Bachelorarbeit

One Trillion Trees

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Contents

Abstract

Climate change mitigation strategies such as reforestation and emission reduction involve complex, long-term processes that are often difficult to communicate and understand. This thesis investigates how an interactive, simulation-based climate model can support both conceptual understanding and factual knowledge regarding the long-term impacts and limitations of these strategies.

To address this research question, an interactive climate simulation was developed that allows users to explore the effects of emission changes and reforestation efforts on global temperature development. The simulation was evaluated through a pre/post test study with ten participants using an questionnaire with eight questions. The collected data were analyzed using a Wilcoxon signed-rank test.

The results indicate a statistically significant improvement in participants understanding after interacting with the simulation, suggesting that simulation-based approaches can effectively enhance both factual knowledge and conceptual insights into climate change dynamics. These findings highlight the potential of interactive simulations as educational tools for communicating complex climate processes and supporting informed understanding of mitigation strategies.

1 Introduction

Climate change is widely regarded as one of the major global challenges of the 21st century. Rising global temperatures are closely associated with increasing concentrations of greenhouse gases in the atmosphere, particularly carbon dioxide (CO_2), which are largely driven by human activities such as fossil fuel combustion, industrial processes, and land-use change. The continuous increase of CO_2 in the atmosphere intensifies the greenhouse effect and leads to long-term alterations of the Earth's climate system, including higher average temperatures, more frequent extreme weather events, and rising sea levels.

At the same time, natural carbon sinks such as forests, soils, and oceans play an important role in the global carbon cycle by absorbing and storing atmospheric CO_2 over long periods of time. Among these sinks, forests are often highlighted due to their dual role as carbon reservoirs and providers of additional ecological benefits such as biodiversity preservation and climate regulation. Consequently, large-scale reforestation and afforestation efforts are frequently discussed as potential mitigation strategies to counteract anthropogenic emissions. However, the actual effectiveness of such measures strongly depends on factors including tree growth rates, land availability, climate feedbacks, and future emission trends.

While emission reductions directly influence the amount of greenhouse gases entering the atmosphere, reforestation primarily affects how much of these emissions can be absorbed over time. Both mechanisms operate on different temporal and spatial scales and are subject to uncertainties that make long-term climate projections challenging. Understanding the relative influence and interplay of emissions and carbon sequestration is therefore essential for interpreting potential climate futures and for communicating the limitations and possibilities of different mitigation strategies.

To support an intuitive understanding of these complex relationships, simulation-based models provide a valuable tool. By abstracting key climate processes and allowing users to interactively modify parameters, such models can make the consequences of different assumptions and decisions more tangible. In particular, visual simulations can help illustrate how cumulative emissions, carbon uptake through reforestation, and time-dependent processes jointly shape atmospheric CO_2 concentrations and global temperature development.

This thesis explores the relationship between global CO_2 emission trajectories, reforestation scenarios, and global temperature change through the development of an interactive, simulation-based climate model. Rather than aiming to predict real-world outcomes, the model is designed as an exploratory and educational tool that allows users to experiment with different mitigation strategies and observe their long-term implications. The system represents the Earth in a simplified two-dimensional view and enables users to adjust the scale of tree planting over time, modify annual global CO_2 emission levels, and advance the simulation to explore how these choices influence atmospheric CO_2 concentrations, global temperature trends, and forest area development. By combining interactive controls with visual feedback over extended time horizons, the simulation seeks to support an intuitive understanding of both the potential and the limitations of reforestation as a climate mitigation strategy. The integration of climate tipping points further emphasizes the non-linear nature of the climate system and highlights how delayed or insufficient emission reductions can lead to critical threshold crossings and potentially irreversible changes.

Based on this approach, the central research question of this thesis is:

> *Does an interactive, simulation-based climate model improve users understanding of the long term impacts and limitations of reforestation, emission reduction strategies and related factual climate knowledge?*

2 Related Work

Because climate change and the impact of global CO_2 emissions, as well as the role of natural carbon sinks such as reforestation, are highly relevant and widely studied topics, numerous studies have investigated the effects of emission trajectories and large-scale reforestation on atmospheric carbon levels and global temperature development.The following studies have been particularly influential in shaping the methodology and focus of this research, providing key insights into global CO_2 emission trajectories, the role of reforestation as a carbon sink, and the use of simulation-based approaches for understanding climate change processes.

Tölgyesi et al. [29] assess the global carbon sequestration potential of ecosystem restoration, including forests, shrublands, grasslands, and wetlands. Using actual sequestration rates, they find a maximum potential of 96.9 GtC-only 3.7-17.6 percent of anthropogenic emissions, highlighting that restoration should focus on biodiversity and ecosystem resilience rather than carbon offsetting.

Aprilia [3] examines the carbon sequestration potential of community forests in Sidodadi Village, Indonesia. Using non destructive allometric methods, the study finds high carbon storage for Jabon and Balsa trees, highlighting the forests role as vital carbon reservoirs. The paper emphasizes that empowering local communities in sustainable management supports both climate mitigation and local livelihoods.

Galik and Jackson [11] analyze reversal risks in forest carbon offset projects, where sequestered carbon may be released by disturbances like wildfires, storms, or pests. They highlight that management strategies maximizing carbon storage can increase vulnerability, and argue that integrated policies, such as buffer pools, insurance, and harvested wood product accounting are necessary to mitigate reversal risks.

De la Plaza et al. [7] critically examines large scale biosequestration and Carbon Dioxide Removal strategies like BECCS, highlighting that climate finance often favors industrial monoculture plantations over natural forest restoration. Such projects can cause ecological degradation and socioeconomic harm, including biodiversity loss, water disruption, wildfires, and displacement of local communities. The authors advocate for rights-based, community-led governance as a more effective and equitable approach to ecosystem restoration and carbon sequestration.

