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

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Declaration

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Gayathri

GAYATHRI GIRISH NAIR August 16, 2024

Acknowledgements

Abstract

Ever since industrialization, CO_2 levels in our atmosphere have continued to rise 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. But they are also fragile, so education about forest management is important. This is especially true for those in the 15 to 24 age group as they constitute 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 category are have a strong sense of accountability, and are open to change [2]; thereby making climate change education very important for this group.

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

Thus, “MycroForest” as proposed here, is a web based microworld aimed at teaching young adults about the connection between forest management and CO_2 levels in the atmosphere. The tool enables learners to take on the role of a forest owner in a virtual world. They may draft management plans involving planting trees or felling them for wood. Consequences of plans are reflected on the composition of the forest, CO_2 levels in the atmosphere, and the learner’s virtual monetary assets. Using this tool, learners can be set challenges of increasing complexity ranging from maximising income from the forest, to maximizing carbon capture while also generating income.

Under the hood, MycroForest is composed of a simulation, User Interface (UI) components, and input variables. The simulation is a simplified representation of tree growth and the carbon cycle using an object oriented approach. Designing a simulation that reflects patterns seen in nature, drafting a user friendly interface to best support possible effective learning scenarios, and developing the app using the NextJS framework were key design and implementation challenges faced as part of this project.

The proposed teaching tool was evaluated at a 2 hours session with 10 Transition Year students on the TAP Bridge2College Programme at Trinity College Dublin. Feedback was also obtained from tutors at the event. Overall, response to the app is largely positive with student finding it “informative”, “fun” and “simple to use”.

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

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1 Introduction

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

1.1 Motivation

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

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

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

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

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

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

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

Thus, teaching about the link between forest management and atmospheric CO2 levels while also allowing learners to explore economic viability of forests through timber harvesting and other means of generating income from forests is a great way to promote awareness about the need to conserve forests, harvest responsibly, and discover new ways to sustainably earn from them. This also encourages learners to think about the financial motive, an indirect but fundamental influencer that underpins deforestation, which in turn, is a direct driver of climate change. The MycroForest teaching tool as presented in this work, strives to do this.

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

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

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

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

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

1.2 Goal

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

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

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

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

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

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

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

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

1.3 Referencing

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

1.4 Ethics

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

1.5 Document Structure

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

2 Background

This section reviews other similar tools and describes existing work in areas like forest management, simulation design, education technology, and Human Computer Interaction (HCP) that guided key design decisions. Please note that this section also mentions how ideas from existing work has been reflected in “MycroForest”, the teaching tool that is the product of this work. Following section 3 shall describe the application in detail.

2.1 Forest Management

2.2 Education Technology

Education technology (EduTech) refers to software designed to facilitate learning. These include tools that are used to actively impart knowledge like e-books, mobile learning tools (e.g. Duolingo, Khan Academy), microworlds, serious educational games and ones that indirectly support it like assessment tools (e.g. Kahoot, Google Forms), learning management systems (e.g. Blackboard, Canvas, Moodle), text based tools (MS Word, Google Docs), knowledge organization tools (e.g. Evernote, Notion, Mendeley), synchronous collaboration tools(Zoom, MS Teams), etc. [24] Depending on design, EduTech tools can be empowering or constraining. [25] When they promote learner engagement, they have been shown to improve depth and persistence of learning. [11]

Many studies define engagement as active participation or positive interaction of the learner with the teaching tool or learning material as well as with peers and faculty. Others describe it based on the amount of time, effort, or energy invested in the learning activity. [24] Engagement improves learning because it invokes mindfulness in learners causing them to employ conscious effort and thought that results in development of personally meaningful knowledge. This is important because the likes of John Dewey, a pioneer in the “pragmatism” school of thought [26] and whose ideas inspired the much celebrated pedagogical paradigm of constructionism, subscribe to the notion that knowledge is only useful to someone when they find it personally meaningful. [19]

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

A child's sandbox is an example of a natural microworld where sand and tools like the bucket or shovel act as OTTW such that interacting with them through play leads to the child developing an intuitive understanding of density and volumes. [19] Logo, Boxer, and SimCalc are examples of some of the earliest digital microworlds used as a teaching tools, often to educate about mathematics or physics related principles. [27] Given advancements in technology (object oriented programming languages, improved graphics, web based applications) and the ability of microworlds to represent interdependent chains of cause and effect found abundantly in human and natural systems such as economics, the food web, disease progression, plant growth, and the effects of climate change on ecosystems, they are useful in multiple domains beyond mathematics and physics. [27-29]

At the heart of any microworld, is its ability to facilitate self-regulated learning (SRL) wherein the learner takes initiative in managing their own learning. According to Rieber from 1996, self-regulated learners are (i) intrinsically motivated (they find the activity rewarding or enjoyable), (ii) metacognitively active (they engage in planning an goal-setting), and (iii) behaviourally active (they tweak the environment to suit individual learning styles). [19] These characteristics closely parallel the 3 widely accepted components (affective/emotional, cognitive, behavioural) that comprise student engagement as described by Bond et. al. in their extensive statistical analysis of literature concerning EduTech and student engagement. [24] Thus, facilitating SRL promotes learner engagement in the activity. This reinforces the notion established through years of studies, that well-designed Microworlds make for particularly engaging teaching tools [8-10, 21, 27]. The Piagetian Learning Theory (PLT) by Jean Piaget whose ideas strongly inspired the proponent of microworlds Seymour Papert, and the Flow Theory of Optimal Experience (FTOE) by Mihaly Csikszentmihalyi are 2 popular theoretical frameworks that define necessary conditions for SRL. [19]

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

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

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

Many a time, microworlds that try to teach about real world systems comprise a simulation model. This is especially the case if educational material is based on a natural system as is the case with MycroForest. To maintain learner engagement, it is necessary that simulation-as-microworld learning tools follow the "match the user principle" such that ideas presented "expand as the learner is ready" so as not to overwhelm. This is known as model progression. It is also necessary to ensure that such tools entail good UX to avoid learner frustration. [9, 19, 29]

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="4">Simulation</td><td>Graphical feedback accompanied by short, embedded multimedia explanations result in better understanding of ideas by students compared to when only graphical or textual feedback was provided instead.</td><td rowspan="2">Most students learn from microworlds only when exploration occurs within context of some carefully designed learning activity that provides structure.</td><td rowspan="2">Microworld</td></tr>
<tr><td>Providing short explanations intermittently boosts understanding as this makes it easier for learners to link thoughts to experiences. The alternative of a tutorial is less effective because it separates explanation from experience.</td></tr>
<tr><td>Learners consistently reported lesser frustration when feedback was graphical rather than textual.</td><td>Students who engaged in content related discussions demonstrated increased learning.</td><td rowspan="2">Game</td></tr>
<tr><td>Instructional support is best provided while students use the simulation as opposed to before, because the latter can lead to students forming early hypotheses that are generally hard to displace later even if evidence points against it.</td><td>Three game characteristics most favored by children in a study wherein student designed games were evaluated by other students</td></tr>
</table>

	Students significantly benefit from simulations that build up complexity in stages (model progression) allowing enough time for developing a good grasp on easier tool mechanics and ideas before moving on to more complex ones.	were (i) storyline quality, (ii) competition, and (iii) appropriate challenge.	

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

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

Overall, there is significant evidence to suggest that hybridization of the constructivist concept of a microworld with elements of a simulation and gaming can results is a particularly effective and engaging learning environment. [9, 10, 19, 30]

2.3 Simulation Design

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

A “model” here, refers to a representation of some primary system. When such a model can be updated over time based on simulated conditions to mimic true behaviour of a dynamic primary system, it is referred to as a “simulation”. [31] Thus, at the heart of every simulation is a model of the system that it represents.

