Limitations

Project limitations are as follows.

1. **Limited Testing:** Evaluation of MycroForest was conducted with 10 students. It was not possible to have more students try the tool as schools were on holiday and deadline for submission of this work meant that waiting until more students were available was impractical. Responses from 10 learners was interpreted based on simple descriptive statistics like mean scores. More elaborate analysis like say, hypothesis testing when sample size is as small as 10, was deemed unnecessary since results cannot be confirmed as being statistically significant. This means that evaluation as presented in this work is not conclusive although it shows the approach to follow. Notwithstanding criticisms, the positive results suggest that MycroForest is on right lines and merits further use and evaluation, as the Bridge2College team plans to do.
2. **Challenges Not Built-In:** Currently, pressing Ctrl + Alt + 1, Ctrl + Alt + 2, … Ctrl + Alt + 5 on the keyboard, progressively reveals only those tool features required for each corresponding challenge proposed as part of the learning activity. Challenge 5 reveals all features of the application. Apart from such selective reveal, explicit instructions that guide learners though challenge goals are not built into the tool as say, a walkthrough. Thus, learning experience may be less rewarding without an educator. That said, research suggests that microworlds are most effective when used by students in the presence of a knowledgeable facilitator who can provide guidance/structure to learning and ensure correctness of learner conclusions. MycroForest is thus, intended to be used in the presence of an educator. Further, educators might find the tool flexible because it has no rigid built-in challenges/learning activity, custom activities to be designed around it. To this end, while it is possible to change visibility of features with ease, altering current progressive reveal settings, requires minor source code changes which limits flexibility of the application. However, there is an easy solution to this as presented in the next Future Work sub-section, point 6.
3. **Forest-World Scale Mismatch and Large CO2 Fluctuations:** CO2 levels fluctuate more in MycroForest than on Earth, as carbon released/absorbed by up to 36 trees is multiplied by a factor of 2.4e+8 to simulate impact on global atmospheric CO2 levels by entire forests on Earth. This inaccuracy is not so great as to hinder learning. Cause effect relationship between learner management actions and microworld atmospheric CO2 concentration changes as well as quality of life classification associated with CO2 levels remain realistic. That is, fluctuations remain within appropriate quality of life categories for specific management strategies. E.g. on earth, CO2 concentration has remained in the 180 to 430 range throughout known history [153]. In MycroForest, natural fluctuations with no or responsible felling causes CO2 concentration fluctuations up to 700 ppm. On earth, it would be idea to keep level below 430, in MycroForest, a higher concentration of up to 700 ppm, is considered tolerable. Learners were briefed about this and that they have more leeway in the tool

than we do on Earth since it is only an abstract representation of all forests on Earth. In both MycroForest and the real world, as CO2 levels get higher still (> 700 ppm), this leads to very dangerous climate conditions ~~corresponding to poor forest management practices and anthropogenic carbon emissions.~~ Another undesirable consequence of the CO2 fluctuation in MycroForest is that levels sometimes drop too low, and few trees die due to lack of it. This is not common on Earth. However, death of parts of the forest due to chance events like diseases/disasters do occur in the real world, and so, occasional death of few trees may be presented as reflective of natural chance conditions to keep the educational experience sufficiently realistic. Reducing this instability could involve eliminating tree carbon exchange scaling factor and scaling down all environment carbon amounts while maintaining Earth's ratios, then reconfiguring hyperparameters for realistic system behaviour. This wasn't attempted due to time constraints. This may also be occurring due to indirect effects of some unmodelled parameter or behaviour. Further discussion with the domain expert and more thorough research could uncover any missing key relationships, however doing so was not possible within the project timeframe.

4. **Simple Simulation Model:** Currently, the underlying tree growth and carbon exchange simulation model is simple, only CO2 is explicitly modelled as a resource that trees require since this is most relevant to carbon sequestration. Other growth conditions are assumed to be ideal. Modelling plant growth in more detail will likely produce a more realistic model which may even result in lesser fluctuation of atmospheric CO2 levels as mentioned above. However, given that educational focus is on changing atmospheric CO2 concentration in response to forest management strategies as opposed to plant growth processes, the current simple model was found to be adequately accurate, capturing key cause effect relationships well, as confirmed through experiments and validated by the fact that students were able to observe real world management strategies via the tool.
5. **Lack of Error Messages:** Learners reported that they would like more helpful error messages. There already exist some error displays like text boxes turning red and not accepting changes when input is invalid (e.g. text in a numeric field). Further testing of the tool is required to identify situations that require added error messages that could appear in a closeable pop-up box on the screen.
6. **Income Generation v/s Carbon Sequestration:** The domain expert noted that incorporating economic gain from forests alongside CO2 reduction in challenges might suggest to learners that both are equally important. The app included these conflicting goals to illustrate the difficulty of sustainable forest management and the opposing nature of economic and climate-friendly objectives. However, given the urgency of climate change, carbon sequestration is more critical than income generation from forests. Challenges 4 and 5 make it more difficult to exploit forest timber without CO2 levels reaching critical. Thus, if learners attempt all proposed challenges, they are less likely to consider both goals equal. Further, educators are free to develop their own different learning activities with other challenges that might circumvent this risk. In the B2C learning session, educators stressed the need for

actions against climate change in the real world during the introduction to mitigate this risk to some extent.

