, trees can be felled/planted every X no. of years, known as the rotation period. This scheduling of management actions at the start of each rotation, mimics real-world forestry/agriculture practices. A rotation is defined as time between the formation/regeneration of a crop and its harvest [116]. (*Back To Graph*)

Money

Virtual currency in MycroForest is "coin". Ways to earn from the forest are (i) Timber, (ii) Non Timber Forest Products, and (iii) Forest Recreation. (*Back To Graph*)

Timber

Timber in the microworld refers to wood harvested upon felling a tree.

Availability: Availability of this resource depends on number and size of trees felled.

Income: At the end of each simulation timestep, harvested wood is sold and used. In reality, wood prices vary by type, but on average, it is priced at approximately $3.3 per kg or €3.03 per kg [117]. In MycroForest, timber is valued at 3 coins per kg.

Expenditure: Felling the biggest trees can cost up to 3000 coins [118]. This max amount is multiplied by percent of full growth a tree has reached at time of chopping to obtain $Cost_{fell} = \frac{Height_{tree}}{Height_{tree}^{max}} \times 3000$. Planting a tree costs 277 coins [119]. (*Back To Graph*)

Non Timber Forest Products

Selling non-timber forest products (NTFPs) (mushrooms, berries, honey) fetches coins.

Availability

A good number for wild ***mushroom*** yield from a European forest is 44.5 kg/ha/year [120]. That is, 44.5 kg per 10000 m^2 per year = 0.00445 kg/year/m^2. Thus, for the 1740 m^2 forest in the microworld, the value is around 7.743 kg/year ≈ 8 kg/year. On average, around 20 kg of ***honey*** can be harvested from one bee hive per year [121]. In Europe, wild honeybee colony density has been estimated to be around 0.26/km^2 [122]. 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 annually to result in total generation of around 9.05e-4 kg/year. With intensive ***berry*** picking, it is possible for a small group of people to harvest around 10 kg of wild berries per year by foraging [123]. Based on this, it is assumed that 5 kg of berries are foraged from MycroForest per year.

Overall, total availability of NTFPs would 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 $\mu = 14\ kg/year$ and standard deviation $\sigma = 2.5$. Also, this stream is dependent on biodiversity score and amount of deadwood in the forest (saprophytes like mushrooms thrive on deadwood [124]) as follows.

- Let max 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, 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 per kg [125], wild berries can fetch around €25 per kg [126], and wild honey can fetch around €65 per kg [127]. Thus, selling price for NTFPs may be assumed to be 170 coins per 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 [128]. 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 [129], 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. (*Back To Graph*)

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 fetches coins.

Availability: As of 2022, there are 808,848 ha = 8088480000 m^2 of forest in Ireland. It is expected that they receive around 29105759 visits per annum [130]. 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 the microworld can receive around 7 visits/year. This can vary significantly based on several factors like climate, economic situation, etc. Thus, here too, availability is 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 forest as people generally prefer visiting healthier forests rich in life. Thus, availability of visitors 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: Admission/Parking Charges = 5 coins [131, 132], Guided Tours = 10 coins [131, 132], Special Activities (Zip Lining, Mushroom Picking, etc.) = 30 coins [131, 133, 134], or Group Events (Birthday Parties, Yoga, etc.) = 20 coins/individual [135]. Assuming 1 of all visits to be a guided tour, another 1 to be a special activity and the rest to be normal visits with 1 group (20 individuals) activity/year, annual income $= 10 + 30 + (Availabilty_{rec} \times 5) + (20 \times 20)$.

Expenditure

Opening a forest for public recreation involves establishment of infrastructure which has associated one-time expenses. In 2006, restoration of around 44 hectares = 440000 m^2 of forest land cost about €8,000,000 [32]. Adjusting for change in currency value, in January 2024, that is around €10,114,114 (CPI Inflation Calculator). Thus, in the microworld, initial one-time cost to prepare forest land for recreational activities = $\frac{10114114}{440000} \approx 23$ coins per m^2. Thus, for a 1740 m^2 forest, this ≈ 40020 coins.

Established infrastructure needs maintenance, which requires employees and resources. It was not possible to find definitive numbers about how many employees are required to maintain forest recreation facilities. This varies greatly. The estimate for no. of workers per m^2 of forest in the microworld was based on no. of people that Coillte (large forest owner in Ireland), with around 4.4e+9 m^2 of managed forest land [136], employs. In 2016, it employed around 862 people [137]. Considering no. of employees to be 850 people, no. of people employed per $m^2 = \frac{850}{4.4e+9} = 1.93e - 7$ employees/m^2. Thus, no. of workers for a 1740 m^2 forest $= 1740 \times 1.93e - 7 = 0.00034$. If each employee works for 8 hrs/day for 5 days/week for 52 weeks/year, then each employee works around 2080 hrs/year. In Ireland, as of 2024, forest workers get paid around €18 per hour [129]. 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. It was difficult to acquire numbers for this. Thus, it is assumed to be a fraction (1%) of initial establishment cost $= 0.01 \times 40020 \approx 400\ coins/year$.

Thus, total maintenance cost for $= 400 + 13 = 413$ coins/year. (*Back To Graph*)

3.4.2 Input Variables

Input variables here, refer to a collection of 41 global variables that comprise all informed simulation hyperparameter values based on research. These settings were separated from the rest of the program to facilitate easy experimentation with different simulation settings needing no code updates. Table 21Table 21. Categorized input variables. displays these variables organized into 9 categories.

Category	Variables
Tree	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
Carbon Dynamics	C_START C_PC_DECAY CO2_FOSSIL_FUEL_ANNUAL_EMISSION_START TREE_VOLUME_MAINTENANCE_PC DECAY_PC_SOIL SOIL_RELEASE_PC
Land	BIODIVERSITY_CATEGORIES LAND_AGE_COMP LAND_FREE_PC_START LAND_SIZE SPECIES_COMPOSITION_START
Finances	COST_MGMT_ACTION FUNDS_START INCOME_SOURCES
Time	INIT_NUM_YEARS TIME_MAX SIMULATION_DELAY
Targets	TARGET_CO2_START TARGET_INCOME_START
Forest Management	ROTATION_START TIMBER_USAGE AVAILABILITY_SCALE_FACTOR
Air	AIR_MASS ENV_SCALE ENV_SCALE_COLORS

Table 21. Categorized input variables.

Please find a description of each variable in Appendices 8.6.

3.4.3 UI Components

UI components were built using ReactJS and encapsulate visual and interactive elements of MycroForest. Page specific components are those that are used only within a single page. These are more specialized compared to page agnostic ones that may be useful across multiple application 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 present 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 40 keeps code modular and enhances maintainability and reusability.

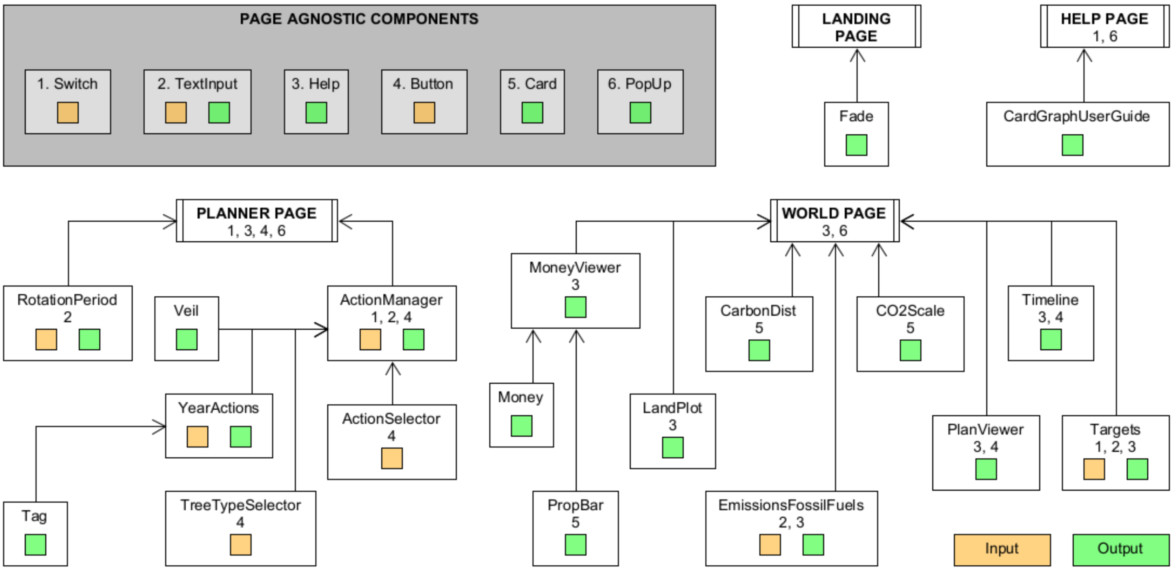

Figure 40. Illustration of how UI components relate to each other. Application pages may be thought of as root components. Page specific components are linked via arrows either directly or indirectly with their parent page. Page agnostic components are displayed within a grey box on the top left corner 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

MycroForest is a standalone, client-side, static web site with no separate backend or database since users need not sign-up/log-in to use the tool. All data is stored in JavaScript variables within React Components, meaning that system state is not persistent and gets updated upon browser refresh. However, learners can save and reload world state if needed. A database or user authentication was not included as this does not greatly add to the learning experience. It only serves to further complicate development, making successful completion within given timeframe, more challenging.

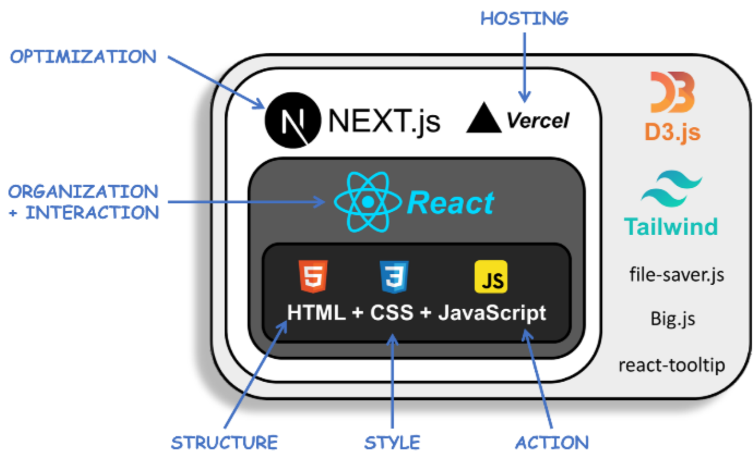

Figure 41. MycroForest – Tech Stack

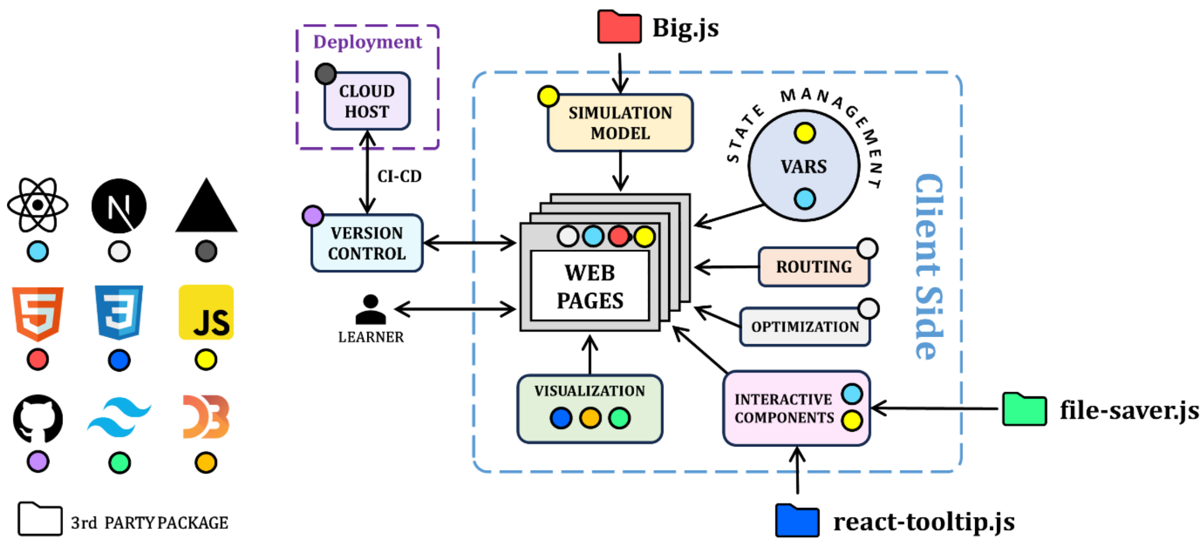

Figure 42. MycroForest - Technical Architecture. A coloured-coded circle maps each technology with associated function in the architecture diagram.

Following points explain the role of each technology leveraged.