The Global Carbon Budget 2025 report by Friedlingstein et al. [10] synthesizes global CO2 emissions and their redistribution among the atmosphere, ocean, and land. Fossil emissions reached a record 10.3 GtC in 2024. Natural sinks are increasingly constrained by climate variability and change, and the remaining carbon budget to limit warming to 1.5°C is nearly exhausted, leaving only about four years at current emission rates.

The OECD report “Climate Tipping Points” [20] warns that climate tipping points like ice sheet collapse or permafrost thaw are already possible at 1.1°C warming and likely between 1.5–2°C. Crossing one tipping point can trigger cascading effects, leading to irreversible impacts that current economic models underestimate. The report stresses limiting warming to 1.5°C and implementing transformational adaptation to enhance societal resilience.

The white paper by Trillion Trees [19] argues that low cost “1 Dollar per tree” models are misleading, as focusing solely on tree numbers often results in underfunded projects that fail to deliver lasting climate, biodiversity, or livelihood benefits. The report introduces a data driven framework highlighting planning, local stakeholder participation, diverse interventions, maintenance, and long-term monitoring, promoting sustainable Forest Landscape Restoration rather than simple tree planting.

Ackerman and Stanton [2] estimate that under a business as usual climate scenario, the United States could face economic costs of up to 3.6% of its GDP by 2100. Approximately half of these costs (1.8% of GDP, corresponding to about 1.9 trillion USD annually) are attributed to impacts such as hurricanes, sea-level rise, increased cooling demands, and water-related effects. The study concludes that the economic costs of inaction substantially exceed the investments required for mitigation, thereby underscoring the urgency of immediate emission reduction efforts.

Bussotti and Pollastrini [5] review the opportunities and limits of tree planting for climate mitigation. They note that terrestrial sinks can only absorb part of global emissions, with effectiveness constrained by nutrient and water limitations. Key challenges include the growth defense trade off, which reduces longevity and increases climate vulnerability, and biophysical trade offs like albedo changes and VOC emissions that can offset carbon sequestration benefits. The authors conclude that tree planting cannot replace emission reductions and recommend nature based silviculture that prioritizes ecosystem resilience and biodiversity.

The systematic literature review by Vlachopoulos and Makri [30]analyzes the impact of digital games and simulations on higher education by synthesizing findings from 123 empirical studies. In terms of affective outcomes, the study highlights significant increases in student motivation, engagement, and overall satisfaction. A key conclusion is the pivotal role of the instructor, who must act as a facilitator to align game mechanics with pedagogical goals and provide necessary guidance. Despite these benefits, the authors note challenges such as high design costs and a lack of unified terminology in the field.

Rutten et al. [23] review a decade of research on computer simulations in science education and find consistent evidence that simulations can enhance learning outcomes when used alongside or in place of traditional laboratory activities. In particular, simulations are effective at visualizing otherwise unobservable processes, which supports conceptual understanding. The authors emphasize that instructional design and appropriate scaffolding are more important for learning success than technological immersion alone.

The study by Basheer et al. [4] explores the impact of integrating simulations into eighth grade chemistry lessons on academic achievement, motivation, and perceptions of classroom climate. The results reveal that academic achievement in the experimental simulation group increased significantly. The researchers identified strong positive correlations between achievement, motivation, and classroom climate, with no significant gender differences observed

Wu and Lee [31] argue that climate change games can effectively support education and engagement by enabling experiential learning and systems thinking. By allowing players to explore future consequences of present actions, such games foster understanding of complex climate dynamics. However, the authors underscore that guided reflection and further research are necessary to assess long-term learning and behavioral effects.

Sun et al. [25] propose an enhanced methodology for designing GUIs in large-scale scientific and engineering applications, emphasizing modularity and iterative user testing. Using a 3D space telescope system as a case study, they show that separating control interfaces from computational cores and employing intuitive interactive elements, like graph based selection and dynamic show/hide buttons, improves usability for users with varying expertise.

The study by Granlund et al. [12] explores the design and instructional potential of web simulations for education and training. By merging dynamic simulation-based learning with the accessibility of the web, web simulations allows learners to engage with environments that are typically too costly, complex, or dangerous to access. The authors highlights that creating such environments is a multidisciplinary task requiring both modeling expertise and pedagogical knowledge

The 2023 IPCC [16] Synthesis Report confirms that human caused warming has already reached 1.1°C, with extreme events and sea-level rise affecting ecosystems and societies. Immediate, deep emission reductions, net-zero CO2, renewable energy expansion, and ecosystem restoration are required to limit warming to 1.5–2°C. The remaining window for effective action is urgent, and global cooperation is essential.

The paper by Duchatelet et al. [8] introduces a special issue focused on how simulation-based learning is assessed and evaluated in higher education and professional training. It brings together nine studies from different disciplines to deepen understanding of how simulations are designed, used, and how effective they are in supporting learning. The authors discuss common strengths and weaknesses across these studies and highlight areas where more research is needed to better measure and understand simulation-based learning outcomes.

Chapter 38 in the book "Handbook of Human Factors and Ergonomics" [17] introduces the core concepts of usability and user experience and explains how they relate to designing and evaluating interactive systems. It defines usability as how effectively, efficiently, and satisfactorily users can achieve goals with a product, and UX as the broader subjective experience including emotions and satisfaction. The authors describe user centered and iterative design approaches to create better interfaces.