There exist several ways of modelling dynamic biological processes like forest growth, forest yield, forest succession, primary productivity, carbon storage, nutrient cycling, water balance, etc. This is because given their inherent high complexity, the large time periods over which ecological processes may play out, and their critical role in supporting life, simulating them is one of best ways to understand them better and conduct experiments without disturbing real-world systems. [32]

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

2.3.1 Agent Based Simulation (ABS)

ABS is a type of simulation that leverages an Agent Based Model (ABM) as the underlying model.

ABMs represent a system using independent agents with their own memory and rules that interact with each other and the environment. [33]

In the space of biological and ecosystem as well as climate modelling, ABMs are extremely popular. [33] This is because such systems are most often composed of discrete entities that independently interact with a shared environment or each other over time to accomplish their own separate goals such that composite behaviour patterns emerge as a consequence. This inspires natural progression towards modelling these entities as agents in an ABM. [33, 34] Also, ABMs impose no restrictions as to how many attributes or rules each agent can have, which makes it an attractive option for modelling complex systems like forests or entire ecosystems. [35] Furthermore, students who used education technology incorporating ABMs have been shown to outperform others on account of having understood cause and effect relationships more readily. Such students reported being able to “see” patterns better. This is thought to have been a consequence of the “agent perspective” and learners having found the idea of individual contribution within a shared environment resulting in emergent behaviour intuitive and straightforward. [30] Thus, MycroForest models tree growth and carbon capture as an ABM where trees are agents, and they interact with the environment composed of land and carbon reservoirs like air and soil.

ABMs support varying levels of abstraction. This may be readily observed in context of plant growth modelling. In population level ABMs, an agent refers to an individual plant. This facilitates capture of emerging forest level behaviours. On the other hand, individual level ABMs take this a step further and are more nuanced with agents now referring to specific modules within a single plant. This could be structural components like leaves, roots, and so on, or more abstract constituents like pools of carbonates. [35] Since MycroForest aims to teach about forest level changes under the influence of a learner’s management plan as opposed to plant physiology or the growth mechanism, the ABM within MycroForest is a population level one with a forest comprising a population of trees.

Underlying assumptions that influence key mechanisms like increase in tree volume or reproduction pattern, can also vary in terms of both approach and level of detail. [35] The following 2 examples of slightly different plant growth ABMs built on empirical and mechanistic approaches respectively, demonstrate this difference. [35]

Example 1: JABOWA [35, 36]

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

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

  This equation incorporates attributes of the tree agent, namely $D =$ Diameter at Breast Height (DBH), $H =$ tree height, $D_{max} =$ maximum DBH, $H_{max} =$ maximum height and $LA =$ leaf area, with R being an added constant and δ suggesting "change" in volume D^2H. Tree height is computed as $H = 137 + b_2D - b_3D^2$ with b_2 and b_3 being species specific constants, based on the ratio gleaned from available data on real tree diameters and heights. This equation also captures known phenomenon such as growth being directly proportional to amount of sunlight received using the term $R \times LA$ and it also being inversely proportional to energy required to maintain living tissue as captured using the term $1 - \frac{DH}{D_{max} \times H_{max}}$. Notice that volume of the tree is computed as D^2H. This is derived from the formula for the volume of a cylinder $= \pi r^2 h$ and therefore, stems from an assumption of the volume of a tree being akin to that of a cylinder. Another assumption here, is that other growth conditions are optimal. These assumptions simplify the model and makes computation faster.
- Thus, the aforementioned growth mechanism simplified via assumptions like that of optimal growing conditions, models growth rate of the tree using an empirical formula that incorporates agent attributes like diameter and height based on rules influenced by statistical insights gained from data.
- The JABOWA ABM built upon empirical equations that modelled just 9 tree characteristics (species, age, size, spatial location, growth rate, mortality, shade tolerance, reproduction, competitive ability) and 7 environmental characteristics (canopy gaps, light availability, spatial location, environmental stress, aging, altitude) was able to simulate real ecosystem behaviours such as competition, secondary succession and change in vegetation at different elevations. This goes to show that complex systems can be simulated in useful detail even when some of that complexity is abstracted away through simplifying assumptions.

<u>Example 2</u>: PLATHO [35, 37]

- Consider the PLATHO model which simulates plant growth to understand resource allocation patterns. It accomplishes this through sub-models that each capture a different plant process. Phenological development, photosynthesis, water and nitrogen uptake by roots, biomass growth, respiration, and senescence are the 6 mechanisms so modelled. This is also a population level ABM wherein each plant is an agent.

- Within a plant, assimilates, structural biomass, carbon-based secondary compounds, and reserves comprise 4 key biochemical pools that PLATHO takes into consideration. The simulation is a result of repeatedly computing resource fluxes between these pools and generating, storing, as well as transferring resources accordingly. The whole system, therefore, revolves around executing functions that update the state of certain plant and environment variables to meet the demand for resources like nitrogen, carbon, water and so on, at various plant organs.
- This type of modelling also incorporates some assumptions like "potential allocation to defensive compounds is inversely correlated to maximal plant growth rate" and simplifications such as representing volume of a tree as that of a cylinder. Since there may be multiple actions that can be executed in response to certain program states, there is a need for prioritization. This is facilitated by assumptions or rules based on existing knowledge such as "photosynthesis is less affected by nitrogen deficiency than growth".
- Although often not necessary for simpler systems, with complex primary systems, the mechanistic modelling approach can represent parts of the model using mathematical equations. Given below, is one expression that is a part of the PLATHO model. It calculates total potential carbohydrate demand as needed for structural growth and synthesis of defensive compounds.

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

  Here, r_{max} is the maximum growth rate, W_1 is the amount of living structural biomass, Δt represents the time step, f_T is a factor in the range 0 to 1 that is a function of air temperature, and f_{Ph} is a factor in the range 0 to 1 that is a function of the phenological stage of the plant based on its seasonal growth cycle.
- Overall, the PLATHO model facilitated testing of several hypothesis and revealed likelihood of responses to different conditions. It successfully reproduced several observed results like the effect of nitrogen fertilization on rate of biomass gain validated upon comparison of simulated and measured values of apple trees which largely matched. Even when simulated results differed from observed truths such as when the model overestimated the effect of CO2 on the concentration of defence-related compounds in spruce needles, this triggered further investigate and revealed the importance of effects such as acclimatisation of plants to increased levels of CO2 over time, thereby contributing to increased understanding.

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

Literature often presents empirical and mechanistic methods as contrasting ways of modelling. Often, this distinction is clear. Mechanistic modelling involves formulating a conceptual representation of some primary system based entirely on knowledge of its underlying structural elements and functional mechanisms. Such models may or may not represent processes or parts thereof using mathematical expressions. Algorithms or functions based on informed assumptions are the key drivers of simulation. On the other hand, empirical modelling is rooted in entire systems being represented using a high level mathematical function based solely on statistical relationships uncovered from measured data. This is useful when outputs or attribute values of a primary system is available as data, but knowledge about its underlying structure or functioning is limited. [31]

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

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

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

Biology, ecology and climate change are thus, examples of domains wherein simulation of primary systems may call for an ABM which is built on hybrid modelling approaches that combine mechanistic and empirical elements to better suit unique requirements. [31] Thus, the ABM within MycroForest models key processes like tree growth and reproduction using high-level mathematical expressions based on certain mechanistic, informed assumptions or rules about underlying mechanisms and structure of the system like the relationship between height and diameter of trees, coniferous trees generally being more long lived than deciduous ones, and so on. This results in a model that mimics real-world phenomenon but is still fast enough to be computationally feasible and provide smooth user experience.