- **HTML:** Hyper Text Markup Language enables structuring and content arrangement.
- **CSS:** Cascading Style Sheets (CSS) facilitates website styling. It can be used to add colour, animation, etc. and thereby format HTML elements.
- **Tailwind CSS:** Tailwind CSS is a framework that integrates CSS into HTML for ease.
- **JavaScript:** JavaScript (JS) enables user interaction facilitating detection of events like mouse move, click etc. It also allows embedding of working logic or functions.
- **Big.js:** The Big.js library facilitates precision computation using very large/small numbers. Unlike native JavaScript numbers, which have precision limitations, Big.js stores numbers as objects with arbitrary precision. MycroForest models carbon amounts and environmental properties (e.g. mass of atmosphere) using large values as on Earth. Storing these (e.g. 5.1e+21, 6.25e+18, etc.) as JavaScript "number" objects led to overflow/underflow upon computations. Big.js helped overcome this.
- **file-saver.js:** The file-saver.js library enables saving files on the client side. When the learner clicks on the "download" icon on the planner page, the `saveAs(...)` function from the library may be used to save world data as a JSON file.

- **ReactJS:** ReactJS is a JavaScript library for building user interfaces. It allows creation of reusable UI components and easy state management via efficient virtual Document Object Model (DOM) manipulation. A DOM is the in-memory tree-like representation of webpage structure defined by HTML that the browser maintains [138]. React is especially apt for heavy user interaction as in MycroForest, because the built-in react-dom library maintains a virtual copy of DOM and rebuilds it upon state updates such that only necessary changes are reflected on the real DOM. This optimizes DOM update, which is otherwise computationally expensive. A React component is simply a function that returns JSX (JavaScript XML), notation that allows HTML/JavaScript-like content to coexist in React components allowing self-containment of structure and logic. Private data associated with components in React is referred to as States. MycroWorld's code most frequently uses React hooks `useEffect`, `useState`, and `useContext`. A "hook" is a function that allows state variable updates. The `useState` hook does just this. Every time state is updated, ReactJS ensures re-rendering of relevant components. The `useContext` hook allows states to be globally accessible. The `useEffect` hook allows one to set up logic that gets executed each time particular state updates occur, or the corresponding component is first loaded. Thus, MycroForest leverages ReactJS to modularize app structure, encourage code reusability, and optimize DOM updates.
- **react-tooltip.js:** The react-tooltip library provides a ready-made tooltip component that is otherwise cumbersome to create.
- **NextJS:** Next.js is a React framework that simplifies building performant web applications. It offers features like Server-Side Rendering (SSR) and Static Site Generation (SSG). The advantage of SSR is that the HTML for the webpage is generated on server side and sent to client instead of it having to be built on client side, thereby hastening page loading. This also allows search engines to find the webpage more easily. Not all components can be rendered on server side. Those that users can interact with, are rendered on the client side because displayed content depends on user interaction (e.g. text input by user) and thus cannot be pre-rendered. All files with the line "use client" on the top of the page, are client side rendered. Others are server side rendered. NextJS optimizes rendering by allowing parts of the webpage to be server side rendered even if there are some interactive components that requires client side rendering. SSR is generally an attractive feature when content fetched from the server is dynamic (e.g. changes per user like with personalised recommendations). However, MycroForest is "static", meaning that content displayed, barring implemented randomness, is same for all users. So SSR is not of much benefit here. That said, NextJS has SSG capabilities which readies the webpage at build time and much like SSR improves search engine optimization and initial loading time. SSG is advantageous for static web apps like MycroForest. Furthermore, in MycroForest, NextJS's `useRouter` provides client-side routing with a file-system-based convention, allowing easy page organization and automatic route generation as well as navigation without needing a separate backend.

- **D3.js:** D3.js is a graphics library that allows creation of custom plots. In MycroForest it was used to create the dynamic land content change / tree-growth visualization involving a customized scatter plot representing land with trees.
- **GitHub:** GitHub is a cloud code warehouse that facilitates version control. All project code over time is stored in a GitHub repository here. It was configured to allow code "pushes" to the repository that update only changed portions of files while preserving past versions in history which may be restored if required.
- **Vercel:** Vercel is a cloud platform where web apps can be deployed. It was built by creators of NextJS and hence the 2 are compatible. Mycroforest is currently hosted on Vercel here. MycroForest's Vercel project is linked to its GitHub repository such that new pushes to GitHub trigger a new deployment of the application on Vercel. This set up facilitates Continuous Integration and Continuous Deployment (CICD). Vercel boasts a strong Content Delivery Network with multiple edge locations in Europe (Dublin, Frankfurt, Stockholm, Paris, London) and built-in performance optimization (caching, streaming, response compression, etc.). This ensures that learners in Ireland can use the tool with minimal delay and disruptions. Currently, MycroForest is hosted via a Hobby account. Key measures of usage include fast data transfer volume, fast origin transfer, edge requests, and data cache reads. Monthly limits are generous even for the Hobby account and thus supports multiple parallel users, although an exact number is difficult to estimate based on Vercel's limits and restrictions documentation. Nevertheless, usage limits may easily be scaled by subscribing to the pro plan or paying for additional usage. Moreover, the account owner is notified via email in advance if usage approaches limits to possibly avoid downtime. The Hobby plan was sufficient for the Bridge2College 2 hour learning session with the application accessed on 8 machines simultaneously. Incurred usage for that month (June) including tests were: Fast Data Transfer = 100.74 MB / 100 GB, Fast Origin Transfer = 1.92 MB / 10 GB, Edge Requests = 5,383 / 1,000,000, and Data Cache Reads = 301 / 1,000,000.

3.5.2 Avoiding Bad Software Design

Note: Following content is based on knowledge from lectures and material put together by Prof. Siobhán Clarke for the CS7CS3 – Advanced Software Engineering module that this author took at TCD as part of the MSc. Computer Science programme (2023 – 24).

Generally, bad code has 4 defining characteristics as in Table 22. It is difficult to change, prone to breaking, difficult to reuse, and contains hacks instead of apt fixes. While developing MycroForest, measures were taken to prevent such consequences of bad design. Code adheres to the Model View Controller (MVC) design pattern and Object Oriented Programming (OOP) paradigm. 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 22. Countermeasures taken against common characteristics of bad software design.

Figure 43 shows Model View Controller (MVC) separation in code. Simulation model files are in a "model" folder, React Components are in a "components" folder, and each webpage has its own page.jsx file following NextJS conventions. The model handles simulation logic, the view is the returned JSX (what the learner sees), and the controller here, is the code above the return statement in components and pages because it processes input, interacts with the model, and updates the UI, acting as a bridge between the model and view. Following the MVC design pattern [139] supports the Separation of Concerns (SoC) principle which advocates for any complex Software System to be designed as a conglomeration of smaller, simpler, specialized components with distinct functions [140]. The OO idea of encapsulation also encourages this as it enhances code maintainability and reusability.

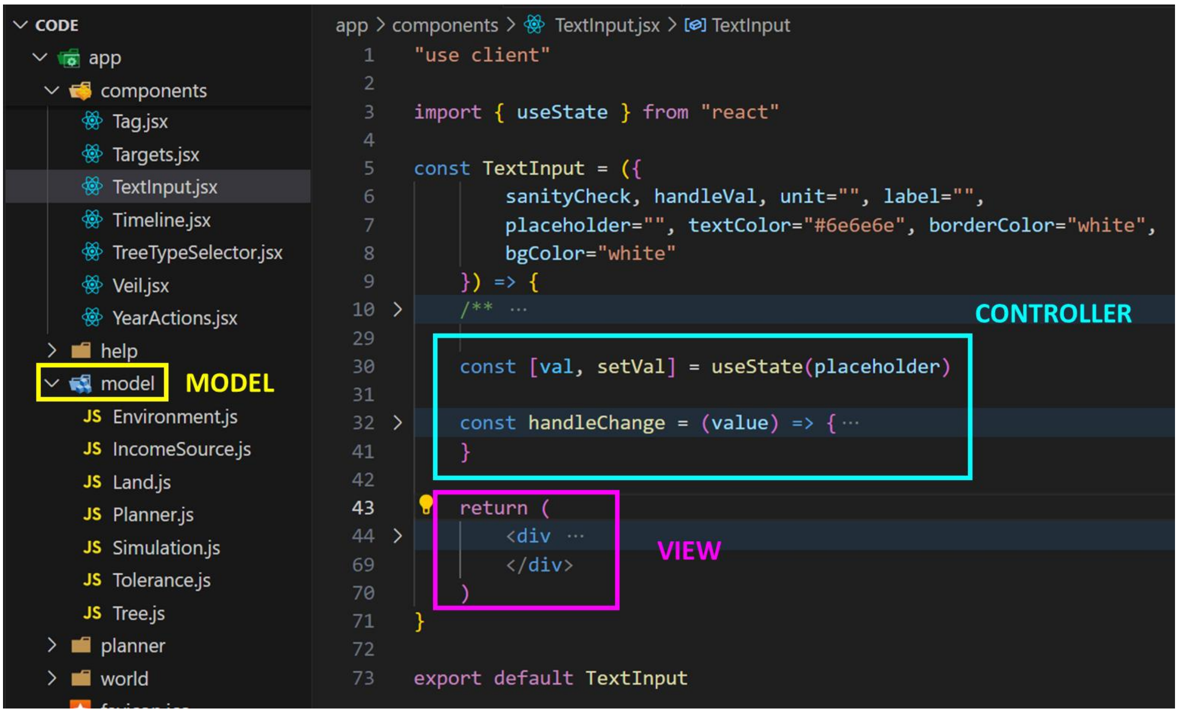

Figure 43. Model View Controller separation in code.

The entire simulation model is contained within a global `sim` variable in the world/page.jsx file. Both UI components and controller logic access this same model, thereby adhering to the Single Source of Truth (SSOT) SW engineering principle [140].

3.5.3 Code Re-Design

The importance of following software engineering best practices was experienced first-hand during project development. Figure 44 shows the difference in code structure between an early MycroForest prototype and the current version.

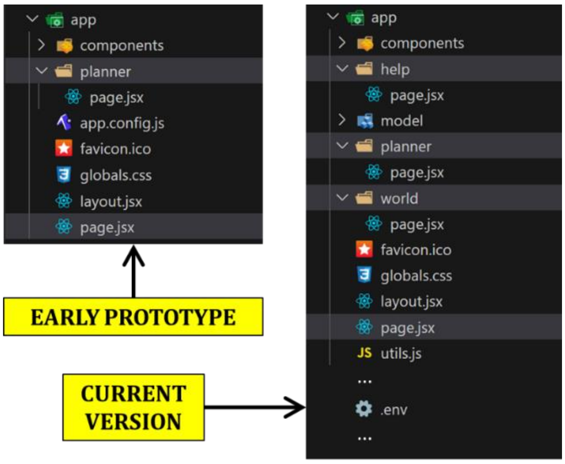

Figure 44. Early prototype v/s now. Difference in code structure.

The underlying simulation model of the prototype is very similar to the current model. UI components, though fewer (since was incomplete), still serve the same purposes as counterparts now (e.g. old LandPlot like new LandPlot, old timeline and new Timeline serve same purpose, old planner has similar plan viewer).

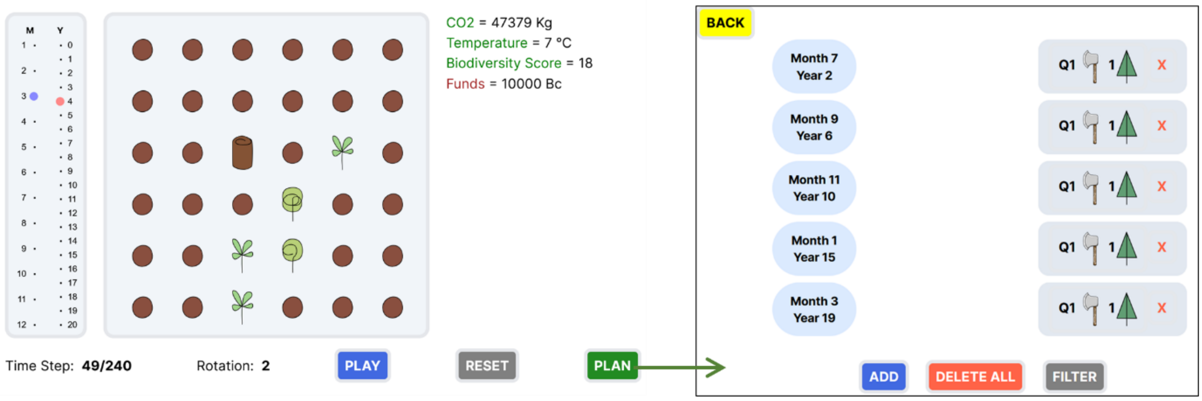

Figure 45. Early prototype.

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 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 it. Thus, to use even just one of these variables, other files had to import the entire object (`import GlobalConfig from '../app.config.js'`). In new code, all simulation model hyperparameters (input variables) are maintained separate from the rest of the application in an environment file (.env). Any other file can access individual variables via `JSON.parse(process.env.NEXT_PUBLIC_<VARIABLE_NAME>)`. This made it much easier to change configurations (edit hyperparameter values, add/delete parameters) without affecting the rest of the code. The latest version maintains global miscellaneous functions used by multiple files in another utils.js file which 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 later approach. In the early prototype, simulation model classes, and all other functions were placed in a single World.jsx component that was imported into the main landing page. This violates 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, focus was on brining designed 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 took a back seat. Soon, this monolithic codebase was extremely difficult to work with, primarily because code was very hard to change. Hours had to be spent investigating highly coupled function calls to find sources of error or areas for improvement. Further, changes often broke functionality at multiple, even directly unrelated, 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. This time, good coding practices were incorporated throughout development and quick fixed were no longer favoured over more long term solutions.