7. **Time Navigation Mechanism:** Currently, when the user navigates to any point in time before current simulated year, the microworld is re-initialized, and simulation steps are repeated until requested year is reached. That is, event flow is unidirectional. E.g., if the learner pauses at year 100 and wishes to view world state at year 10, then under the hood, the microworld state is first reset to year 0, and then followed by 10 simulation step updates to display state at year 10. Although this saves a lot of memory as world state for every year need not be held in memory, it is not scalable with performance likely slowing down if more years are to be simulated. For a simulation period of 300 years ~~and a warm-up period of 200 to 500 years,~~ the slightly slower response when navigating back in time is negligible and does not significantly impact UX. However, future work should explore alternatives.

Future Work

Following are few starting points for expansion on this work.

1. **More Testing:** MycroForest requires further evaluation to determine whether observed responses are conclusive. More testing with responses recording suggestions for error messages can help incorporation of more error messages in the tool and alleviate limitation 5. With a larger sample size (> 30 tool evaluators, the central limit theorem is considered applicable when sample size ≥ 30), as more data is available, results are likely statistically significant and more extensive analysis can be conducted. For example, to assess whether learners find tools like MycroForest (microworlds) engaging, hypothesis testing can be conducted using the mean and standard deviation of responses to the evaluation item "Tools like MycroForest makes learning engaging" from the questionnaire filled in my learners. Null and alternate hypotheses could be H_a: "mean engagement score is < 4" and H_0: "mean engagement score is $\geq$ to 4" where a score of 4 implies neutral response with 1 and 7 indicating most and least perceived engagement respectively. Assuming a standard significance level of 0.05, a t-test statistic can be computed (t – test statistic instead of z score because population standard deviation is unknown) followed by the p-value such that if p-value ≤ 0.05, H_0 can be rejected and one may conclude that learners do indeed find tools like MycroForest engaging. Similar analysis may also be done for other areas of interest w.r.t the teaching tool like ease of use, satisfaction, perceived educational value, and more. Further, Natural Language Processing (NLP) techniques like topic modelling using the LDA algorithm can be applied to textual open ended responses to extract most liked and disliked aspects about the tool.
2. **More Detailed Simulation:** Plant growth and carbon exchange simulation may be made more detailed and realistic by modelling other factors like effect of soil nutrients, water, etc. This may mitigate limitations 4 and 5. Alternatively the possibility of leveraging existing third party detailed plant growth models may be considered. E.g. TreeSim is a Python based Individual Tree Simulation framework

[154]. This was not considered for this project as it is not directly compatible with web technologies used. Also, such solutions are often difficult to customize and expect several input parameter values that must be supplied like specific supported tree species, altitude, latitude, etc. Thus, simplifications necessary to make the tool less overwhelming to young learners, like presenting just 2 generic tree species, would have been very difficult if the if existing hyper-realistic plant growth simulator had to be integrated. This is why it was avoided here. However, further work can explore more tools as few might prove compatible for this use case.

3. **Expose More Parameters to Learners:** Currently, only forest management and fossil fuel usage emissions related model parameter values can be manipulated by users via the GUI. This was intentional as this keeps the tool focussed on climate aware forest management. However, exposing more model settings can expand possible learning scenarios. E.g. A slider may be provided that allow users to adjust the proportion of harvested timber being burned for energy v/s being turned into lumber that preserved sequestered carbon for longer.
4. **Activity Persistence and Built-In Team Mode:** A natural expansion of MycroForest would be for it to be a dynamic web application with an added database that stores learner data and progress. The tool could also support team creation and communication (e.g. a feature like group chat or the Blackboard discussion space).
5. **More Income Streams:** Other income streams from forests like agroforestry may be incorporated.
6. **Selective Reveal Settings:** The need for small code changes in order to hide/show MycroForest features, as mentioned in limitation 2, can be circumvented by introducing "settings" in the tool wherein educators may toggle UI panels/features ON/OFF via the GUI.
7. **Alternate Time Navigation Implementation:** Investigating alternate ways to facilitate forwards and backwards time navigation can help overcome limitation 7. Smooth, memory/computational resource efficient, bi-directional traversal is challenging. Most existing similar tools, including those analysed in this work, do not support this. Cashing, parallel/distributed processing, and keeping track of changes between simulation steps are areas to explore for solutions. It may also be interesting to experiment with world state compression/decompression or encoding/decoding mechanisms to make storage more efficient.