2.3.2 Discrete Event Simulation (DES)

A Discrete Event Simulation (DES) is simulation paradigm that models the primary system using a Discrete Event Model (DEM). This is among most popular simulation paradigms and is particularly suited to modelling process flow. [38] It breaks down system behaviour into an ordered sequence of events or processes that can but need not occur at regular time intervals. [33]

This event or process oriented worldview that underpins DES allows for some real-world time to be abstracted away as time between events is not simulated. Modelling evolution of the system from event to event instead of from moment to moment makes it possible to simulate slow systems in a shorter time frame. Time periods between events when there is minimal change is not simulated and thus, does not contribute to duration of the simulation. Also, events can be structured such that state changes over long time periods in the real world is executed within a single event to make the simulation faster. [39] Time scales over which forests grow and change significantly is generally long. This is one reason why real-world trial and error based assessment of forest management strategies is often infeasible. Thus, the ability to hasten slow, real-world processes in simulation that comes with DES is deemed very beneficial in the forestry sector. [38]

At the broadest level, all DEMs comprise entities and a priority queue that manages events. [39] Running a DEM usually involves the following 3 steps that get iteratively executed until a stopping condition is met. [40]

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

A use case wherein DES is most popular, is decision making or when there is a need to compare strategies because human decisions can easily be incorporated as separate events added to the simulation queue. This is the prime reason for incorporating DES into MycroForest where it manages timely execution of forest management actions added by the user. In forestry, DES is frequently used to compare different forest management or harvesting strategies in addition to assessing effects of different facility layout or equipment configurations, comparing resource logistics management strategies, and performing cost assessments. [38] The work of K. Westlund, L. E. Sundström and L. Eliasson [41] is a most recent example of this. They present an optimization-simulation framework to assess performance delivery of wood supply chains under varying weather conditions which affect road accessibility and by extension the ability to transport resources. Their framework has 2 parts. An optimization model produces a good wood harvest schedule based on demand and supply capabilities. This feasible harvest schedule along with weather scenarios, customer order details, and forest road segment data are provided as input to a DEM which simulates events in the schedule to facilitate comparison of delivery performance under varying weather conditions as input by the human user. [41]

The idea of entities that generate events comprising a set of instructions to be executed at planned times is one that is very practical to implement in software. DES is very compatible with Object Oriented programming because model entities can readily be implemented as objects with their properties being entity attributes and their methods defining events or event processes. [39]

Simulations in general are used for one of two purposes being either to analyse some phenomenon or system, or to provide a training environment to teach about it. There is evidence of DES being beneficial when incorporated into teaching tools as its structure makes it easy to incorporate learner decisions into the existing event schedule. [38, 42]

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

2.3.3 Hybrid Simulation

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

Such a hybrid approach to simulation incorporating elements of more than one simulation paradigm is not uncommon. It is frequently observed in the health care, supply chain management, manufacturing, and construction domains. In fact, the combination of ABS + DES is considered to be most effective in “any situation which includes resources that must perform activities as well as human interactions where individual behaviours alter how these activities proceed" [43]. This once again points towards the decision to incorporate this combination within MycroForest being sound.

HS is often adopted as an attempt to manage complexity of particular primary systems. It allows for complex problems to be broken down into smaller parts such that the simulation paradigm most suited to each part may be employed. Moreover, HS accommodates abstraction of parts of the system thereby helping strike an accuracy or complexity and performance trade-off balance. [44, 45]

A key challenge with HS is compatibility of integration of the two simulation paradigms adopted. Ensuring interoperability between elements from different simulation methodologies can be difficult. [44, 45] In addition to these two simulation paradigms, MycroForest also leverages a more general Object Oriented (OO) design as shall be discussed in the following section, to simulate the remainder of system mechanisms. This OO design ties DES and ABS together because it is compatible with DES as previously discussed, as well as with ABS as agents may be objects and agent types, classes. [43]

2.3.4 Object Oriented Design

Object Oriented (OO) here, refers to the general software design pattern of viewing a system as a sum of several objects or entities with their own data and functions that interact with each other. Object Oriented Simulation (OOS) is when the idea of the world being composed of "objects" is incorporated into the design of the simulation. An important reason for popularity of this notion is that it is the most natural way to represent many real-world systems. For example, a single cell may be modelled as being composed of objects representing its various functional units like cell membrane, nucleus, mitochondria, cytoplasm, etc. Even abstract or non-physical elements of a system, like say the force of gravity in a physics simulation, can be modelled as an object if some unique attributes and functions can be associated with it. [46]

Given below are 4 ideas that are referred to as the 4 pillars of OO design. [47, 48]

1. **Abstraction**: This principle dictates that only most relevant attributes and functions be implemented. Further, this entails that functions be implemented at a high enough level for callers to be able to leverage it for desired results without being concerned about the intricacies of how it works. For instance, it can be made possible to call a function drive(A, B) that takes the caller from point A to B without having to call functions like startEngine(), shiftGears(), or pressAccelerator(). The main advantage of following this principle is that it helps manage complexity and minimize use of computational resources while making code more reusable and maintainable. In MycroForest for example, the main aim is to have trees absorb and release carbon such that their presence or absence results in changes in CO2 in the atmosphere as is observed in the real world. Thus, it is only necessary to keep track of how much carbon is stored in a tree. Details about where this is stored and the

mechanism of carbon allocation between different plant organs is irrelevant. Thus, the volume of the tree may be simplified to that of a cylinder and amount of carbon in a tree can be abstracted to x% of the mass of that tree such that x = average value of the proportion of carbon in real trees based on real world data.

2. **Encapsulation**: This principle urges that each object be self-contained with clear responsibilities and specialized attributes as well as functions to perform its unique role within the system such that only those properties or methods that other objects or functions need to be able to access is exposed publicly whilst all others remain private. The main advantage that this presents is modularization or separation of concerns which in turn ensures that code is flexible and can be updated with minimal breakage. For example, in the implementation of MycroForest, there exists a function called computeBiodiversityScore() within the Land class. A "class" is the term used to refer to the type or definition of an object. Consider a Shirt class with an attribute colour. Then, Shirt("blue") and Shirt("red") would both be objects of the Shirt class. This computeBiodiversityScore() function contains the algorithm that computes biodiversity of the land based on composition of the forest. This is a private function that no objects outside the Land class can directly call. Thus, code elements outside the Land class object cannot compute biodiversity score themselves, but they may still access its value via a public attribute of Land that stores it after computation. At one point during development, there was a need to rectify an older way of computing biodiversity score wherein a forest with the most no. of old trees was assigned highest score to another approach where a certain ratio of young to old trees as observed in natural forests was to be scored highest. Since encapsulation of the functionality of biodiversity score was implemented, this was easy to do with there being the need to update only a single function.
3. **Inheritance**: OO design allows for there to be a class hierarchy where classes lower in the hierarchy known as "children" or "child" classes of those above known as "parent" classes received attributes or functions of the parent class. Thus, child classes inherit properties of their parents. The reason for creation of such child classes is often to personalize or extend functionalities of the parent in several unique ways. For example, if Vehicle() is the parent class, then Car(), MotorBike(), and Truck() may be children who all inherit properties like colour and functions like drive() from Vehicle() but may also have other features unique to each child. This can aid in reducing code duplication. For example, in MycroForest, classes Timber, NTFP, and Recreation are all children of the IncomeSource class. This serves to say that there are 3 ways of earning from the forest. Income may be generated by selling timber, non-timber forest products (NTFPs) or by selling permits that allow the public to use the forest for recreational activities. Because Timber, NTFP, and Recreation inherit from IncomeStream, the sell() function need only be defined once within the parent class IncomeStream. All children, also inherit this functionality.
4. **Polymorphism**: This idea states that the same attribute or function may be defined again with a different value. A common use case is where children inherit a function from the parent and then redefine or extend it. For example, consider a Mammal()

class with a speak() method. Child classes Dog and Cat may inherit the speak() method and then modify it to facilitate barking and meowing respectively. This allows for behaviour sharing with minimal resource overhead.