As a result, the current codebase is very flexible. Multiple changes were made in response to supervisor feedback leading up to the Bridge2College session with minimal code breakage and need to re-write entire 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 is important as it directly affects amount of CO2 in the air (faster tree regeneration sequesters some carbon that would otherwise have been lost due to decay and prevents it from re-entering the atmosphere). Such as change involves multiple code alteration (e.g. land content representation changes from 2D array to 3D array, `isLandEmpty()` function significantly changes to consider a spot with a partially decayed tree as empty for new plant growth, etc.). Given the new, modular and well-commented codebase, it was possible to identify areas that needed to be changed and administer edits quickly. The new feature was implemented and deployed in just 1 day. With the old code structure, this likely would have cost multiple days.

3.5.4 Object Oriented Programming in JavaScript

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 central to OOP. A class defines an object. It is a blueprint using which multiple objects may be created [141]. Objects in JS look like `ObjectName = {prop1:value, prop2:value, …}`. Beyond syntactic sugar, ES6 classes work just like constructor functions and implement prototypal inheritance, which was an earlier way to achieve OOP behaviour in JS [141].

```
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")}
}
```

In JS, methods and functions support abstractions by being nestable or combinable with other function outputs. The constructor method initializes objects. The `new` keyword creates a new object (e.g. `exampleObject = new ExampleClass("John")`). Public attributes, like `publicProperty` above, can be accessed by any object in the program, while attributes or functions with a # symbol are private and restricted to their defining class, enabling encapsulation. Prepending an underscore _ indicates "protected" status, accessible to child classes but not to others. This is developer etiquette only and not a language-enforced rule. Inheritance is enabled by the `extends` keyword and using the same name for a function/variable allows polymorphism through redefinition.

The simulation model in MycroForest abides by OO principles to ensure code modularity, reusability, maintainability, flexibility, extensibility, and good organization.

3.5.5 Simulation Model

Figure 46 captures OO design of the simulation conceptual model in a class diagram.

Objects of the blue `Tree`, `Land`, and `Environment` classes comprise ABS components, and the green `Planner` class contributes to 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.

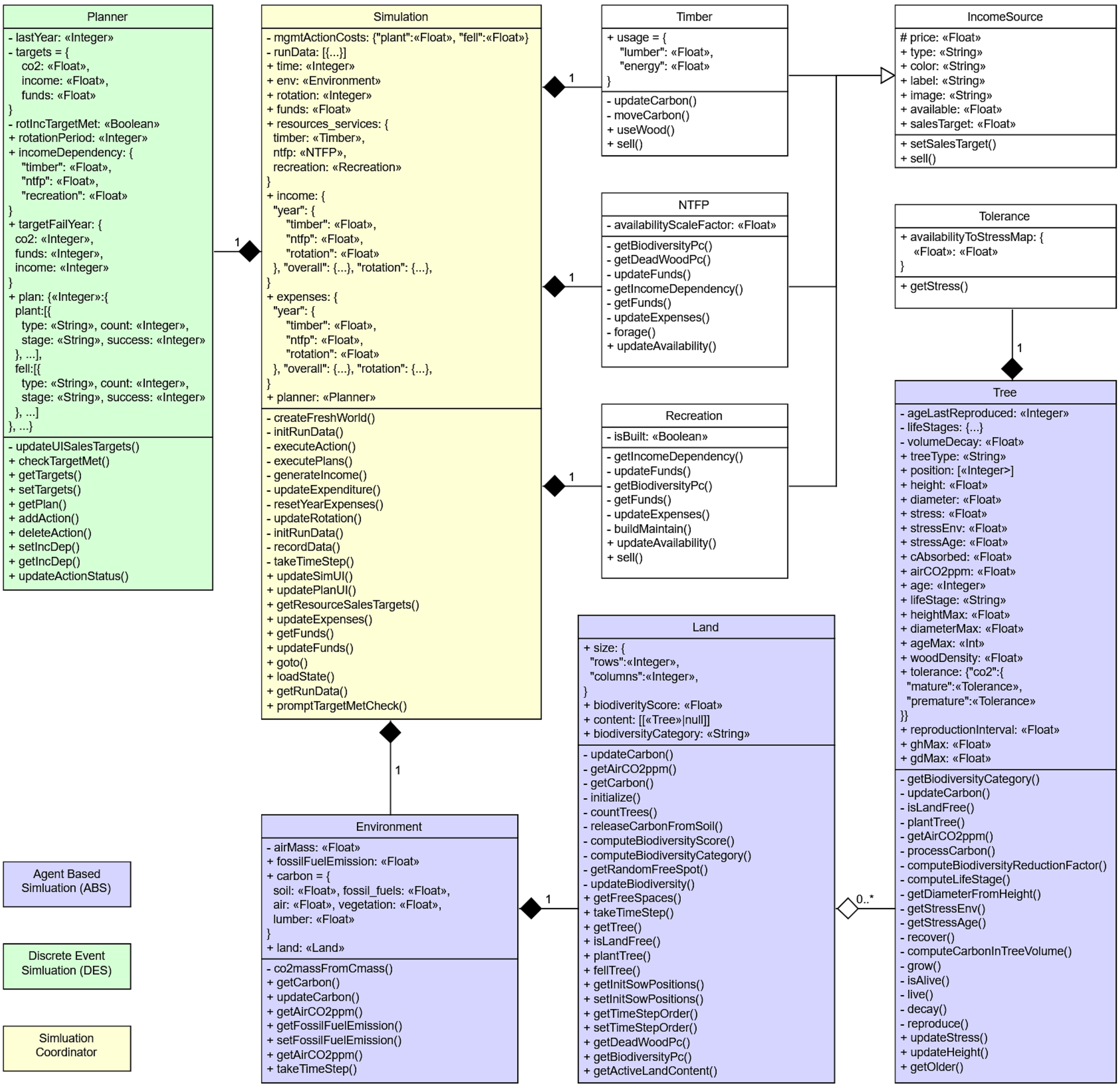

Figure 46. Simulation model class diagram.

Explained below, are key aspects of the 10 classes comprising the simulation model.

Class – Planner

This class facilitates the creation and updating of forest management plans and other learner decisions, such as 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 in the `plan` attribute as a JS object, where each year maps to an object containing management actions ("plant" and "fell"). Each action includes details like no. of trees affected, tree life stage, tree type, and action success status. This `plan` functions like a priority queue in a DES, with earlier actions executed first. Figure 47 displays object structure of a `plan` beside its graphical representation.

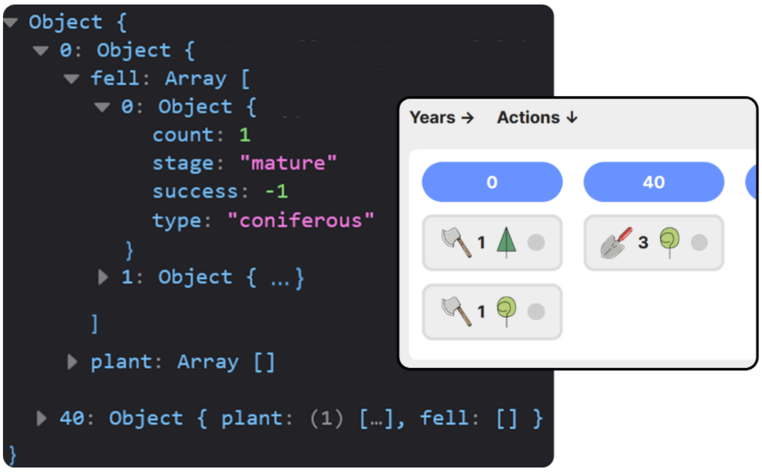

Figure 47. Code representation of management plan.

Initially, `plan` was implemented as an array of year-action mappings, like `[{year:1, action: {actionType: "plant", count: 1, treeType: "coniferous", …}, …}]`. However, this approach was abandoned due to higher time complexity (O(n), with n = 300 years) since it would require searching the array to find and delete actions. The current approach uses a JS object with only years that have planned actions as keys, saving memory. Management actions for next planned years execute only when simulation time matches that year, thereby implementing "Next Event" time advance.

Functions `addAction(…)` and `deleteAction(…)` are called to add/delete actions. The function `checkTargetMet(…)` returns whether given air CO2 concentration or rotation income value meets current set targets. When learners update target text fields, the `setTarget(…)` function updates private `targets = {co2:float, income:float}`.

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

Thus, the Planner class manages all 3 DES steps including execution of calendar (plan) events (management actions) and composite processes as well as triggering of UI and system state updated via `executePlans(…)` and direct/indirect influence on other components like `RotationPeriod`, `Targets`, and `ActionManager`.

Class – Environment

This class defines simulated environmental conditions 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 from .env file with all Input Variables). This class provides functions like `getCarbon()` and `updateCarbon(…)` that facilitate carbon flow. `Land`, `Tree`, and `Timber` objects use these functions to add/remove to/from carbon reservoirs.