The article from Abbass [1] synthesizes current knowledge about global climate change: its impacts, adaptation strategies, and sustainable mitigation measures. It covers how climate variability affects various sectors (like the environment, human health, agriculture, biodiversity, and economies) and discusses approaches for adapting to and reducing climate change impacts. The paper emphasizes that climate change is a major global threat that requires policy action, government involvement, and integrated strategies to build resilience and sustainability

Climate TRACE [6] is a non profit initiative uniting more than 100 universities, technology companies, researchers, and climate experts. It provides independent, high-resolution estimates of global greenhouse gas emissions by applying machine learning methods to satellite and sensor data. The findings are presented on an interactive 3D globe, allowing users to explore emissions worldwide.

In the paper "High-Resolution Global Maps of 21st-Century Forest Cover Change" [13] High-resolution satellite data show that between 2000 and 2012 global forest loss (2.3 million km2) far exceeded forest gain (0.8 million km2), with the tropics being the only climate zone showing increasing annual loss rates. Reductions in deforestation in Brazil were offset by rising forest loss in countries such as Indonesia and Bolivia, while forestry and fires dominated forest loss in subtropical and boreal regions, respectively.

Tracking Standard [15] promotes global transparency in product tracking using a standardized approach. Their interactive World Map visualizes the distribution of accredited issuers and partners worldwide, showing where their standard is implemented and enabling users to explore this global network of tracking systems.

The Observatory of Economic Complexity [26] is an interactive data visualization platform that presents complex global economic data in an intuitive, 3D globe interface. It enables users to explore international trade flows, product specialization, and economic relationships across countries, facilitating a deeper understanding of global economic patterns.

OpenHistoricalMap [21] is a collaborative, open-source project that creates a global historical map by documenting geographic features and changes over time. Users contribute and edit historical data, enabling exploration of spatial transformations, historical infrastructure, and geographic evolution through an interactive mapping platform.

Zoom Earth [32] is an interactive global weather and satellite map that visualizes real-time and forecast weather data, including temperature, precipitation, wind, and pressure. Its temperature layer shows current temperature distributions worldwide, allowing users to explore conditions with an intuitive web interface and animated map controls. The platform also provides other weather layers, storm tracking, and near real time satellite imagery.

In summary, the studies reviewed in this section demonstrate that both future emission trajectories and natural as well as anthropogenic carbon sinks play a crucial role in shaping atmospheric CO_2 concentrations and global temperature evolution. Moreover, simulation based models have proven to be indispensable tools for capturing the complex feedback mechanisms within the climate system.

3 Technical Foundations

This chapter presents the scientific and technical foundations required for the development of the simulation. It summarizes existing models, datasets, and theoretical concepts that are necessary to understand global CO_2 emissions, carbon sequestration, and climate dynamics.

The focus lies on explaining approaches developed by other researchers, including relevant formulas, datasets, assumptions, and simplifications. These external foundations serve as the conceptual basis for the simulation described in the subsequent chapter.

Natural Earth Vector Data

For the geographical representation of the Earth within the simulation, this work uses vector data obtained from the Natural Earth Data repository [18]. Natural Earth is a public domain dataset widely used in geographic information systems and cartographic applications. It provides multi scale cultural and physical vector layers, including country boundaries, administrative regions, and demographic attributes.

Specifically, the 1:50m cultural vector dataset was used as the basis for the world map in this project. This dataset contains polygon geometries for all recognized countries and, importantly, includes associated attribute information such as ISO country codes and population estimates. The inclusion of standardized ISO codes simplifies the integration of country level data (e.g., emission values or simulation results) into the visualization.

The Natural Earth vectors were processed and transformed into the coordinate system and format required by the simulation engine. This involved filtering the features for relevant entities, extracting necessary attributes, and converting them into internal data structures used by the rendering and interaction logic. No original geographic data was created as part of this work. The Natural Earth dataset serves as the foundational geospatial layer that enables the accurate placement and identification of landmasses and associated country information within the simulation.

Average Temperature Data

To provide baseline climate conditions for each country within the simulation, this project uses country level average temperature data obtained from the World Bank's Databank [27]. This dataset aggregates historical average temperature values for individual countries over multiple years and makes them available in a standardized format suitable for comparative analyses.

The average temperature data serve as an empirical foundation for estimating initial climate conditions prior to applying scenario-based temperature changes. By associating each country polygon with its corresponding average temperature, the simulation can represent differences in baseline climate characteristics between regions.

The data were downloaded and processed to align with the geographic boundaries provided by the Natural Earth dataset. This involved matching the country ISO codes in the temperature dataset to the ISO codes in the spatial vector file, ensuring that temperature values could be linked unambiguously to the correct geographic entity. The processed temperature values is then used in a internal heatmap.

It is important to note that this dataset does not determine future temperature trajectories, which are controlled parametrically within the simulation. Instead, the World Bank average temperature data provide a realistic starting point for each country's climate profile upon which simulated temperature changes are projected.

CO_2 Emissions per Capita Data

To model country specific carbon dioxide emissions within the simulation, data on CO_2 emissions per capita were obtained from *Our World in Data*, based on datasets compiled by the Global Carbon Project [22]. This dataset provides harmonized and internationally comparable emission statistics for a wide range of countries and years, making it well suited as an external data foundation for global-scale climate simulations.

Using emissions on a per-capita basis allows the model to represent differences in average individual emission behavior across countries, rather than relying solely on absolute national emission values. This approach helps to account for disparities between highly populated countries with relatively low per-capita emissions and smaller countries with significantly higher per-capita emission levels.

Within the simulation, each country is assigned a CO_2 emission value per capita derived from the dataset.

Analogous to the temperature dataset, the emission data are based on historical and estimated values and do not reflect future policy or technological developments. Consequently, in the simulation, future emission trends are controlled through user defined parameters that scale the baseline emission data, allowing the exploration of different hypothetical emission scenarios while preserving a realistic initial data foundation.