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

Furthermore, OOS has the advantage that communication between objects is simple to implement with the standard practice being via function calls and variable fetching. This is much less resource intensive than other methods of communication such as message passing, or event based ones that could require continuous listening for events or the need to store state of all objects at each timestep to facilitate replayability. This simplicity that does not demand strict enforcement of more paradigm related principles, also makes it easier to integrate both other paradigms with the remainder of the simulation. [46]

All simulations require some form of simulation time synchronization. This can be challenging when HS is adopted. [46] MycroForest overcomes this challenge by implementing a Simulation class that coordinates processes of all other simulation objects. It does this by taking the first step that triggers a time step update. This motion to update time is propagated to nested objects and soon leads to all simulated objects moving forwards in time. The tree agents that are a part of the growth ABS execute their independent behaviours within their respective time update functions. The Simulation object also contains a Planner object comprising an ordered sequence of learner defined forest management events which get executed at planned years.

2.3.5 Time Advance

The time advance mechanism is a key component of every simulation. A time advance mechanism refers to how progress of time is modelled within the simulation. There are generally 2 ways to implement this. [43]

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

MycroForest implements time advance using the Time Step method such that $\Delta t = 1$ year. MycroForest aims to allow users to scrub forwards or backwards through a timeline GUI and move to any simulated year to view the state of the world at that point in time. This adds replayability to the simulation which improves understanding of the cause – effect relationship w.r.t the learner's created management plans and corresponding changes in the microworld. It is easier for the learner to measure impact of their decisions and determine when to execute management actions if the model progresses predictably in fixed time steps. Moreover, forest management activities such as felling trees and planting them in the real world, is generally planned such that unit of time is years. This is because trees, depending on their species, generally have long lifespans ranging from anywhere between 50 to 3000 years with the oldest known living tree, the Great Basin Bristlecone Pine, estimated to be at least 5000 years old. [49]

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

A common approach to minimizing the influence of Δt on model behaviour is to set it to be very small so that changes are almost smooth. This is, however, not feasible in case of MycroForest because of the long lifespan of trees. If $\Delta t = 1$ day, the simulation would simply take too long to run, given that the aim is to allow learners to view changes over 300 years. It is necessary to simulate between 200 to 300 years. The more time that can be simulated, the more visible long term effects of forest management plans become. This is because significant changes in carbon levels on Earth occur over centuries. Also, real world forest management actions are often planned in rotations to allow trees enough time to mature between timber harvests. A rotation period, i.e. time between subsequent timber harvests, range from 5 to 150 years with common values being 20 or 40 years [50]. Thus, while both 1 month and 1 season were initially considered to be Δt, this was later abandoned for 1 year because annual update is compliant with real world forest management planning time frames, is large enough to visualize significant changes in tree growth over their long lifespans and allows the simulation to cover a long enough timeframe so as to be able to see effects of changing carbon levels, all while keeping the time taken to animate through it reasonably short.

2.4 Human Computer Interaction

Human Computer Interaction (HCI) is the discipline concerning design and implementation of interfaces between human users and computer systems that ensure realization of user goals through appropriate system responses with good usability - functionality balance to maximize effectiveness of human - machine communication where usability is a measure of a system's capability to enable efficient and appropriate task fulfilment. [51, 52]

Interfaces are determined by the amount and variety of inputs and outputs they are to handle. Based on this, human – computer interfaces get categorized as Uni – Model wherein user input is received via a single channel (a.k.a. modality) or Multi – Model when more than one input channel like facial/body movement detection (vision based), voice recognition (audio based) or keyboards/mouse interaction (sensor based) methods of communication is involved in the interaction. While Multi – Modal interfaces are more likely to grant a more immersive or wholesome user experience, it has 2 notable disadvantages. [52] Vision or audio based HCI often requires special technology (e.g. infrared cameras, speech recognition software, haptic devices, etc.) which can reduce accessibility and affordability of the associated system. Also, multiple communication modalities with a computer system can be distracting, especially for young learners using a teaching tool. Hence, MycroForest provides a simple Uni – Modal means of HCI wherein learners interact with the tool via familiar mouse and keyboard sensor based interactions.

Another common HCI grouping is that of active and passive HCI. Active HCI involves direct and deliberate interaction between users and systems in a command – action event flow wherein systems respond only upon user initiated action. For example, a typical email send action requires that the user click on the send button first. MycroForest presents an active HCI. This allows for experiential learning and increased user control, both of which contribute towards a good learning experience. [53] Passive HCI on the other hand involve systems that detect the user and pick up on non-physical or indirect environmental queues to which they then respond. Voice commands like "Hey Siri" is an example of this. [54]

Furthermore, current technological advancements like Augmented Reality (AR), Artificial Intelligence (AI), the Internet of Things (IoT) and improved computational capability in general, drives HCI further, to realization of Intelligent HCI and Ambient HCI. Voice recognition, face/gaze detection, naturalistic textual and verbal conversations, etc. are indicative of Intelligent HCI. Ambient HCI is when devices embedded in the environment enable humans to interface with machines without any apparent physical barriers like the need for a keyboard/mouse. [54] Future technologies like Human Brain Interfaces may take this further still and completely blur the line between human and synthetic senses.

The HCI discipline is, however, fragmented with no single universally acknowledged set of principles to guide HCI theory application. Instead, there are several good perspectives with some like Norman's model from 1988 being more practical than others such as Nemirovsky's Audience Participation Model from 2003. [51]

Its intuitiveness makes Norman's Model a particularly popular choice. This model splits the HCI experience into 7 iterative steps: (i) Goal establishment. (ii) Intention formation. (iii) Action sequence specification. (iv) Action execution. (v) System state perception. (vi) System state interpretation. (vii) System state evaluation. These are organized such that steps (i) to (iv) comprise an "execution" component and steps (v) to (vii) comprise the other "evaluation" component. Further, undesirable HCI is defined as a consequence of the "gulf of execution" and the "gulf of evaluation" which may be thought of as misalignment between "task language" (user's conceptual understanding and the actions they can take to achieve their goals) and "core language" (system's internal processes, responses, etc., and how it represents information to the user). Other researchers like Abowd and Beale in 1991 extended Norman's ideas by defining the User Interface (UI) as a bridge connecting the languages. They state 4 key mappings between task and core languages that the UI must ensure is strong. These are (i) Articulation (user maps their goals to actions), (ii) Performance (system interprets user actions correctly and makes appropriate state changes in response), (iii) Presentation (system presents updated state), and (iv) Observation (users updates mental model/understanding based on presented changes). [55]