The `getAirCO2ppm()` function is important because it computes air CO2 concentration based on carbon in air (`carbon[air]`) and mass of the atmosphere (`airMass`). Mass of carbon in air differs from mass of CO2 in it since CO2 has 2 added Oxygen atoms. Thus, the `getAirCO2ppm()` function calls `co2massFromCmass(carbon[air])` to compute mass of CO2 based on mass of carbon and molar mass of CO2 as follows.

```
this.getAirCO2ppm = () => {
      /** Computes conc. of CO2 in air given mass of Carbon in it.
        * @return: Concentration of CO2 in the atmosphere in 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 C, returns that of CO2 assuming all C exists as 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 to track amount of carbon to be released into air from the fossil fuels reservoir per year, emulating anthropogenic fossil fuel usage. Initially, this was a public attribute. Later, it was changed to be a public "static" variable because upon simulation reset to year 0, the environment object is recreated. Value of `fossilFuelEmission` can be changed by the user. When a preexisting Environment object is replaced with a new one, all its public variables are re-initialized with default values, meaning that the user would need to re-enter chosen `fossilFuelEmission` value after each time they `goto(0)`. Making fossilFuelEmission static public, avoids this. Unlike public variables that get created and destroyed along with object instances, static variables retain value as long as there is at least one object of the class.

The EmissionsFossilFuels UI component through which learners both view and set fossil fuel emission levels, interacts with the Environment object to use getFossilFuelEmission() and setFossilFuelEmission(…).

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 mechanism. Environment's takeTimeStep() involves first emulating fossil fuel usage by moving 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 in Environment's land attribute.

An Environment object is key in the carbon flow ABS since it both acts like an agent and independently updates carbon reservoirs (air, fossil fuel) via takeTimeStep() alongside being an environment that other class objects interact with given that it provides functions (getCarbon(), updateCarbon(…)) that update carbon reservoirs.

<u>Class – Land</u>

Main responsibilities of a Land object are as follows.

- **Spatial Representation:** Attribute size stores no. of rows and columns in land grid. **Land Content Management:** Attribute content holds information about tree distribution. It is a 2D array wherein each element represents a grid cell and can either contain an empty list [] or a list with 1 or 2 Tree objects such that only 1 among them is alive. Initially, all land [x, y] positions contained either null or a single Tree object (dead/alive). This was abandoned for the current design where grid cells contain a list, because this allows new trees to exist at the same spot while a dead one is partially decayed. This behaviour was implemented in adherence to the suggestion from Dr. Caldararu to better represent real-world plant behaviour. Functions plantTree(…) or fellTree(…) may be called to add or remove trees. The Simulation object leverages this while executing planned management actions. A tree can be added only on free spots. The isLandFree(…) function checks if a given spot is free. A spot on the land is considered free for planting if it is empty (content [x, y] = []) or if there is only 1 decayed tree on it with half of original max height remaining. At any point in the simulation, only the last added tree is considered to be active and will get displayed on screen. The getActiveLandContent() function returns a land spot's active content. If another tree exists 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 as this is what the learner can interact with (it is not possible to chop, fell, or execute any other action on decaying trees). Upon initialization, 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. An alternative is to present learners with empty land, allowing them to determine age/species composition and grow a forest from scratch through inoculating land with seedlings via a management plan. 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 random seedling positions and update order, land composition changes with each browser refresh. Thus, 2 global variables (`initSowPositions` and `timeStepOrder`) store initial seedling positions and land spot update order to ensure that upon returning to the world page from the planner page, starting composition and land spot update order remains same, reproducing initial states.

- **Soil Carbon Release:** Soil naturally loses a certain portion of its carbon content per year. The `releaseCarbonFromSoil()` function simulates this. `Land` is considered an ABS agent because is interacts with the `Environment` and moves carbon between soil and air.
- **Biodiversity Tracking:** A `updateBioDiversity()` function calls 2 others, `computeBiodiversityScore()` and `computeBiodiversityCategory()` to compute $B = \frac{B_{species}+B_{age}}{2}$ as discussed in section 3.4.1. This requires counting no. of trees, facilitated by the private `countTrees()` function which returns tree counts in a JS object `{deciduous: count, coniferous: count, seedling: count, sapling: count, mature: count, old_growth: count, senescent: count, dead: count}`.
- **Simulation Advancement:** The `takeTimeStep()` function implements time step updates. 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 natural annual soil carbon loss before finally updating biodiversity score and category.

Class – Tree

The `Tree` class represents an individual tree as an agent. 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 here, is `getOlder()` which the Land class triggers from its own `takeTimeStep()` function. Function `getOlder()` emulates all independent annual life functions of a tree (aging, stress recovery, growth, reproduction) if it is alive or the process of decaying, otherwise.

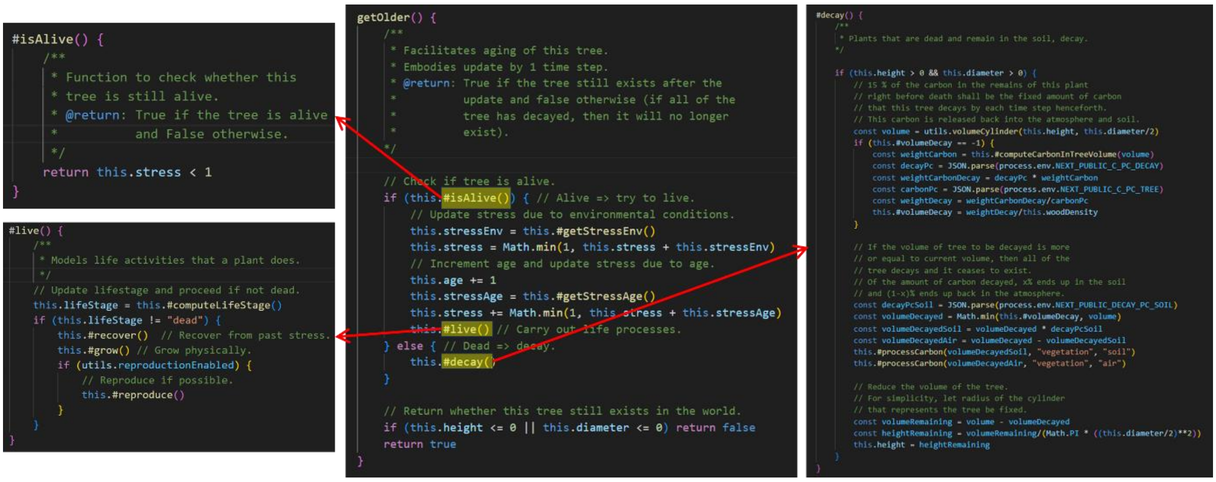

Figure 48. Tree class getOlder() and composite functions.

Trees die when stress from environmental conditions or aging exceeds 1. In each simulation time step, the `getOlder()` function increments tree age and compounds environmental and age-related stress. If the tree is alive, the `live()` function is called. It allows the tree to recover a portion of past stress based on remaining health using the `recover()` function. The `grow()` function models tree growth and transfers carbon from the air to vegetation reservoir, using the `processCarbon(…)` function, which interacts with the Environment object to update carbon reservoirs. The `grow()` function also moves carbon from air to soil, simulating carbon lost due to shed biomass. The `processCarbon(…)` function transfers carbon after scaling by a factor of 2.4e+8 to simulate impact of entire real-world forests using at most 36 trees. If the tree is dead, the `decay()` function is called instead of `live(), which` transfers carbon from the vegetation reservoir to air and soil to model decomposition.

Class – Tolerance

The Tolerance class manages the mapping between environmental conditions and stress experienced by trees. The `getStress(…)` function returns tree stress level based on resource (CO2) availability. The private attribute `availToStressMap` stores predefined mappings of CO2 concentration to stress levels. This class may be designed to be extendable, allowing for future additions of other environmental factors (e.g., sunlight, water, temperature) by having it be a generic template so that child classes representing each factor may inherit from, and extend it.

Class – IncomeStream

Generating income involves selling products (timber or NTFPs) or services (recreational activities). This class captures general characteristics of an income stream, including attributes like `available` (quantity of the resource/service) and `price` (selling price per unit). It has a public `sell()` function, which calculates income as `available` × `price`.

Class – Timber

This class extends `IncomeStream` to handle timber sales from the forest. It introduces the `useWood()` function, which simulates timber being used for lumber (e.g., construction, furniture) and for generating electricity. These uses produce different amounts of carbon emissions. The private `moveCarbon()` function adjusts carbon levels in air and lumber reservoirs to reflect how lumber usage locks carbon away, while burning timber releases all stored carbon into the air.

Class – NTFP

This class extends `IncomeStream` to handle income from NTFPs like honey, berries, and mushrooms. Unlike timber, which becomes available based on tree felling decisions, NTFP availability is modelled using a normal distribution influenced by biodiversity score and deadwood. The `forage(…)` function calculates cost of employing workers to harvest NTFPs. The `updateAvailability()` function, called by the `Simulation` object's `takeTimeStep()` function, computes the amount of NTFP available per timestep.

Class – Recreation

This class extends `IncomeStream` to generate income from selling forest visit permits or event tickets. Visitor numbers are modelled using a normal distribution by `updateAvailability()`. Employee wages and a one-time infrastructure cost for creation and maintenance of forest recreational services is computed by `buildMaintain()`.

Class – Simulation

An object of this class serves as the gateway to the entire simulation model, coordinating all other objects and implementing the time step mechanism with two functions: `takeTimeStep()` and `goTo()`. The `takeTimeStep()` function updates all simulation objects for one year, as shown in the following code snippet..