Global Reforestation Potential Estimates

Estimates of global reforestation potential used in this project are based on the study by Fesenmyer et al. [9], which refines earlier assessments of land availability and carbon sequestration capacity for reforestation as a climate change mitigation strategy. The study addresses methodological critiques of previous global restoration models by incorporating improved land use constraints, climate limitations, and ecological feasibility criteria.

The authors provide country-level estimates of the maximum feasible reforestation area, expressed in hectares, as well as corresponding upper bounds for potential carbon sequestration. These estimates represent theoretical maximum values under biophysically and ecologically plausible conditions and are not intended as short-term or policy-based projections. In contrast to earlier, more optimistic assessments, the refined model emphasizes that reforestation potential is spatially heterogeneous and strongly constrained by existing land use, climatic suitability, and ecosystem dynamics. As a result, only a limited subset of countries accounts for a substantial share of the global reforestation capacity.

In this work, the data derived from this study serve as a scientific basis for identifying countries with particularly high reforestation potential. Based on these estimates, a subset of ten countries with the highest potential is selected and incorporated into the simulation. The concrete integration and computation of these values within the model are described in detail in the implementation chapter.

Climate Tipping Point Thresholds

The climate tipping points contained in the simulation are based on the temperature threshold estimates reported by the OECD [20], which were previously discussed in the related work section.

The OECD report provides temperature ranges at which the likelihood of triggering major climate tipping elements increases significantly. These threshold estimates serve as reference points for defining discrete tipping point events within the simulation. Each event is associated with a specific global mean temperature level and represents a qualitative change in climate system stability.

Within the scope of this project, the OECD thresholds are used to link simulated global temperature to identifiable tipping point events that are displayed along a temporal axis. This approach allows users to explore how different emission and reforestation scenarios influence not only continuous temperature trends but also the risk of crossing critical climate thresholds.

CO_2 Concentration and Temperature Relationship

To translate atmospheric CO_2 concentrations into changes in global mean temperature within the simulation, this project draws on the simplified radiative forcing approach discussed by Thunder Said Energy [28]. While recognizing the inherent complexity of the Earth's climate system, the referenced note provides an approximate mathematical relationship linking CO_2 concentration increases to radiative forcing and subsequent temperature effects, which can be incorporated into model formulations.

The underlying concept is that increases in atmospheric CO_2 raise the net radiative forcing of the Earth's energy balance, thereby triggering an increase in global mean temperature. This effect is typically described through logarithmic forcing equations combined with a climate sensitivity parameter gamma that translates radiative forcing into temperature change. Such formulations are consistent with widely used approximations in climate modeling and offer a tractable way to estimate temperature responses to changes in greenhouse gas concentrations.

In the context of this work, these simplified relationships provide the basis for converting simulated atmospheric CO_2 levels into corresponding temperature effects on a global scale. The simulation does not rely on a full general circulation model but rather uses such established empirical approximations to ensure that changes in concentration sensibly influence projected temperature trajectories.

4 Planting a Trillion Trees

System Overview

The system is designed to be intuitive and easy to understand. Users can interact with various elements, all of which provide immediate visual feedback, ensuring a smooth and engaging user experience. The model integrates multiple interconnected components, so that any adjustment, such as changing annual CO2 emissions or tree planting rates, directly impacts key results like global temperature, CO2 concentration per capita, and hectares of forest restored. The interface allows users to explore individual countries, displaying basic facts such as population, per capita CO2 emissions, and average temperature. A toggleable heatmap provides an intuitive visual representation of temperature changes across the globe. Additionally, the system includes a timeline that highlights critical tipping points. These tipping points shift dynamically based on user settings, allowing users to visualize how interventions or lack thereof might influence the timing of climate thresholds in future years. This combination of interactive controls, visual feedback, and predictive modeling provides users with a clear understanding of how different actions can influence global climate outcomes.

4.1 Simulation Model

The simulation model computes global climate developments on a yearly basis and links these results with country specific baseline information. The primary observable output of the model is global temperature change, which evolves over time based on underlying emission trends and reforestation rates. While CO_2 emissions and sequestration are not directly visualized, they are internally calculated as key intermediate variables driving temperature development.

User-defined parameters, such as emission trends or reforestation efforts, dynamically influence the global calculations. The resulting global temperature changes are then combined with country-level baseline data, including CO_2 emissions per capita and average temperature, to generate meaningful national-level representations. This approach ensures that the simulation consistently reflects the interaction between global climate dynamics and country-specific characteristics.

To initialize the simulation, initial year data is required. As a reliable foundation, the global CO_2 emissions of 2024 are used [14]. The starting atmospheric CO_2 concentration is set to 422.5 ppm [14], which serves as the baseline for calculating the temperature increase relative to pre-industrial levels. To determine temperature changes, the CO_2 concentration in ppm is converted to its equivalent mass in tons [24]. The initial number of trees planted is set to zero hectares.

The simulation allows users to interact with several live settings. These include the **CO_2 growth rate**, representing the annual percentage increase or decrease of global emissions, **reforestation**, specifying the number of hectares of trees planted per year, and the **heatmap toggle**, which enables or disables temperature visualization. Whenever these settings are changed, the simulation dynamically recalculates all future years and stores the results for each year.

The core of the simulation is the **yearly iterative computation**, handled by the `SimulationCalculator` class. For each year, the following steps are performed:

1. **CO_2 Accumulation:** The CO_2 concentration for the next year is calculated based on the previous year's CO_2, the global emissions, and the annual CO_2 growth rate:

$$CO2_{\text{next}} = CO2_{\text{current}} + GlobalEmissions \times \text{growth factor}$$

2. **Reforestation Impact:** Newly planted trees reduce atmospheric CO_2 based on each country's **forestation potential**, which specifies both the maximum available forestation area and the total amount of CO_2 that can be sequestered if this area is fully utilized [9]. The simulation accounts for the cumulative effect of all previously planted trees and applies their combined CO_2 uptake to the global atmospheric CO_2 mass.