One challenge with Norman's Model even with Abowd and Beale's explicit UI extension is that is that it can still seem abstract from a developer or UI designer's perspective. Thus, it may be advantageous when aiming to design applications in accordance with Norman's Model to also try to adhere to more practical guidelines like Jacob Nielsen's usability heuristics which is a set of 10 rules to avoid common interface design problems. These are (i) Use simple language with no irrelevant information. (ii) Speak the user's language such that information is presented in a familiar fashion. (iii) Minimize memory load such that the user need not remember all information between dialogues. (iv) Maintain consistency. Words or actions must mean the same thing throughout. (v) Provide timely and apt feedback. (vi) Clearly mark exits to allow users to undo mistakes or revert state to a previous version. (vii) Incorporate few shortcuts for the benefit of expert users. (viii) Display good error messages. (ix) Design to prevent errors. (x) Ensure help is readily available. [51]

To address the lack of consensus on a single set of best principles in the field, V. Hinze-Hoare in 2007 conducted a survey of HCI literature and assigned scores to key principles within them weighted based on proportion of overall citations the corresponding authors received. This analysis suggests 8 fundamental principles of HCI in decreasing order of weightage being (i) Recoverability (ii) Familiarity (iii) Consistency (iv) Substitutivity (v) Task Migratability (vi) Synthesisability (vii)

Predictability (viii) Perceptual Ergonomics. [51]. The first three were most significant and is inherent within Nielsen's 10 principles.

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

2.5 Related Work

2.5.1 Climate Change Education

2.5.2 Existing Tools

There exist multiple low and high tech interactive tools [3-7, 56-60] that model forests or forest growth, often in the context of climate change and/or forest management. A common purpose of such tools is to serve as decision making aids for experts in the field like working foresters. Another popular use is as educational tools. This section shall explore 5 such tools in detail.

Tool 1 – SimForest (Educational Simulation)

[58]

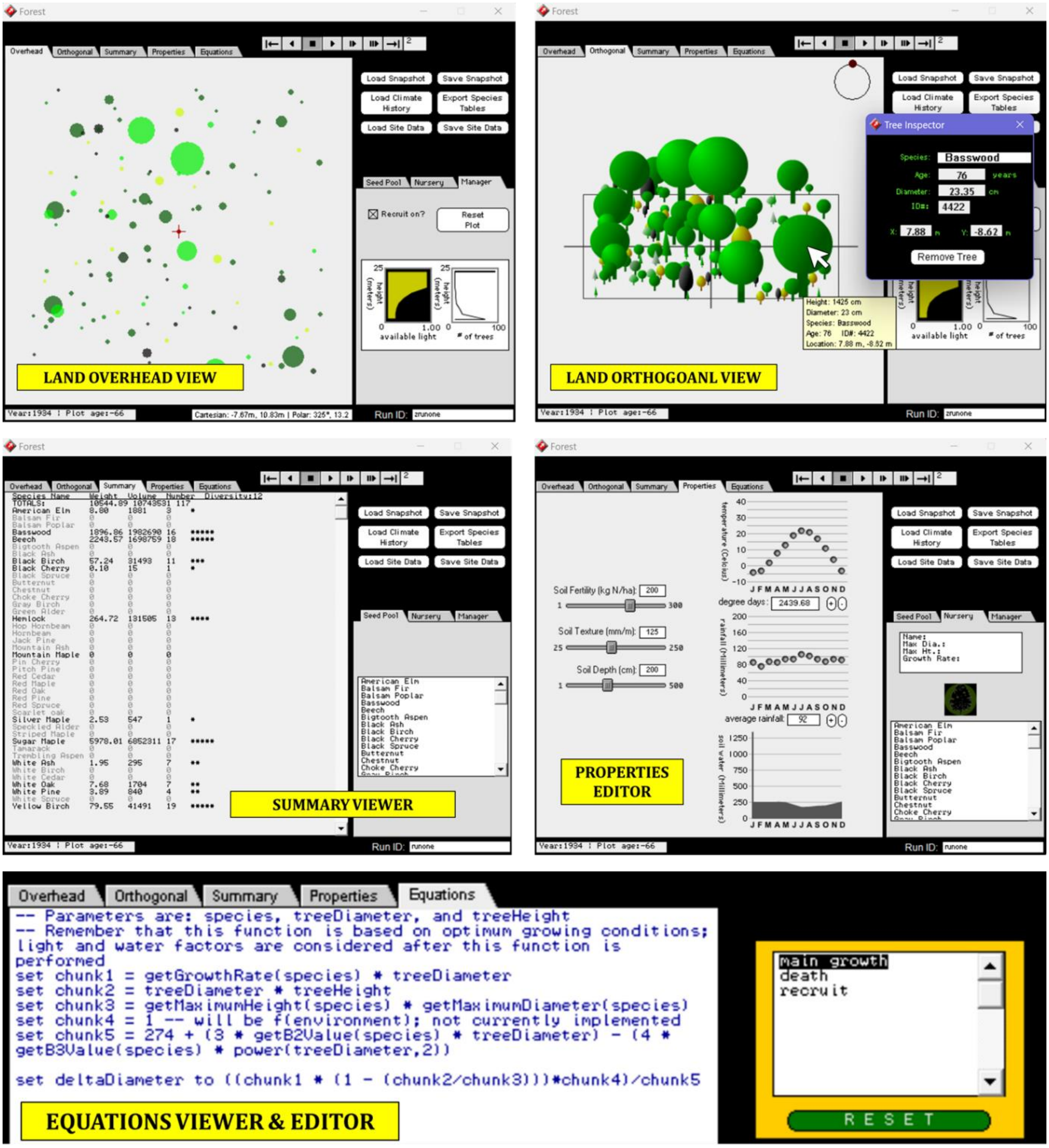

Figure 1. SimForest UI.

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

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

<table>
<tr><th colspan="2">SimForest</th></tr>
<tr><th>Pros</th><th>Cons</th></tr>
<tr><td>Rich set of manipulatable controls.</td><td>No big cons.</td></tr>
<tr><td>General forest growth simulation around which multiple learning scenarios may be developed.</td><td rowspan="2">Does not consider atmospheric CO2 levels.</td></tr>
<tr><td>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).</td></tr>
<tr><td>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.</td><td rowspan="2">Only available on PC and requires download and possibly some set up (OS, Java, or Swing related compatibility issues possible).</td></tr>
<tr><td>Clean user-friendly UI.</td></tr>
<tr><td>Allows moving through times at various speeds.</td><td rowspan="3">Does not consider economic value of forests.</td></tr>
<tr><td>Good data visualization.</td></tr>
<tr><td>Allows multi-level control (high-level or black box, as well as low-level or glass box).</td></tr>
</table>

Table 2. SimForest - Pros and cons.