```
#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()
}
```

The `takeTimeStep()` function is triggered by `goTo()`, which is crucial for navigating the simulation timeline. It takes target year as input, computes the number of timesteps between the current and target year, and updates system state accordingly. If the target year is ahead, `takeTimeStep()` is called multiple times to advance the simulation. If it is behind, the simulation is reset with `createFreshWorld()` before advancing. The `updateSimUI()` function refreshes the UI with latest state. When the learner presses the play or the next/previous step button in the `Timeline` UI component, a loop advances the simulation by 1 year every 100 milliseconds, creating a smooth animation effect.

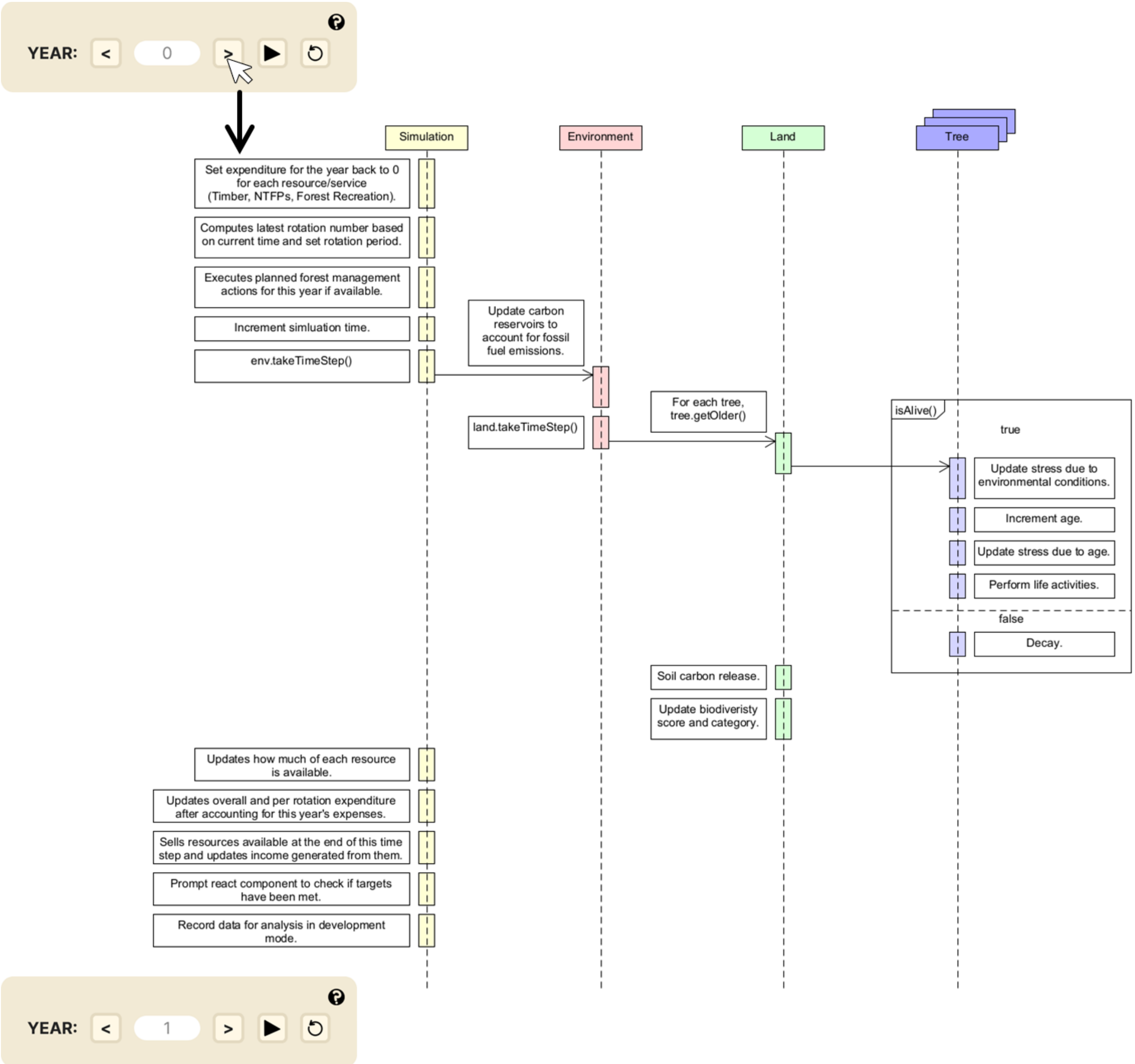

Figure 49. Graphical display of event flow within one user initiated timestep.

3.6 Summary

This design section covered project scope, pedagogical approach, HCI design, system design, and technical design choices. Throughout, collaboration with domain experts in education technology and environmental science ensured correctness of underlying simulation model and effectiveness of MycroForest as a teaching tool.

Project scope includes developing a user-friendly interface that provides realistic cause-and-effect simulations of forest management strategies on land composition and atmospheric CO2 levels, excluding detailed biochemical processes. The tool supports learning through gamification, where users set and achieve goals related to CO2 levels and income generation. Functional and non-functional requirements prioritize user experience, educational value, and system performance.

Pedagogically, MycroForest integrates elements from simulations, microworlds, and gamification to enhance learning. The tool supports constructionist self-regulated learning (SRL) by allowing users to explore and manipulate variables to design and evaluation of custom forest management plans. Also proposed were 5 structured challenges that align with established learning theories and incorporates storytelling tactics to make the learning activity impactful and engaging.

Research highlighted the importance of good UI and UX for effective learning. Therefore, MycroForest's design followed HCI and data visualization principles, such as Norman's Model and Nielsen's Usability Heuristics. This section detailed design of key application pages, UI interactions, and associated rationale. Data visualization theory considered was also discussed w.r.t what data was visualized, why, and how. MycroForest's interface is graphics-heavy with minimal text, familiar icons, and built-in help to guide users.

MycroForest is a standalone, client-side static web application with no separate backend or database. Its system architecture comprises three main components: the simulation model, UI components, and input variables. The simulation model, detailed with the research and logic behind its design and variable selection, manages all microworld entities and oversees the flow of money and carbon. Key input variables and the organization of UI components are also discussed.

Technical design of MycroForest is structured around reusable React components promoting modularity and reusability. System and codebase design followed good software design practices like the model view controller design pattern, separation of concerns, object oriented programming, single source of truth and don't repeat yourself. The tech stack incorporates frameworks like NextJS and ReactJS along with classic web technologies like JavaScript. A Continuous Integration and Continuous Deployment (CICD) pipeline facilitated by GitHub (for version control) and Vercel (for deployment) ensured continuous delivery in adherence to adopted agile workflow. Notable coding choices and simulation model class diagram was also explained in this design section.

Overall, design, architectural and technical decisions discussed in this design section ensures that MycroForest is both user-friendly and technically robust, providing a smooth and effective learning experience.

4 Implementation

This section discusses development methodology adopted and few key challenges faced.

4.1 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.

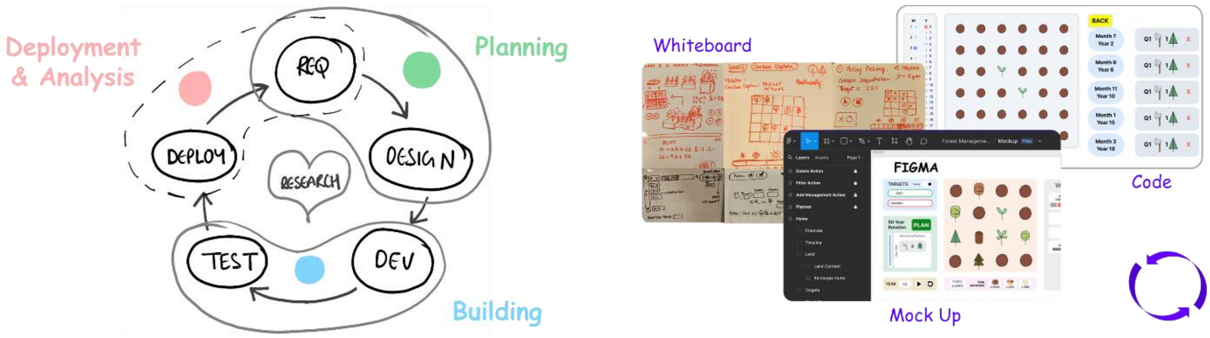

Figure 50. Agile strategy and iterative workflow.

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 [142]. Main associated advantages include greater flexibility (frequent changes allowed), lower risk (complex projects broken down into smaller parts), better communication (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, agile is also widely adopted in Software Development (SW Dev) [143].

There exist many flavours of Agile for SW Dev like SCRUM, KanBan, and XP, [143] but the Agile strategy itself is a broad set of ideas originally laid out in the Official Agile Manifesto. Here, the overarching aim 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-large teams in corporate settings. Considering 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 ability to diligently stick to steps in an established framework.

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 resembling a product backlog (inspired from Scrum) wherein features were checked off after implementation and testing. Table 23 provides a glimpse of a portion of this product backlog table. It helped 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 to ensure delivery of new valuable project artifacts (e.g. simulation concept model update, UI mock-up, etc.) or developed working features at each 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

Table 23. 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, to set up CICD such that every new feature pushed to GitHub, triggered deployment of a new version of MycroForest.

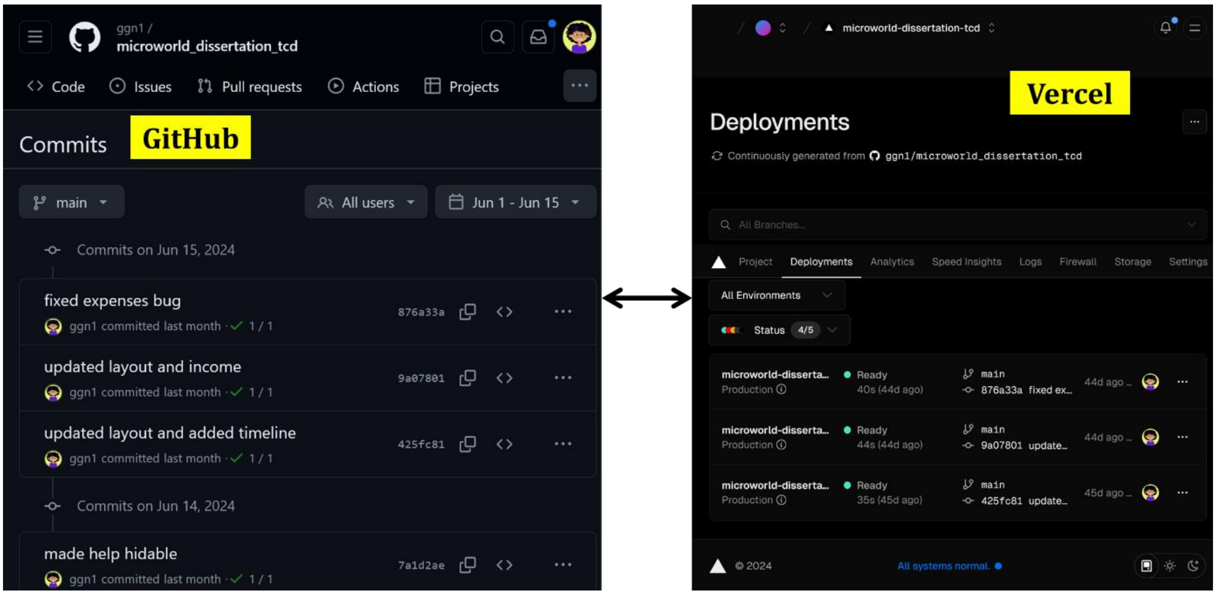

Figure 51. GitHub - Vercel CICD.

4.2 Project Timeline

Figure 52 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

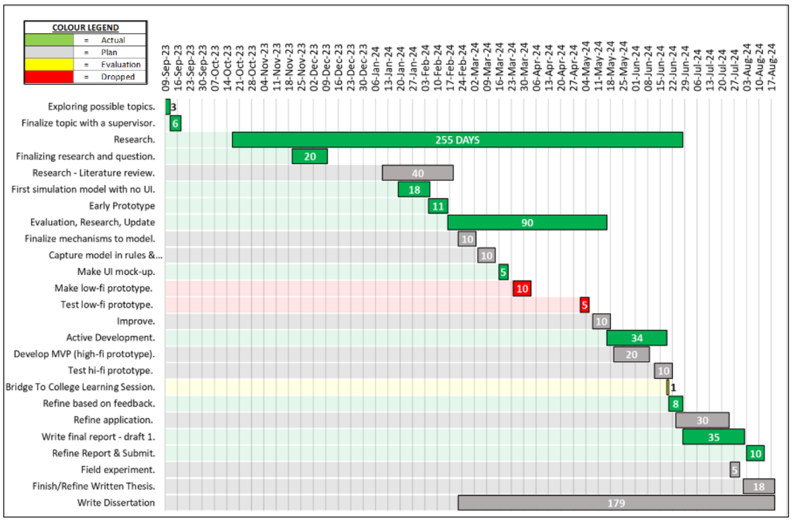

Figure 52. Project Timeline - Plan v/s Actual. Gray colour represents the original plan. Green colour is associated with the actual schedule of planned task execution. Red indicates originally planned tasks that were dropped, and yellow highlights the Bridge to College Learning session when students 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 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, and the order in which tasks were completed were gathered from GitHub commit history. All activities related to this project is available on GitHub spanning 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 paragraphs 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 simulation model v1, which initially had air CO2 levels, temperature, and water as environmental stressors. Land plot was to be split into 4 quadrants to mirror real-world forest sub-plots. The model was to simulated time in days, months, and years, factoring in seasonal temperature variations. Timber demand was to be the primary target that users set and tried to meet.

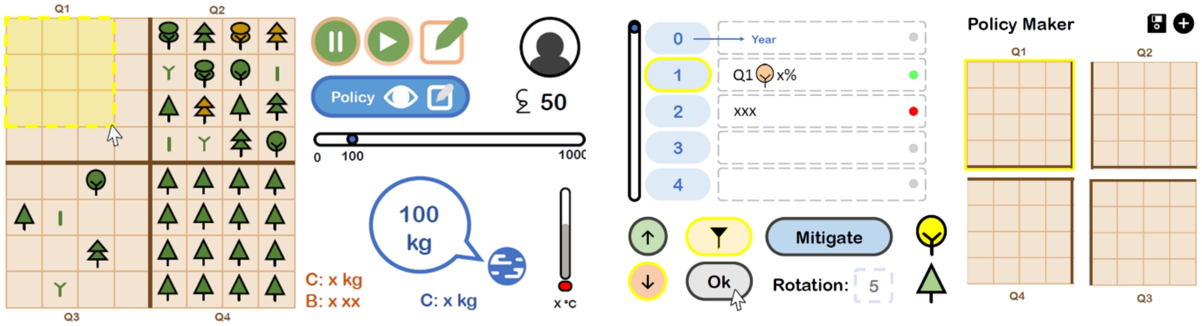

Figure 53. First mock-up of the tool made using MS PowerPoint.

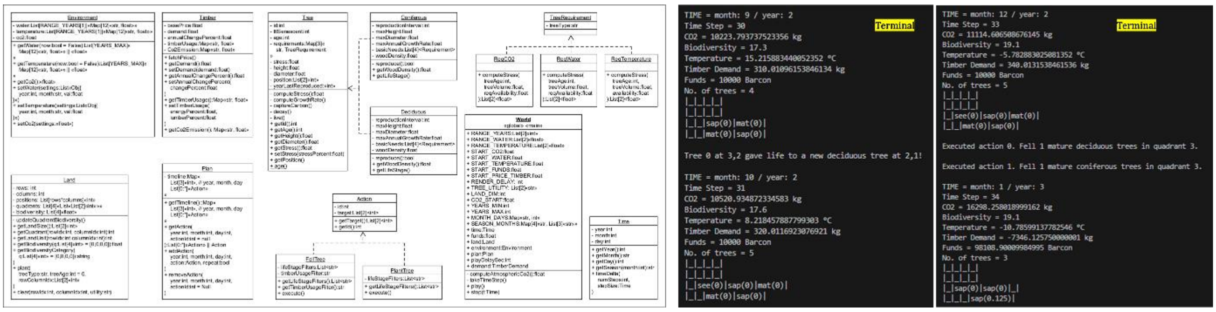

Figure 54. Initial simulation conceptual model and rudimentary printed terminal output of land changing land content and environmental parameter values.

(28 Jan 2024 – 03 Feb 2024): Implementation of forest growth as part of simulation model v1 is complete. However, all logic is in a single World component with no SoC. There are no global variables that store model hyperparameters and separate them from rest of the program. Output is printed on the terminal. There is no UI. Also, the management plan is coded as a list with a nested list for each day in simulated time.

(04 Feb 2024 – 05 Feb 2024): Forest management actions (plant, fell) have been developed. Time step duration was changed from day to month. The forest management plan is now coded 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 work as expected. Target setting and user interaction apart from timeline controls is yet to be implemented. No alternate income streams. All logic is still in 1 World component although there is a separate file for simulation hyperparameters.

Figure 55. Early web-based partially working prototype.

(16 Feb 2024 - 15 May 2024): Early prototype is analysed for efficiency and scope of improvement. The decision is made to re-implement it, this time, more closely following good design principles as previously discussed in section 3.5.3. The tool was simplified. Research informed better simulation model hyperparameter values and helped determine parts of the original conceptual model to retained v/s discarded. Key decisions made includes: • Let time step = 1 year. • Introduce other income streams. • Focus on CO2 as only explicitly modelled environmental stressor w.r.t tree growth. • Get realistic simulation model hyperparameter values. • Introduce lumber carbon reservoir. • Add plan viewer on home page. • Add landing page, help icons, help page. • Finalize challenge ideas. • Display income and expenses in its own panel. • Let CO2 concentration be main climate change indicator. • Introduce fossil fuel usage emissions and fossil fuels carbon reservoir. • UI mockup.

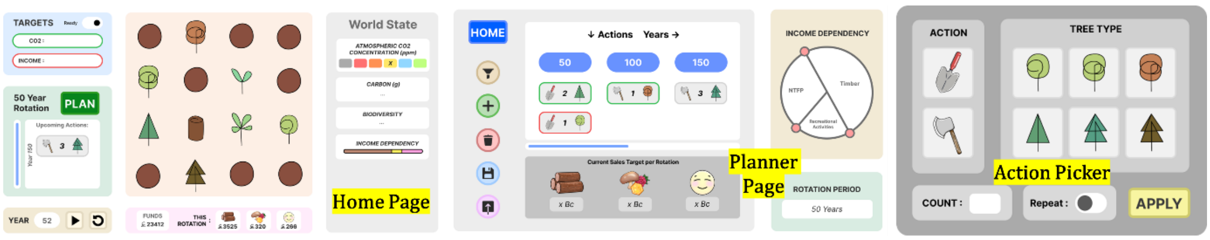

Figure 56. More complete mock-up made using the Figma application.

(16 May 2024 - 26 May 2024): A new GitHub project hosts the improved tool idea with a stronger, more practical conceptual model and UI shall be developed in closer adherence to good development practices. A stable (forest survives, atmospheric CO2 level fluctuation is less extreme) carbon cycle was achieved. Plant growth model along with the timeline panel, CO2 panel, carbon distribution panel, and biodiversity information panel was implemented. Planner page does not exist. Simulation model is OO.

Figure 57. Output after initial stage of home page implementation using re-defined conceptual model and UI design.

(27 May 2024 - 1 June 2024): Target setting and monitoring is complete. Management action picker UI components and basic features like action creation or deletion is done.

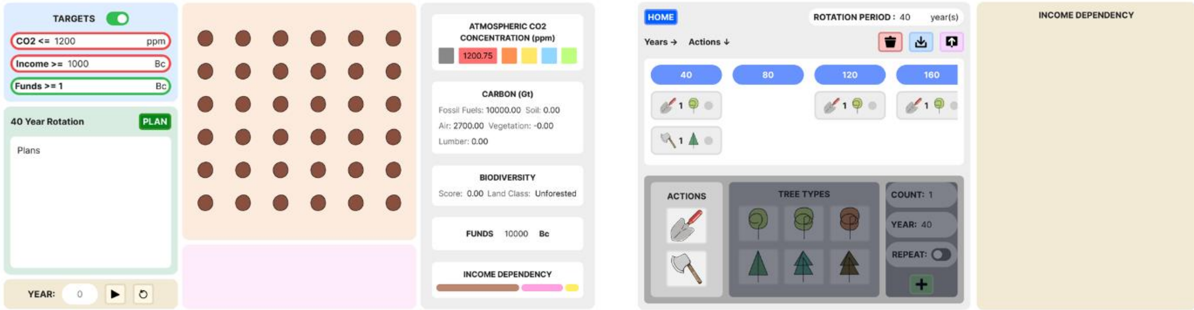