First, the total global forestation potential is computed as the sum of all available hectares across the selected countries. The effective number of planted hectares is then limited to this global potential, ensuring that reforestation does not exceed physically available land. The effective hectares are distributed proportionally among countries according to their share of the total forestation area. Countries with larger available areas therefore receive a larger fraction of the reforestation effort.

For each country, the CO_2 absorption per hectare is calculated as the ratio between its total sequestration potential and its available forestation area. The total CO_2 reduction is obtained by summing the absorption contributions of all countries.

The resulting atmospheric CO_2 concentration after reforestation is computed as:

$$CO2_{\text{after}} = CO2_{\text{next}} - \sum_{i=1}^{N} \left(\frac{tCO2e_i}{ha_i} \cdot \left(ha_{\text{eff}} \cdot \frac{ha_i}{\sum_{j=1}^{N} ha_j} \right) \right)$$

where $CO2_{\text{next}}$ is the atmospheric CO_2 mass before reforestation, $tCO2e_i$ is the total CO_2 sequestration potential of country i, ha_i denotes its maximum available forestation area, and ha_{eff} is the effective number of planted hectares, limited by the global forestation potential. N is the total number of countries considered. This proportional allocation ensures a realistic and globally consistent representation of reforestation impacts while respecting regional land availability constraints.

3. **Temperature Calculation:** The updated CO_2 mass is converted back to ppm, and the global temperature increase is calculated using a simplified radiative forcing formula:

$$\Delta T = \text{climateSensitivity} \times 5.35 \times \ln \frac{CO2_{\text{ppm}}}{CO2_{\text{pre-industrial}}}$$

As discussed in the previous chapter, key constants such as the climate sensitivity and the radiative forcing coefficient of 5.35 are adopted from established scientific literature. The pre-industrial atmospheric CO_2 reference value of 280 ppm is also taken from the same source [28]. This iterative, year-by-year process enables the simulation to capture the combined effects of anthropogenic emissions and reforestation measures on global atmospheric CO_2 concentrations and temperature. As a result, the model provides a dynamic and interactive representation of long term climate evolution under different emission and mitigation scenarios.

4.2 Graphical User Interface

The graphical user interface is designed in a clean and intuitive manner in order to provide users with a clear and immediate understanding of the simulation and its core functionalities. A minimalist layout and consistent visual structure help reduce cognitive load and allow users to focus on the essential aspects of the simulation without unnecessary distraction. Interactive elements are used to enhance usability and improve user experience. Various user actions are accompanied by visual feedback, such as hover animations, subtle transitions, and color changes of buttons, which indicate interactivity and system responses. These visual cues support the user in understanding possible actions and system states, thereby increasing transparency and ease of use. Overall, the interface design aims to create a smooth and accessible interaction flow while maintaining clarity and functional simplicity.

Figure 1 shows the welcome screen of the simulation. At this stage, the user can choose whether to start a short tutorial or skip it and directly enter the simulation. If the user decides to start the tutorial, an introductory walkthrough is presented that explains the key features of the simulation. As illustrated in Figure 2, the tutorial highlights individual interface elements while the remaining parts of the simulation are visually withdrawn through a black blurring effect. This design approach directs the user's attention to the currently explained component and facilitates a clear understanding of the relevant functionality. Each tutorial step comes with a concise textual description that explains the purpose of the highlighted feature and how the user can interact with it. If the user does not want to complete the tutorial, it can be terminated at any time by clicking the close icon or by clicking anywhere outside the highlighted area. Additionally, the tutorial allows the user to navigate back to previous steps in order to review already explained features.

As shown in Figure 3, the simulation information panel provides an overview of the total number of trees planted up to the current year of the simulation. In addition, it displays the current global temperature increase relative to pre-industrial levels. To support a clear and intuitive understanding of this information, icons are used to visually represent the displayed metrics.

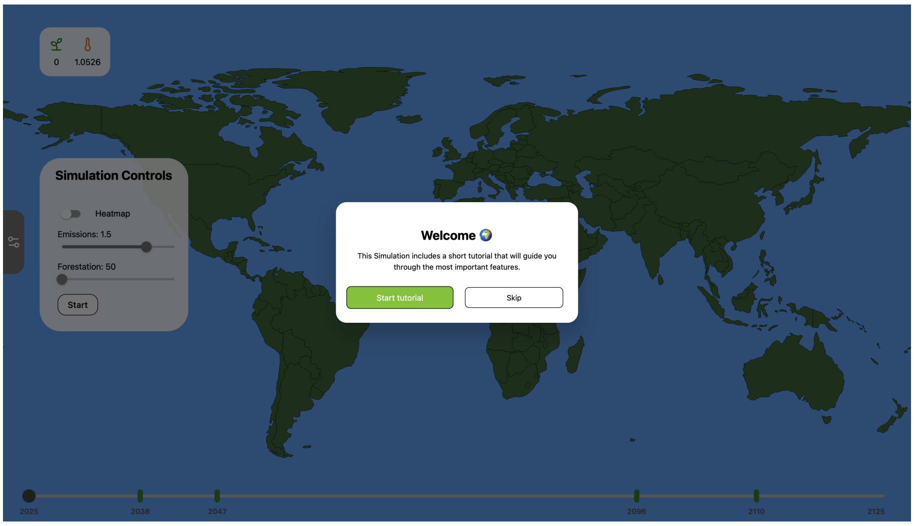

Figure 1: Welcome screen

Another important user interface component is the simulation control panel 4. This panel allows the user to adjust key simulation parameters, such as the annual reforestation rate and the percentage change in emissions per year. In addition, the user can toggle the heat map and start the simulation, enabling it to run automatically without the need to manually drag the timeline. To provide clear feedback, all interactive elements respond to user actions, for example through hover effects. Furthermore, the control panel can be hidden using the button on the left-hand side, allowing the user to maximize the visible simulation area for an unobstructed view of the simulation.