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

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

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

[3]

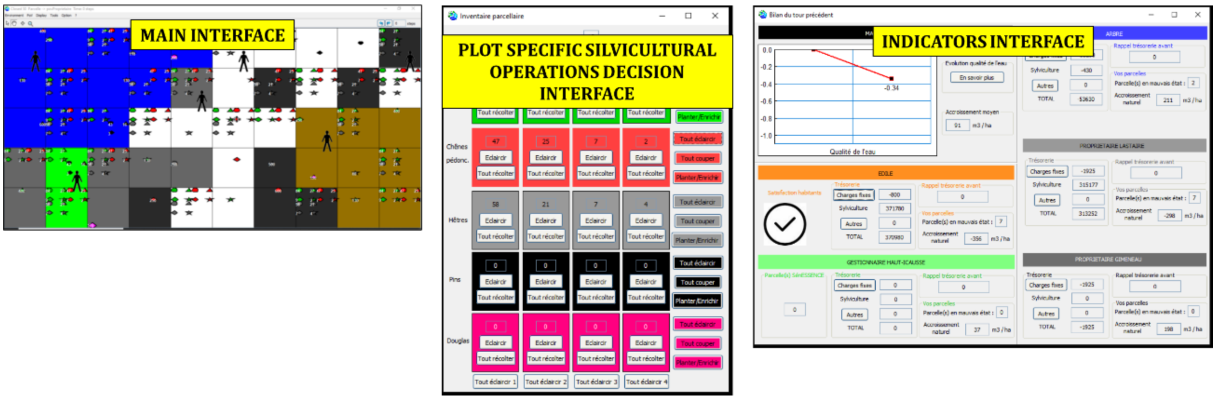

Table 3. Foster Forest UI – The main interface displays the 50 land plots simulated. Different views (owner view, eligibility for conservation plan view, etc.) can be selected to be overlayed on these plots. The above main interface image shows the ownership view coded per participant. The indicators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

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

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

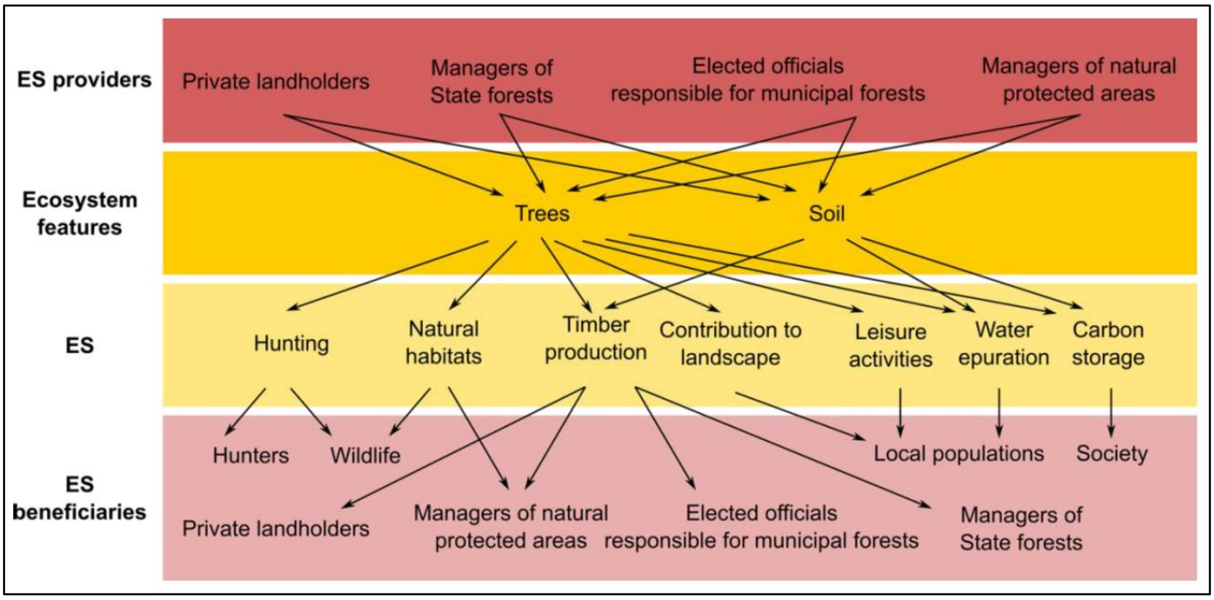

Figure 2. Foster Forest conceptual model summary (ES stands for Ecosystem Service).

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

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

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

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

Table 4. Foster Forest – Pros and cons.

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

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

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

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

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

[4, 57]

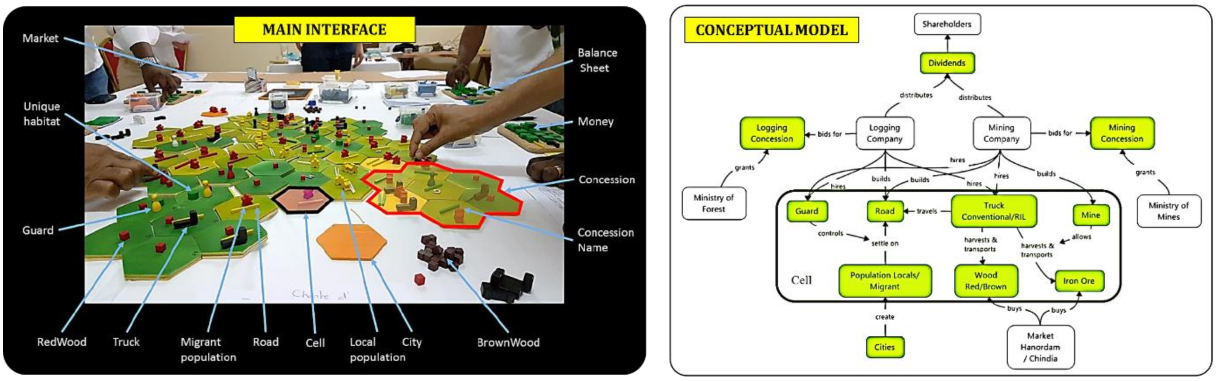

Figure 3. MineSet interface (left) and conceptual model (right). [4]

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

In 2023, P. O. Waeber et. al. tried this game with Forestry graduate students online via a zoom call. They confirm good engagement, a great learning experience, and emergence of realistic strategies. Participants expressed a need for a fully digital version of this game and/or similar ones for use as widely accessible, effective, transformative learning tools. [57]

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

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

Table 5. Mine Set – Pros and cons.

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

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

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

Tool 4 – About That Forest (Educational Game)

[5]

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

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

Table 6. About That Forest – Pros and cons.

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

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

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

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

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

[6]

Figure 4. Forest Kids UI elements.

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

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
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.	the facts as I focused more on memorizing tile symbols to get the matches right before the timer runs out to score maximum points.

Table 7. Forest Kids – Pros and cons.

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

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

Discussion

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

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

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

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

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

Following points briefly define what each quality entails.

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

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

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

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

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

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

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

Overall, Mycroforest meets all intended criteria w.r.t this project. It is a sufficiently realistic, engaging, and easily accessible web-based application aimed at the youth. Although the app itself is not multiplayer, it allows for team learning activities in addition to individual ones. Unlike many existing tools that try to do multiple things at once, Mycroforest focuses exclusively on forest management, it's effect on atmospheric CO2 levels, and impact of financial motives. This app is built to be easy to get into and use with lots of built-in help.