Figure 58. Output of the phase wherein implementation of the planner page had begun.

(02 June 2024 – 11 June 2024): Landing page is added. Other income streams are incorporated. All home page panels are implemented. Selective panel reveal to enable model progression across challenges added. All implemented features are fully working.

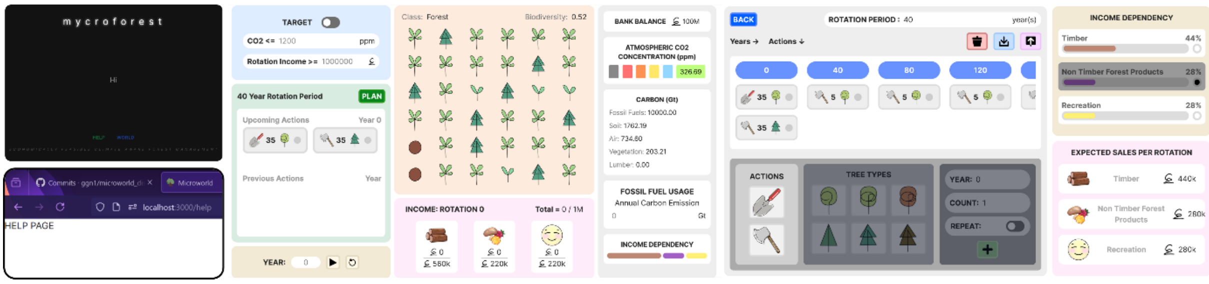

Figure 59. Preliminary complete implementation of all planned features and pages.

(12 June 2024 – 18 June 2024): Simulation model parameters more realistic upon further research. User guides in the form of easily accessible ❓ icons and a help page is added. A 5 minute [introductory video]() is created to quickly inform learners of tool features at the Bridge2College learning session on 19th June 2024. Initial form of virtual currency called "Barcon" is replaced with the simpler, more universal "coin". Money viewer is implemented. It is made possible to step through the timeline one year at a time via addition of single time step buttons < and >.

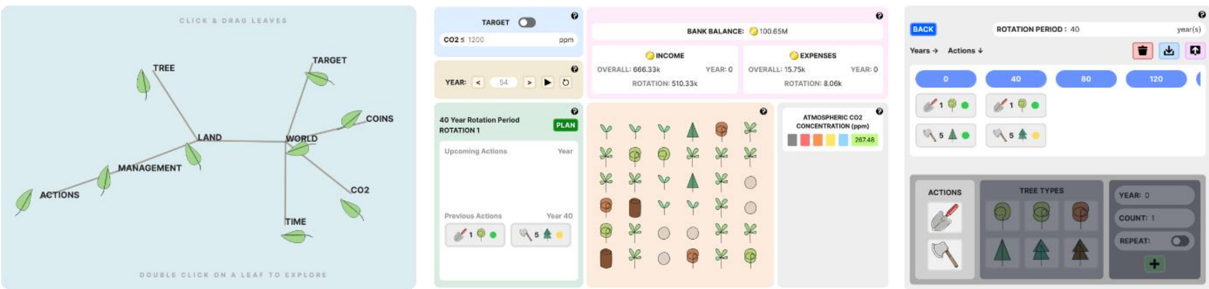

Figure 60. Version of the application that students in the Bridge to College program evaluated. The current implementation is almost identical to this one with only minor changes as per feedback. Students only attempted 2 of the 5 challenges. Hence the image only depicts those features that were visible to the students over the 2 challenges.

(20 June 2024 – 27 June 2024): Tree Age information added upon hovering over land content icons and colour is used to distinguish between seedling and sapling icons of different species in response to learner and evaluator feedback. Text and graphics in user help guide is made simpler and more comprehensive. Other income stream activation is made binary instead of continuous between 0 and 100% as it was realised that the latter is flawed given that it is not the norm (i.e. just because a forest owner plans to rely on NTFPs for only 5% of their target income, would they not still harvest and sell if more than 5% worth of income is available as NTFPs). Forest owners either fully committing to an income stream or not considering it at all (binary activation) is more realistic and easier to comprehend. A new option to view income stream based breakdown of "income" and "expenses" in the money viewer is implemented. An attempt was made to consider the ocean as an additional regulator of the carbon cycle by introducing water as another carbon reservoir to make the model more realistic. This however proved to be extremely challenging due to complex chemistry (air-water carbon exchange is complicated given the need to model partial pressure of CO2 in air and water; moreover, carbon is present in multiple carbon cycle relevant non-gaseous forms in water [144]) that needs to be modelled accurately for stable model behaviour.

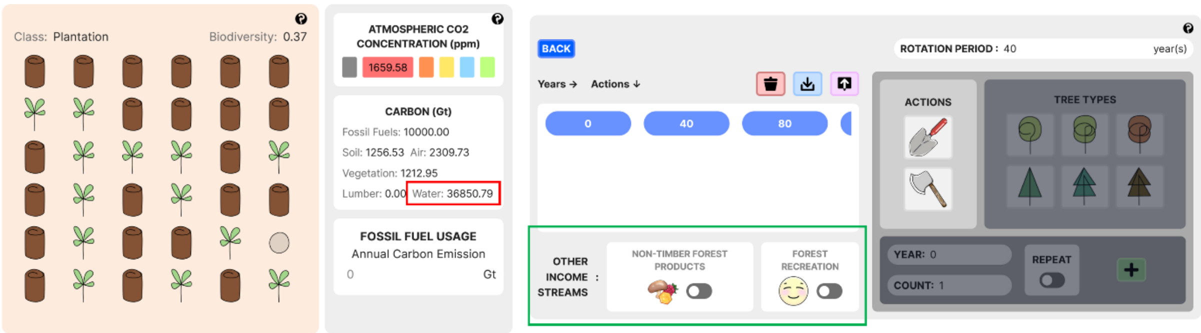

Figure 61. Output showcasing attempt to incorporate the "water" carbon reservoir and the change of income streams from continuous quantitative to binary activation.

(28 June 2024 - 1 Aug 2024): Trying to include the water carbon reserve led to high model instability (atmospheric CO2 levels fluctuated very quickly). Thus, this idea was dropped given that it only served to further complicate the model with no added educational value. Code base was cleaned to removed unused components. More comments were added to improve understandability. This was end of active development. Focus shifted toward preparing this document.

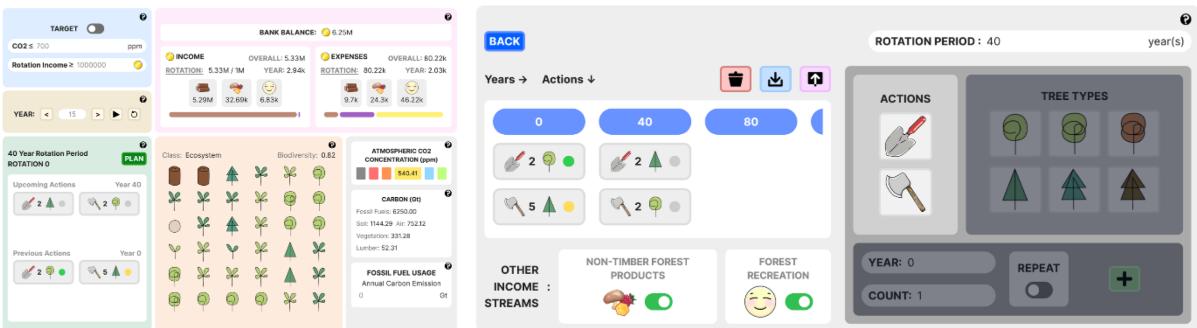

Figure 62. Home and planner pages of the final complete application at the time of submission (challenge 5 view).

(3 Aug 2024 - 15 Aug 2024): Refinement of this document and submission.

4.3 Challenges Faced

Several challenges were faced during this project. Following paragraphs highlight a few.

Complexity Management

Challenge: A major challenge was finding the right level of complexity for the tool. As advised by the supervisor, beginning with creative, divergent thinking, ideas were too grand for scope so convergent thinking followed which narrowed down ideas to what could realistically be achieved. Determining parts of initial broad ideas (find examples in Appendices 8.7) to retain v/s discard, was challenging.

Solution: The solution focused on retaining only elements directly related to afforestation/deforestation, carbon levels, and forest income. Guided by research and a domain expert, many ideas were discarded (e.g. trees getting diseases, detailed land properties like slope/elevation, disaster mitigation management action, etc.) and others were simplified (e.g. trees categorized as "coniferous" and "deciduous" instead of specific species). This ensured that the tool remained focused on the educational goal of illustrating connection between forests, CO2 levels, and financial motives behind deforestation, without overwhelming young learners.

Other Income Streams

Challenge: Looking for income streams other than timber to incorporate within the application to educate about alternate means of income from forests other than wood sales, hunting/fishing and carbon offset credits were considered alongside NTFPs and forest recreation. Presenting too many options can confuse/overwhelm learners. Thus, it was decided to pick 2 other streams to complement the default timber income stream. Determining which among 4 identified options to retain, was challenging.

Solution: NTFP and forest recreation income streams were retained. Hunting/fishing was dropped as according to the domain expert, in the real world, this is often overexploited causing biodiversity loss and forest health decline. Hence, presenting income generation from hunting/fishing permits as sustainable/climate-friendly was deemed inappropriate. Projects like a Reduced carbon Emissions from Deforestation and forest Degradation (REDD+) [145] one as may be applied to the virtual forest in MycroForest, can earn 1 carbon credit per tonne of CO2 or equivalent GHG that it stores, reduces, or avoids from entering the atmosphere. These credits are sold to entities like companies who claim it to have compensated for their carbon emissions [146, 147]. While intended to promote carbon neutrality, effectiveness of carbon credits is debated [147, 148]. High integrity carbon offsetting is notoriously difficult to ensure as verifying project effort validity, estimating amount of carbon offset (unintentional or intentional under/over estimation possible) and determining accurate baseline emissions that would have been emitted were it not for the project, is very difficult to do. Thus, carbon credits are often "junk" (i.e. void) due to projects failing to sequester agreed amount of carbon, overstating amount of carbon offset or the credit having already been used to compensate emissions elsewhere. Moreover, there is the issue of "offset and forget" wherein the very real possibility that bought credits re-enter the atmosphere sooner than estimated is ignored. Thus, carbon offsetting is often considered an "accounting trick" that is likely to lead to more harm than good w.r.t climate change by encouraging buying carbon credits and continuing to emit GHGs instead of real decarbonisation efforts like switching to renewable energy. Negative impact of carbon offsetting is aggravated given the fact that a large portion of carbon credits is likely junk, meaning that net effect is increase in GHGs [145, 146]. Thus, the decision was made to avoid presenting carbon offset credit sales as a climate friendly source of income from forests.

<u>Precision Loss</u>

Challenge: JavaScript, the main language for logic of this tool, struggles with floating-point arithmetic and large integers. When handling global-scale numbers (e.g., atmosphere mass = 5.1e+21, carbon in fossil fuels = 6.25e+18, etc.), computation errors and NaN values occur.

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

<u>Land Content Icon Transition</u>

Challenge: Forest composition changes in response to learner actions show be visualized smoothly. For example, a sapling icon should morph into a mature tree icon. Using separate images for each land content type icon and replacing one with the next created choppy transitions, leading to poor UX which could distract learners.

Solution: Icons were defined using properties of a single SVG `<path>` element. By changing "d", "scale", and "fill" of this path and using `.transition().duration(50)` functions from D3.js, smooth transitioning is achieved, allowing fluid morphing of icons representing different stages of tree growth, thereby ensuring visual coherence.

<u>Tree Composition</u>

Challenge: Earlier, coniferous trees dominated land after the 200-year warmup period, regardless of initial composition. This unrealistic outcome, confirmed by a domain expert, made the simulation less suitable for educational purposes, as such dominance is unlikely given assumed ideal conditions and initial seedling mix.

Solution: Frequent single-species dominance could have been due to the model's failure to consider seed dispersal distance. Deciduous trees, with seeds dispersed further by animals due to wide-appealing fruits produced, were not accurately represented. A new rule allowed deciduous trees to spawn seedlings upto positions away, while coniferous trees still only spawned seedlings immediately adjacent to the parent tree. This adjustment gave shorter-lived deciduous trees a fair chance to compete with longer-lived coniferous trees, ensuring coexistence of both species. This modification is one example of how the model was progressively made more reflective of reality.

Rule Organization

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 realistic simulation model for educational use is challenging due to the complexity of capturing forest growth and carbon flow. The process involves numerous decisions, from conceptual parameters to implementation. It is important to ascertain if 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, appropriate for a HS model as in MycroForest. In 2018, T. Eldabi et. al. adapted the Simulation Lifecycle design and implementation framework first proposed by Brooks and Robinson in 2000 in "Simluation" to work with HS approaches [54]. This iterative framework comprising following 5 stages was followed in this project to bring much needed structure to simulation design.