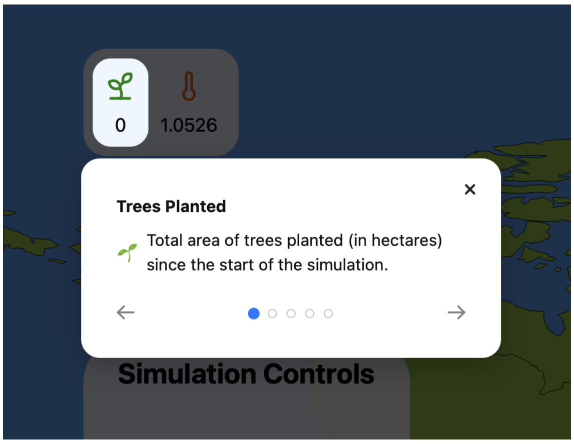

Figure 2: Tutorial screen

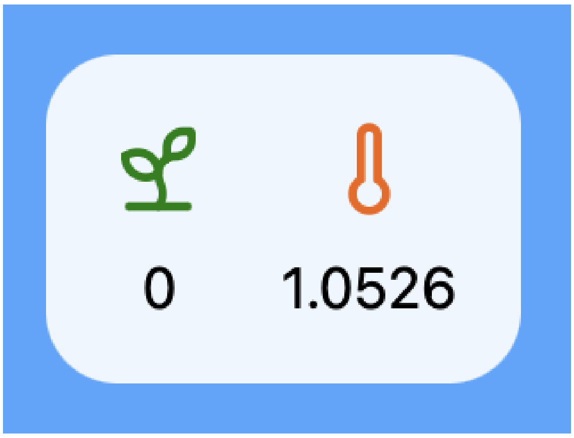

Figure 3: Simulation Info Panel

Figure 4: Simulation Controls Panel

The centerpiece of the simulation is the timeline (Figure 5), which allows the user to observe how different simulation settings impact the global climate. The timeline includes tipping points, which are critical thresholds that are reached when a certain temperature level is exceeded. Once a tipping point is triggered, a corresponding panel is displayed to provide additional information. To enhance visual clarity, tipping points increase in size and change color from green to red as they are approached. Users can preview a tipping point before it is reached by hovering over the corresponding point, which temporarily displays the associated panel. The timeline playhead can be draged manually, allowing users to skip through time, or it can move automatically when the simulation is started via the control panel, as described before.

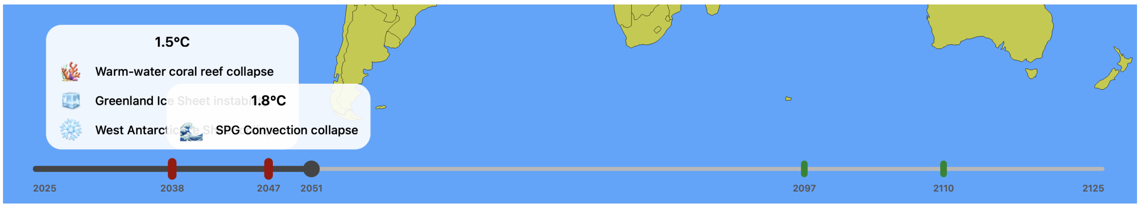

Figure 5: Timeline

To provide a clearer understanding of the total hectares of trees planted, a 3D tree model 6 is randomly placed on each of the ten countries with the highest sequestration rates, corresponding to one million hectares per tree model. As illustrated in the simulation, the trees are rendered in green, while the countries are displayed in a light yellow shade. The contrasting colors visually separate the trees from the country surfaces, providing a clear differentiation between the planted trees and the land.

Figure 6: 3D Trees

As shown in Figure 7, hovering over a country triggers a visual response. The hovered country is highlighted by changing its color to white, making it clearly visible which country is currently selected. In addition to the visual highlighting, an information panel is displayed that provides basic country specific data. These basic statistics are sourced from external datasets, as described in the Technical Foundations chapter. For each country, the panel displays population size, average temperature, and CO_2 emissions per capita. The displayed values are dynamically calculated by combining the baseline country data with the global simulation results. For example, the global temperature increase is added to the country's average temperature. This approach allows users to better understand how global climate changes affect local climate conditions and how CO_2 emissions evolve numerically at a country level. The information panel follows the same minimal and consistent design as the other interface elements. Its position dynamically adjusts based on the cursor location: it appears either to the left or right of the cursor, depending on whether the cursor is located on the left or right side of the viewport.