2.6 Summary

3 Design

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

3.1 Scope

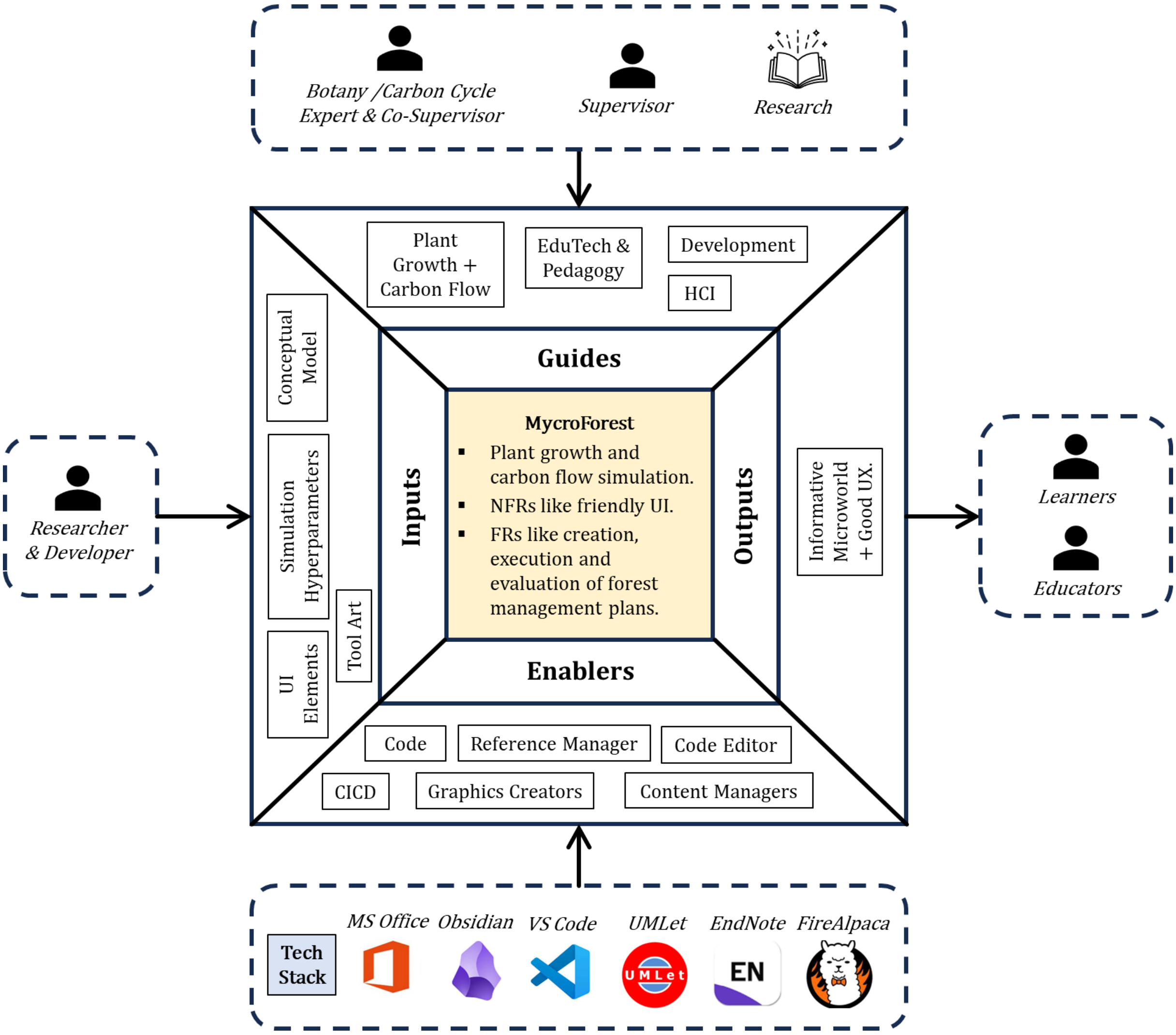

Figure 5. Scope diagram with core focus in the middle in yellow. [61]

[62]

Deliverable Name: MycroForest.

Justification: Objectives of this project are as follows.

- Research the field of education technology, simulations/microworlds, forest management, and climate change, to develop a user friendly, easily accessible, teaching tool that prompts young adults to think about the role of forests in sequestering carbon from the atmosphere and underlying economical motivators that lead to exploitation of forest resources through self-regulated learning.

- Evaluate the tool w.r.t educational value, learner engagement, and usability based on feedback from students who try it as part of the Bridge to College program at TCD.

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

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

Supporting Details: Following tables outline functional and non-functional requirements prioritised using the MoSCoW scale (priority in decreasing order of importance: Must > Should > Could > Would) [63].

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

5	Forest management actions and/or maintaining other income streams shall cost the user some coins.	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 user to view breakup of their income and expenses between different income streams.	COULD
7	System shall include built-in help.	MUST
7.1	System shall present short, component relevant help upon clicking "?" buttons that shall be available related to every major component.	MUST
7.2	System shall have a help page with all user guide materials on it.	SHOULD
8	System shall display land content.	MUST
8.1	System shall display presence/absence of trees on land.	MUST
8.2	System shall display biodiversity score and class related to the land.	SHOULD
8.3	System shall allow users to hover over a tree on land and view its species and age.	WOULD
9	System shall allow users to edit amount of Carbon emitted due to burning of fossil fuels.	MUST
10	System shall allow users to set CO2 and Income targets.	SHOULD
10	System shall allow users to set target CO2 concentration and display whether this target is met (CO2 level <= CO2 target) throughout the simulation.	SHOULD
10	System shall allow users to set target per rotation income and display whether this target is met (income this rotation >= per rotation income target) throughout the simulation.	SHOULD
11	System shall allow users to sign-up and log-in to persist information.	WOULD

Table 9. MycroForest - Functional Requirements (FRs)

#	*NON FUNCTIONAL REQUIREMENT (NFR)*	*PRIORITY*

1	The tool shall be valuable to both individual and groups of learners.	MUST
2	The tool shall provide good UX.	MUST
2.1	The tool shall be easy to use.	MUST
2.2	The tool shall respond quickly enough and present information effectively enough to minimize learner frustration.	SHOULD
2.3	The tool shall adhere to good HCI and data visualization practices (e.g. Norman's model, etc.).	MUST
3	Learners shall find learning activities using the tool valuable.	MUST
4	The tool shall be widely accessible with minimal set up required. Hence it is a web application. It should work well, at least on Firefox, Chrome, Edge, Brave, and Opera browsers on any modern PC or laptop.	MUST
5	The tool shall subject all user inputs to sanitization checks prior to performing internal parameter updates to avoid erroneous or maliscious input corrupting data.	MUST
6	The tool shall be suitable for youth (15 - 25 year old individuals).	MUST
7	The tool shall highlight the role of forests as important carbon sinks as well as draw attention to the underlying financial motives that drive exploitation of forests.	MUST
8	The tool shall not overwhelm learners and instead present user guide related information as short extracts with supporting images. Features of the tool shall also be introduced few at a time, gradually over multiple challenges.	SHOULD
9	The tool shall make available, sufficient amounts of easily findable built-in help.	SHOULD
10	Learners shall find the learning experience using the tool enjoyable.	COULD
11	The tool shall try to provide an optimal level of challenge for learners by allowing multiple challenges of varying difficulty levels to be formulated using the tool.	COULD
12	Gamification elements in the tool and associated learning activities shall motivate learners without distracting them.	WOULD

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

Value Added by Supervisor: TO DO …

Value Added by Co-Supervisor: TO DO …

3.2 Pedagogical Approach

3.3 UI & HCI Design

3.4 System Architecture

3.5 Detailed Technical Design

This section describes key choices made during the development of MycroForest.