Stage 1: *Real-World Problem* [54] – The goal here, is to understand the real-world problem, identify the target system, and pinpoint key components/mechanisms. The "application area" (broad focus) and "application context" (specific focus) are to be defined. W.r.t MycroForest, application area is "forests and climate change," and application context is "effects of forest management activities on air CO2 levels".

Stage 2: *Conceptual Modelling* [54] – This stage involves abstract representation of the target system, capturing "objectives, inputs, outputs, content, assumptions, and simplifications". Output of this stage could be a document with model components, mechanisms, and underlying rules governing functioning, clearly defined. This stage involves working closely with domain experts to validate designs. In this project, multiple versions of a "world rules" document was produced and was discussed with the domain expert co-supervisor to ensure design soundness. Section 3.4.1 above explained the latest of such conceptual model designs.

Stage 3: *Computer Modelling* [54] – Now, the conceptual model is translated into a computational model involving coding, modelling paradigm integration (e.g., discrete-event simulation, agent-based modelling, and object oriented design in case of this project.), and preparation for experimentation. Section 3.5 states latest technical design.

Stage 4: *Verification and Validation* [54] - 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 repeated until model is realistic enough for specific use cases. To validate the MycroForest model, forest management plans with known outcomes were implemented to see if resulting state updates in the microworld matched real-world effects of those plans. For example, a validation exercise would set up following 4 scenarios 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 known observations [26, 27, 30], which suggests that MycroForest's simulation model is appropriately realistic. Observations reproduced include: • Older forests diminish as rotation lengths shorten. • Longer rotation length promotes old-growth forests, enhances biodiversity, and improves carbon sequestration, but wood income is reduced. • 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 old trees is essential to maximal carbon sequestration.

Stage 5: *Solution and Implementation* [54] - This stage involves incorporating the developed model into the specific solution. Here, developed simulation model + input parameters was incorporated into the rest of MycroForest (UI components, app pages).

4.4 Summary

This implementation section outlined practical steps taken to develop MycroForest, beginning with introduction of adopted Agile development approach, chosen for its flexibility and adaptability which allowed for iterative development and regular feedback integration. The section also provides an account of how goals were translated into working software. What the application looked like at different stages of development and few challenges faced is also discussed.

MycroForest development followed a simple Agile strategy, well-suited to the single-developer, academic nature of this project with 3 stages: planning, building, and deployment. Each stage incorporated research as needed. This enabled frequent delivery of working software and continuous evaluation. Tasks were managed using a product backlog inspired table to track and prioritize them. Regular meetings with supervisors ensured consistent feedback integration into design and development. Version control and deployment using GitHub and Vercel enabled CICD.

Project timeline was initially planned in December 2023, with adjustments made as the project progressed. Some tasks like creating a low-fidelity prototype, were dropped in favour of developing an early software prototype, which provided valuable insights into feasibility of the project. The actual timeline differed from the original plan due to unpredictable demands of other academic commitments. Research was conducted throughout the project, as the interdisciplinary nature of MycroForest required ongoing investigation into various aspects of forest management and simulation modelling. The timeline reflects the iterative nature of the Agile methodology, with tasks being revisited and refined to integrate new knowledge and feedback.

Several challenges were encountered during development. A significant one was managing complexity of the simulation model to balance educational objectives with a manageable level of detail. Other challenges included selecting appropriate alternative income streams, handling precision issues in JavaScript, and ensuring smooth transitions between different land content icons. Solutions involved simplifying certain aspects of the model, using JavaScript libraries (e.g. Big.js for precision arithmetic), and employing D3.js for smooth visual transitions.

Implementation of MycroForest was complex, but largely successful. Agile methodology was effective w.r.t iterative development and feedback integration. It accommodated frequent changes that were required to refine the application. Despite challenges, project goals were achieved through careful planning, regular evaluation, and use of appropriate technologies. The final version of MycroForest is a functional educational tool that aligns with most original objectives.

5 Testing and Evaluation

This section discusses evaluation of MycroForest by TY students (target user base) at the Bridge2College learning session and educator as well as domain expert feedback.

5.1 Pilot Testing

MycroForest was tested by friends/family and educators prior to students at the Bridge2College event. Before educators, it was first tested by friends/family (N=4), all of whom reported a valuable experience with few suggestions as follows.

- Initially, the landing page did not have text reading “CLICK” to prompt learners to click on “Hi” to begin the click-through walkthrough. 3/4 testers did not understand click this text without assistance. This led to inclusion of a “CLICK” prompt text.
- Further, 4/4 testers were inclined to press "H" or "W" keys during the introduction, to navigate to the "Help" or "World" page, interrupting the introductory walkthrough which contains important information about the tool. To address this, a feature was added that blocks navigation and requires learners to complete the brief introduction (if it's their first time taking it) before moving to other pages.
- At first, help was not as comprehensive. Testers expressed need for more details in the user guide like information about the different tree life stages, income streams, carbon reservoirs, etc. Help was thus, expanded with more graphics supporting text.

MycroForest was then reviewed by 2 educators who were to conduct the learning activity at the Bridge2College event, as well as the project supervisor, to assess tool readiness/suitability w.r.t providing a valuable interactive learning experience. (educator review 1) Upon integrating feedback so obtained, an improved version was presented again, to the lead educator (educator review 2) who then approved it for use at the Bridge2College learning session.

During educator review 1 on 14 June 2024, the app (as in Figure 63) was deemed promising but required UI updates and simpler learning activity challenges.

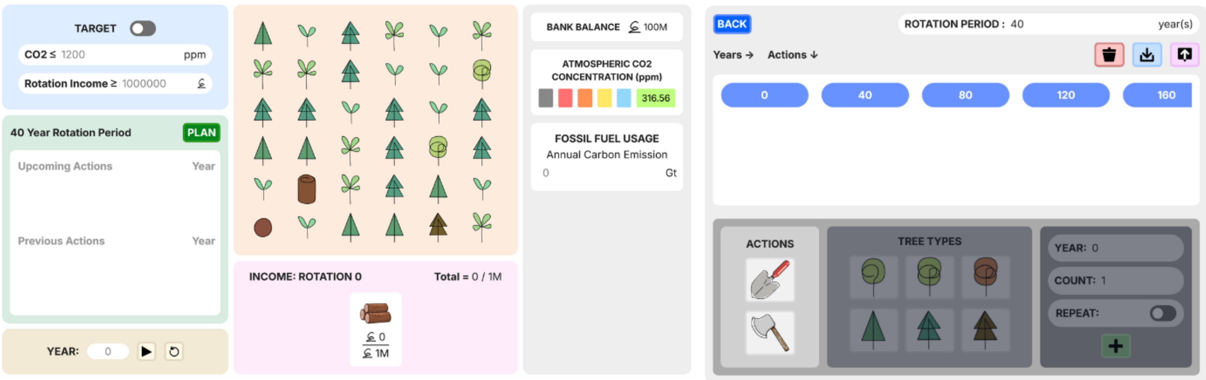

Figure 63. Version of MycroForest first presented to facilitators.

Figure 64 shows 3 challenges initially proposed by this author as learning activities.

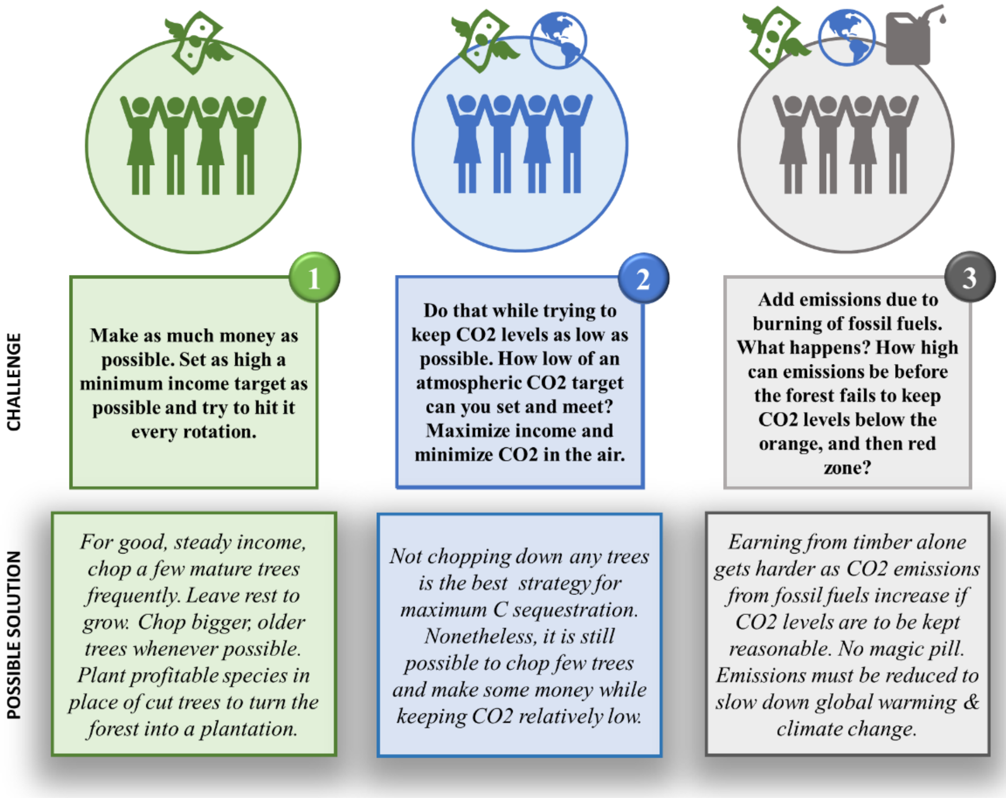

Figure 64. Initial challenges proposed for Bridge to college learning activity.

While educators appreciated scope for multiple learning activities using the tool, they also pointed out that challenges, although not considering other income streams, may still be too complex for a 2hr session. So, they needed to be simplified. Other suggestions were UI related as follows, all of which were implemented prior to the learning session.

- The colour of empty land icon  resembles that of the dead tree icon . This may be confusing. Thus, the colour of the former was to be changed.
- Fictional currency in the microworld, was Barcon ₤. It was deemed that this may be hard to relate to and might distract learners. Hence, it was suggested that it be swapped for the simple, universally relatable idea of coins  to represent money.
- It was suggested that the income per rotation target setter

be hidden 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 interested in overall income only. Thus, the income per rotation target setter, for starting challenges may be too complex and distracting a feature.
- There were no buttons to take 1 year time steps. This was to be added as while 1 year stepping was possible by typing years into the text box, this is cumbersome.
- Viewing information about trees/land content upon on hovering over icons on land was not possible. This feature was planned but not prioritised. An educator pointed out that including it is important since it may save reference material lookup time.
- Similarly, at the time, only the help page was implemented. Readily accessible, help ❓ icons were not yet added. It was suggested this be included ASAP for better UX.

- Lastly, it was not possible to add management actions in years within a rotation period. It was suggested that learners be granted this option as it is more intuitive and reflective of real world practices (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).

All above points were addressed. Challenges were updated and broken down into 5 simpler ones as was discussed in section 3.2. Of these, given the 2 hr time limit, students only attempted the first 2 (Table 24) at the Bridge2College workshop.

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

Table 24. Challenges undertaken by transition year students at the Bridge2College workshop.

After all suggestions were addressed, the lead educator took another look at the tool (Figure 65) on 18 June 2024, a day prior to the learning session, and approved it for use.

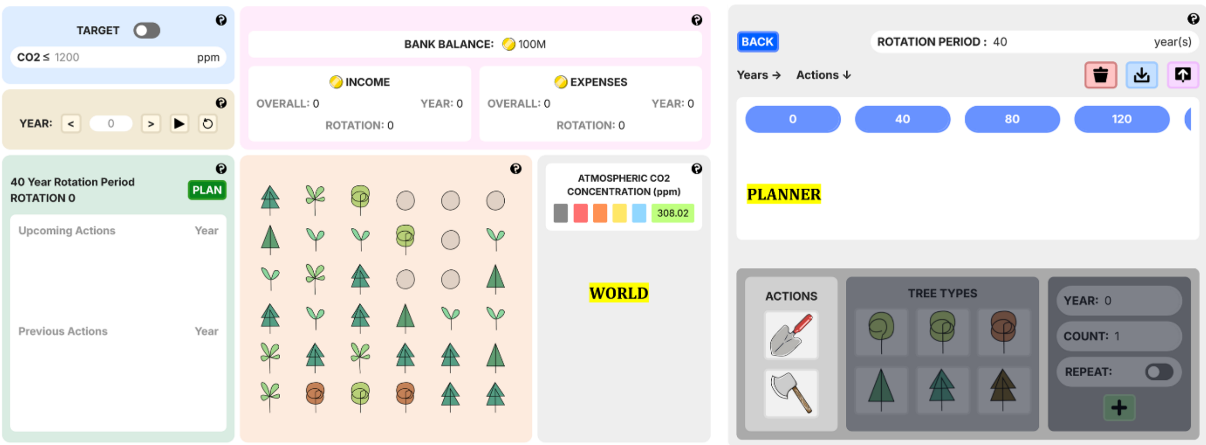

Figure 65. MycroForest as viewed by students at the Bridge2College learning session.