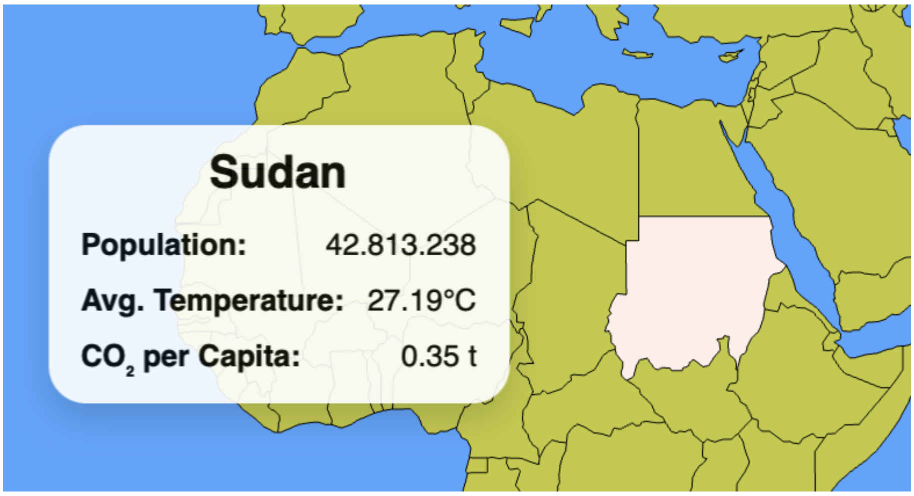

Figure 7: On Hover Country

When the user enables the heatmap, the countries colors change from their original appearance to a temperature based color scale, as illustrated in Figure 8. Countries with an average temperature of exactly 0 °C are displayed in white. From 0 °C up to 30 °C, the color gradually transitions from light orange to increasingly saturated red tones, reflecting rising temperatures. For temperatures of 30 °C and above, countries are displayed in a dark red color to emphasize extreme heat. In contrast, countries with average temperatures below 0 °C are visualized using shades of blue, with darker blue tones representing lower temperatures. This color mapping provides a clear and intuitive visual distinction between cold, moderate, and hot regions, allowing users to quickly assess global temperature distributions.

5 Evaluation

5.1 Evaluation Setup

The goal of the evaluation was to examine whether interacting with the simulation improves participants understanding of climate change dynamics, emission trajectories, and the role of reforestation as a carbon sink. For the evaluation, a questionnaire was developed to assess participants understanding of climate change and

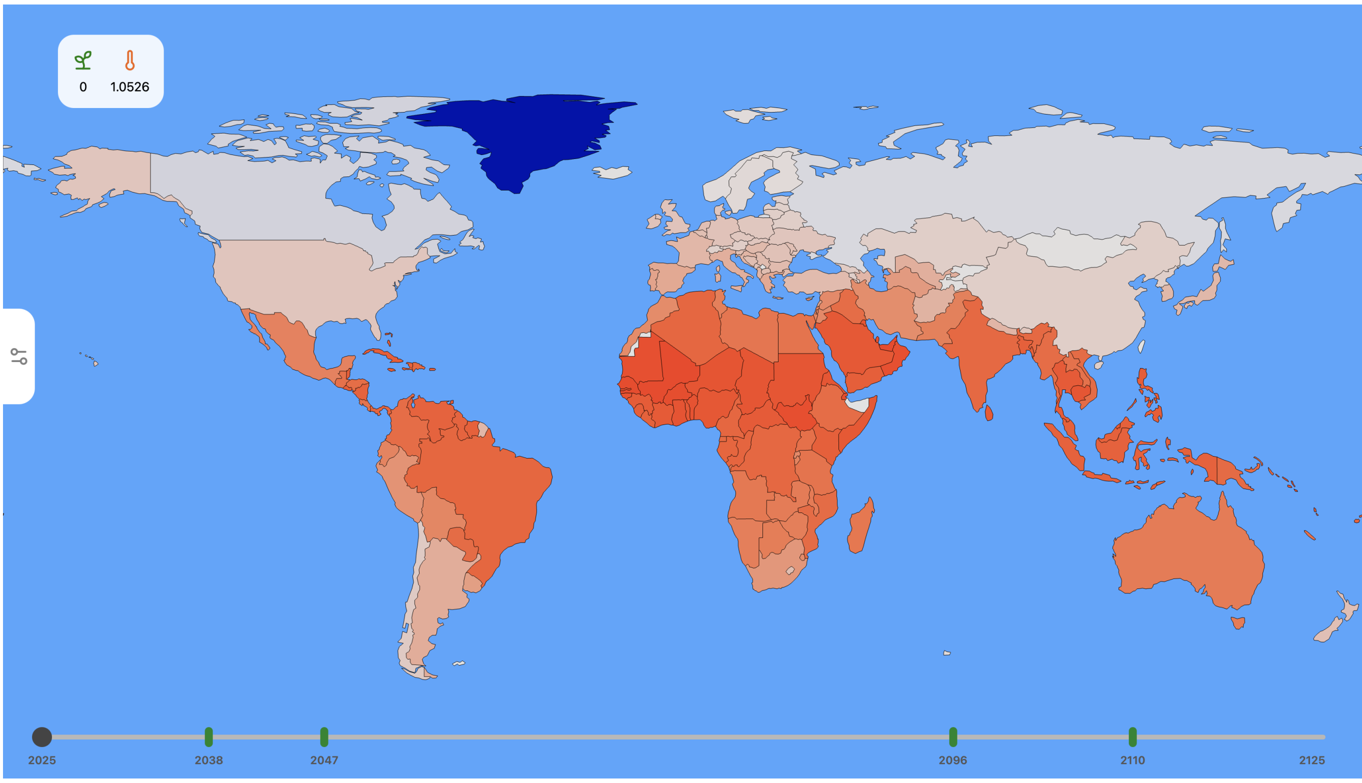

Figure 8: Heatmap

the potential effects of reforestation. The questionnaire consisted of eight questions, covering topics such as global temperature increase, emission reduction, and the effectiveness of reforestation strategies as well as factual knowledge:

1. I think reforestation can significantly help in preventing global temperature increases.
2. I understand the impacts of different levels of temperature increase.
3. Even if emissions are drastically reduced, global warming may continue due to past emissions.
4. I know which countries are most affected by climate change.
5. I know which countries offer the greatest potential for effective reforestation and CO_2 sequestration.
6. I am confident in identifying the countries with the highest CO_2 emissions per capita.
7. Even aggressive reforestation cannot fully counteract the effects of ongoing emissions.
8. I understand how ongoing emissions contribute to future temperature increases.