3.5.1 Tech Stack & Technical Architecture

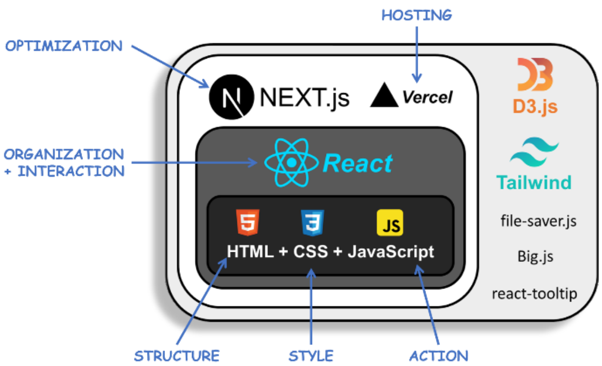

Figure 45. MycroForest – Tech Stack

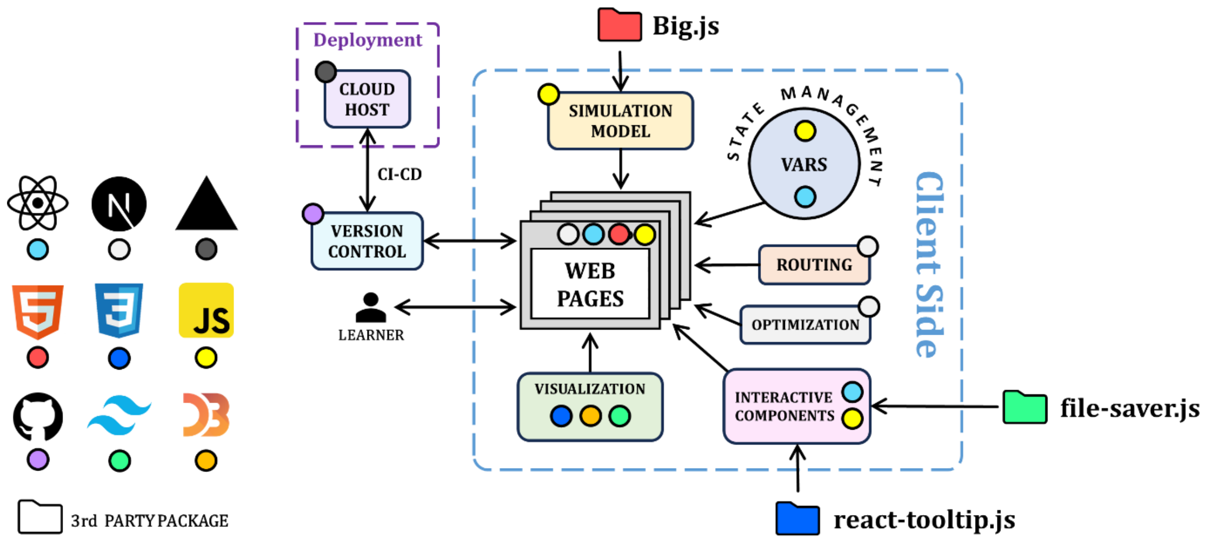

Figure 46. MycroForest - Technical Architecture. A coloured-coded circle maps each technology with its associated function in the architecture diagram.

Technically, MycroForest is a standalone, client-side, static web site. There is neither a separate backend nor a database since users need not sign-up or log-in to use the learning tool. All data is stored in JavaScript variables within React Components. This means system state is not persistent across sessions and gets updated upon browser page refresh. However, learners may save a world's state including their management plan and reload it if necessary. The decision was made to not include a database or user authentication as this does not add much value to the learning experience and would only serve to introduce unnecessary complexity.

Following points explain the role of each key technology leveraged.

- **HTML:** Hyper Text Markup Language is the backbone of all web pages. It is used to establish the structure and layout of content on the site.
- **CSS:** Cascading Style Sheets (CSS) is used to style websites. It can be used to add colour, animation, 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 with the webpage by providing a means of detecting events like mouse moves, clicks etc. It also allows working logic or functions to be embedded into the webpage.
- **Big.js:** The Big.js library facilitates precision computation using very large or small numbers. Unlike native JavaScript numbers, which have limitations in precision, Big.js stores numbers as objects with arbitrary precision. MycroForest models carbon amounts and environmental properties (e.g. mass of atmosphere) using extremely large values as on Earth. Storing such large values (e.g. 5.1e+21, 6.25e+18, etc.) as native JavaScript "number" objects led to overflows or underflows upon calculation. Big.js was used to overcome this problem.
- **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 file-saver library is used to save world state data as a JSON file on the learner's system.

- **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 the structure of a webpage defined by HTML that the browser maintains [128]. This framework is especially suitable for applications with heavy user interaction as is the case here largely because the built-in react-dom library that comes bundled with ReactJS maintains a virtual copy of the DOM and rebuilds it every time states are updated such it is then compared with the real one and only necessary changes are reflected on the real DOM. This optimizes DOM update, which is a computationally expensive operation. A component is simply a special function that returns JSX (JavaScript XML) which is notation that allows HTML-like and JavaScript like content to coexist in React components such that both structure and logical functionality of components may be self-contained. Private data associated with a component in React is referred to as States. MycroWorld's code most frequently uses React hooks useEffect, useState, and useContext. A "hook" in react is a function that allows state variable updates. The useState hook does just this. Every time state is updated, ReactJS ensures that the corresponding component is re-rendered on stage. The useContext hook is used to allow states to become globally accessible throughout all React components. The useEffect hook allows one to set up some logic that shall get executed each time particular state updates occur, or the corresponding component is loaded onto the webpage for the first time. To summarize, MycroForest leverages ReactJS to modularize web 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 Server Side Rendering is that the HTML for the webpage is generated in the server side and sent to the client instead of the it having to be built on client side. This means that initial page loading is faster for the client and search engines can find the webpage more easily since HTML is pre-built and ready for parsing. Not all components can be rendered on the server side. Those that users can interact with, are rendered on the client side because content displayed will depend on user interaction (e.g. text input by user, user having clicked some button, etc.) 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 multiple other interactive components that can only be rendered on the client side. While SSR is generally an attractive feature when content fetched from the server is dynamic (e.g. changes for different users based on user-id as ike with personalised recommendations). However, MycroForest is a "static" web

application. This means content displayed, barring output influenced by random number generators, is same for all users. So SSR is not of much benefit here. That said, NextJS has SSG capabilities which has the web-page structure ready at build time and much like SSR improves search engine optimization and initial loading time. SSG is therefore, advantageous for static web apps like MycroForest. Furthermore, in MycroForest, NextJS's useRouter hook is used for managing client-side routing and its file-system-based routing convention allows for easy organization of pages and automatic route generation and navigation without the need for a separate backend to manage this.

- **D3.js:** D3.js is a graphics library that allows for creation of custom plots. In MycroForest this was used to create the piece of land where trees grow and change shape which is essentially a customized scatter plot.
- **GitHub:** GitHub is a cloud code warehouse. All project code over time is stored in a GitHub repository here. The biggest advantage that GitHub presents is that it can be configured using Git, distributed version control system, to allow code "pushes" to the repository that updates only portions of files in it that have been changed such that previous versions are maintained in history and can be restored if required.
- **Vercel:** Vercel is a cloud platform where web apps can be deployed. It was created by the creators of NextJS and hence the two are very compatible. Mycroforest is currently hosted on Vercel here. MycroForest's Vercel project is linked to MycroForest's GitHub repository such that new pushes to GitHub trigger a new deployment of the application on Vercel. Thus, this set up facilitates Continuous Integration and Continuous Deployment (CICD).

3.5.2 Conceptual Model

3.5.3 Key Algorithms, Data Structures, & Code Design Choices

3.6 Summary

4 Implementation

5 Testing and Evaluation

5.1 Pilot Testing

5.2 Bridge2College Workshop

5.3 Usability Evaluation

5.3.1 System Usability Scale (SUS)

5.3.2 Post-Study Usability Questionnaire (PSSUQ)

5.3.3 Usability Results

5.4 User and Educator Feedback

5.4.1 Instruments Used

5.4.2 Findings

5.5 Summary

6 Conclusion

6.1 Recap

6.2 Limitations

6.3 Future Work

6.4 Personal Reflection

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8 Appendices

8.1 Survey Instruments Used

8.2 Use of GenAI in this Work