5.2 Bridge2College Workshop

The Bridge2College (B2C) program is an out-of-school education initiative undertaken as part of Trinity Access Programmes (TAP) at TCD. It is aimed at developing 21st-century skills in Transition Year students from the Irish secondary school system. The program involves workshops where students engage in collaborative, project-based, and technology-mediated learning, focusing on skills like collaboration, critical thinking, and use of technology, with the goal of boosting confidence in these areas [149].

The particular learning session as part of the B2C workshop wherein MycroForest was used, was held during the summer break. Thus, attendance was lower than usual. Of the close to 100 students who attended the B2C workshop on the day, 10 students interested in Computer Science, took part in the learning activity using MycroForest.

Figure 66. Students interacting with MycroForest at the Bridge2College learning session.

The teaching tool proposed was presented at a 2 hour learning session as part of the B2C workshop to 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, students attempted 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 + 5 minute video).
2. Challenge 1 – Maximize income.
3. Discussion.
4. Challenge 2 – Maximize carbon capture.
5. Discussion.
6. Presentation by this author regarding development of MycroForest with some under-the-hood implementation and approach details that students may find interesting given their inclination towards Computer Science.
7. Questionnaire – UX, educational experience, attitude towards climate change.

5.3 Usability Evaluation

Usability is a critical quality measure of any software application. Most informative of education technology will impart no knowledge if learners find it difficult to use. This section discusses methodology and results of usability evaluation of MycroForest.

Usability is generally assessed based on 3 factors as given below [150, 151].

1. **Effectiveness:** Degree of task completion achieved by users.
2. **Efficiency:** Resources (e.g. time, effort) needed to complete a task.
3. **Satisfaction:** Perceived usability, a subjective measure of ease of use.

The System Usability Scale (SUS) and the Post Study Usability Questionnaire (PSSUQ) are 2 popular tools (questionnaire formats) used to evaluate EduTech usability [151].

5.3.1 System Usability Scale (SUS)

SUS is a short 10-question survey that provides a quick overview of a software application's subjective usability, using a 5-point Likert scale (1 = strongly disagree, 5 = strongly agree). SUS questions were carefully picked and organized. They were formulated based on questions among 50 questionnaire items that induced most extreme responses in an experiment with 20 people. This is appropriate as Likert Scale responses are considered most suitable ways of measuring responses when corresponding questions provoke extreme expression of attitude. Moreover, SUS structures positive (common response is agreement) and negative (common response is disagreement) questions in an alternating fashion to encourage thinking before answering. The final SUS score (0-100) is calculated as sum of scores associated with each question (0-4) multiplied by 2.5 such that odd numbered questions are scored = scale position – 1 and even numbered questions are scored = 5 – scale position. Overall, SUS is an excellence choice for quick and broad usability assessment [150].

5.3.2 Post-Study Usability Questionnaire (PSSUQ)

PSSUQ is another usability assessment format with both a long (19 questions) and short (16 questions) version which uses a 7-point Likert scale (7 = most disagreement, 1 = most agreement). Unlike SUS that primarily focuses on measuring satisfaction [150], PSSUQ covers all 3 aspects of usability (effectiveness, efficiency, satisfaction). Another advantage of PSSUQ 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. Calculating scores for multiple questions in the PSSUQ evaluation framework, simply involves averaging all individual question scores = $\left(\frac{\sum scores}{no.\ of\ questions}\right)$ [151].

In 2023, P. Vlachogianni and N. Tselios conducted a thorough literature review and statistically analysed perceived usability of education technology using the PSSUQ and other evaluation frameworks. They observed the following [151].

- No significant correlation between avg. PSSUQ score and participant age.
- No significant correlation between avg. PSSUQ score and subject studied.
- Mean PSSUQ scores assigned by students pursuing higher education were significantly lower than those of primary/secondary education.
- Based on the Pearson correlation coefficient associated with 58 surveys, there was no statistically significant relationship between no. of participants and PSSUQ score (e.g. 12 participants produced results equivalent to a larger sample size in 90% of studied cases).

Overall, PSSUQ is a well-rounded choice of evaluation framework if detailed feedback is needed to identify specific areas for improvement in a system.

5.3.3 Adopted Questionnaire

PSSUQ has been shown to be effective with small sample sizes [151] 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) [151]. 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 [150]. 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 & 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 25. 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
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 26. 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 27. 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 CO_2. 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 67.

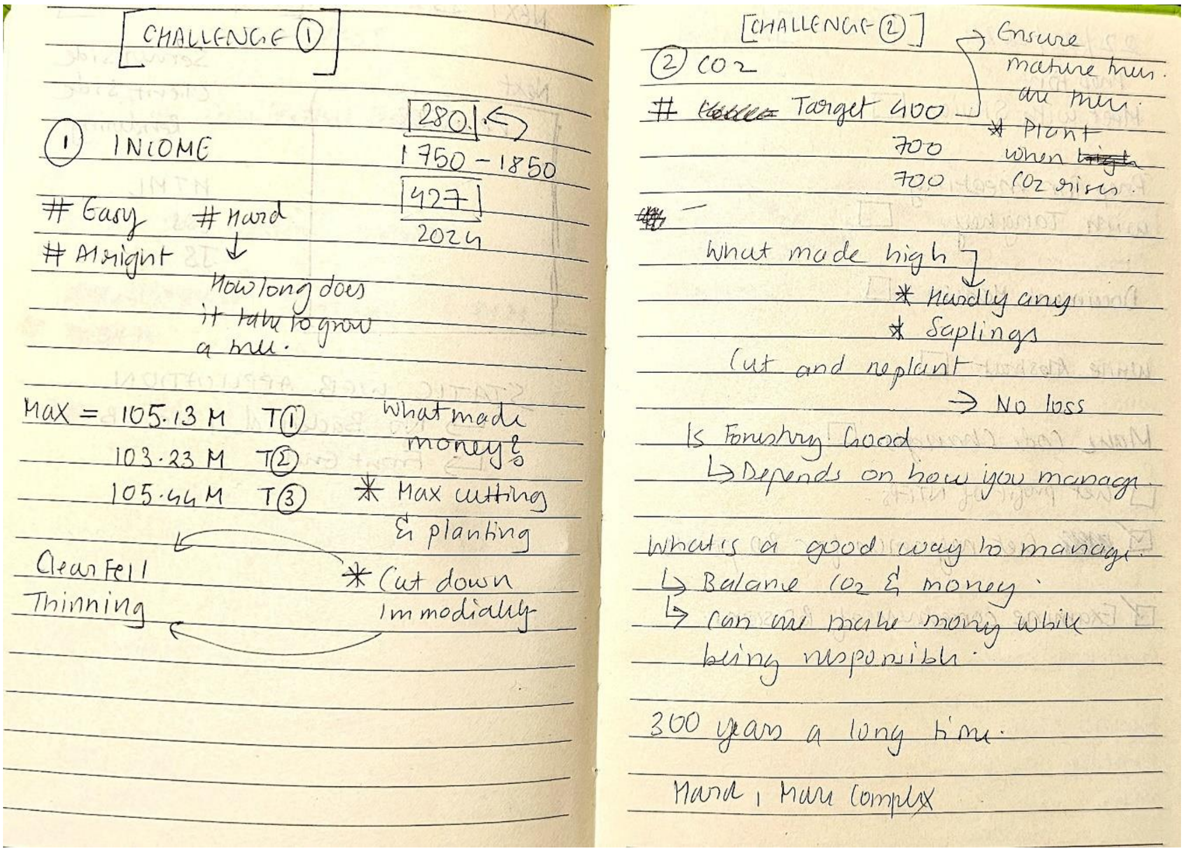

Figure 67. Bridge2College - Learner discussion notes.

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 68. 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 12 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, 20, 36, 50] 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, 20, 39, 65] 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 CO2. 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 CO2 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 CO2 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

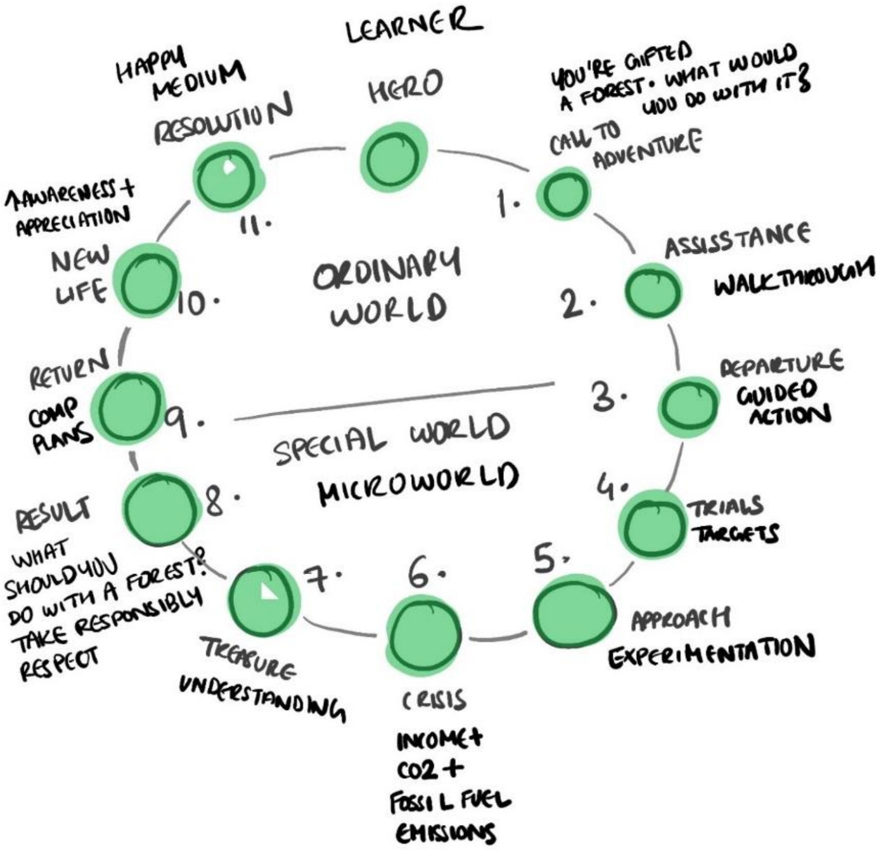
The questionnaire used to gather feedback from learners was created and distributed as a Google Form. Google Forms was chosen because it is simple to use and automatically runs basic analytics on results like creation of response frequency distribution charts. Online questionnaires are also easier to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

8.2 Use of GenAI in this Work

TO DO.

8.3 Hero's Journey Inspiration

Following image displays the attempt to map the Hero's journey framework to the learner's UX in MycroForest



8.4 Landing Page – Click Through Introduction Dialogues

- "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 CO2 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.

8.5 CO2 Concentration Scale Background

Following points present information based on which CO2 concentration – human quality of life and CO2 concentration – photosynthetic efficiency scales were developed.

- Photosynthesis is most effective at CO2 concentrations between 700 and 1800 ppm, with peak efficiency around 1000 ppm. Beyond 1800 ppm, conditions may be toxic for plants [83]. Photosynthesis is difficult below 200 ppm of CO2 and is largely impossible at 150 ppm or lower [82]. Lowest known atmospheric CO2 level ever based on findings from ice cores ≈ 172 ppm (650,000 to 800,000 years ago) [152].
- Throughout human evolution, atmospheric CO2 levels ≈ 200 to 300 ppm. Pre-industrial levels ≈ 280 ppm, and 20^{th} century levels ≈ 300 to 250 ppm [84].
- Predicted atmospheric level of CO2 that would push the world past its target for avoiding dangerous climate change ≈ 430 ppm [84]. One of our best estimates of an atmospheric CO2 level that would be a tipping point beyond which global temperatures would rise by 8 to 10 $°C$ ≈ 1200 ppm [14].

8.6 Input Variable Descriptions

Given below are brief descriptions of each input variable.

Tree: 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.

Carbon Dynamics: 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.

Land: 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.

8.7 MycroForest – Initial Broad Ideas

Below is a list of some initial broad ideas for MycroForest that were arrived at upon divergent thinking in the ideation phase of the project.
- Entities in the microworld shall include trees, soil, land, time, climate, and money. Tree properties include species, age, growth rate, and environmental tolerance. They should capture CO2, have multiple uses, and affect/be affected by biodiversity. Trees are stressed due to aging and living conditions (temperature, water, co2, sunlight, etc). Resource availability may be modelled by a curve resembling real-world distributions.
- Soil shall be a separate entity with properties like acidity, moisture, and texture, since these factors influence plant growth. Land shall include trees and soil and have properties like % of land managed and slope, which affects forest composition. Land may be divided into 4 quadrants, reflecting real-world forest sub-plots.
- Time shall be represented at multiple levels (day, month, season, year, decade).
- Climate may be defined by temperature, and moisture or precipitation or humidity, etc. that changes over the year based on an editable climatogram.
- In addition to income, expenses are associated with management actions. Forest income sources may be timber, NTFPs (animals, plants, fungi), ecosystem service funds, hunting/fishing, eco-tourism, carbon credits, and forest recreation.
- Virtual forests may face biotic (disease, pest, weeds, invasive species) and abiotic (fire, frost, flood, drought) disasters at intervals drawn from some distribution. A Disaster entity may have properties like spread probability and duration.
- Possible decisions that users can make 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 carbon reservoirs realistically.
- World timber demand may be controlled by the user. Timber demand is another target like income or atmospheric CO2 levels that learners can set and try to meet.