The questions were specifically designed to align with the content and features of the simulation, allowing the study to assess whether participants knowledge could be enhanced by interacting with it. Participants were asked to complete the questionnaire before exploring the simulation (pre-test) and again after using the simulation (post-test). A total of ten participants took part in the study. Responses were recorded on a four point Likert scale: Strongly Disagree(1), Disagree(2), Agree(3), and Strongly Agree(4). To determine whether participants responses changed significantly after interacting with the simulation, a Wilcoxon signed-rank test was performed comparing pre-test and post-test scores.

5.2 Results

Table 1 shows the average pre-test and post-test scores for each question, illustrating the changes observed after participants interacted with the simulation. To evaluate

Table 1: Pre- and Post-test scores for each questionnaire item. Values represent the mean scores on a 4-point Likert scale.

Question	Pre-test	Post-test
Q1	3.10	2.10
Q2	2.80	3.30
Q3	2.80	3.30
Q4	2.60	3.30
Q5	1.80	3.70
Q6	2.40	3.30
Q7	3.30	3.90
Q8	2.80	3.70

the results, a Python script was used to read the corresponding pre-test and post-test CSV datasets. A Wilcoxon signed-rank test was then performed, yielding the following results: p-value = 0.00195, Median Pre = 2.81, Median Post = 3.38, and effect size r = 0.98. The p-value is well below the conventional significance level of 0.05, indicating a statistically significant increase from pre-test to post-test scores. The high effect size further suggests that the observed difference is substantial, demonstrating that participants understanding improved markedly after interacting with the simulation. In Figure 9, the results of the Wilcoxon signed-rank test are visualized, showing the pre-test and post-test scores for all participants. The plot illustrates both the overall increase in median scores and the distribution of individual responses, highlighting the significant changes observed after interacting with the simulation.

5.3 Discussion

The results of the Wilcoxon signed-rank test indicate a statistically significant increase in participants scores from pre-test (Median = 2.81) to post-test (Median = 3.38), combined with a high effect size (r = 0.98).

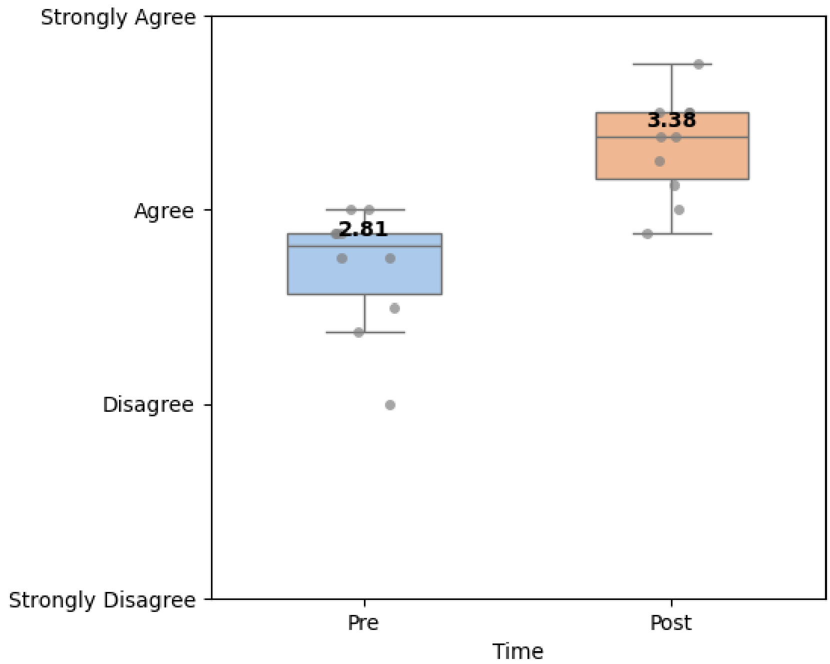

Figure 9: Wilcoxon Test results

The visualization of the results (Figure 9) illustrates this change clearly, showing an overall shift toward higher scores as well as consistent improvements across individual participants. These changes suggest that users not only developed a better understanding of the potential benefits of reforestation and the persistent effects of ongoing emissions, but also improved their basic factual knowledge, such as identifying countries with high CO_2 emissions per capita. In direct relation to the research question, these findings indicate that an interactive, simulation-based climate model can effectively support both conceptual and factual understanding of the long-term impacts and limitations of reforestation and emission reduction strategies.

However, it is important to note that this study was conducted with a small sample of only ten participants. As a result, the findings are preliminary and may not generalize to larger or more diverse populations. Future studies should include a larger sample size and potentially different user groups to validate and extend these results. Additionally, longer-term assessments could investigate whether the observed improvements in understanding are retained over time. Another limitation of the simulation is that it was created by only one developer within a limited timeframe, potentially restricting the features and depth of the simulation.

As an outlook for the project, several potential improvements to the simulation were identified during implementation and evaluation. One possibility is to expand the heatmap functionality, allowing users to switch between a temperature heatmap and a CO_2 heatmap, in which countries are colored according to their per-capita CO_2 emissions. Additionally, including a legend for the heatmaps would improve clarity by explicitly showing which colors correspond to which temperature or emission values, thereby enhancing user understanding.

Another significant improvement could be to make each tipping point selectable, providing additional information when chosen. For example, selecting a tipping point could open or pop-up an article that explains in detail the potential consequences associated with that tipping point. This feature would help users better understand the severity of different tipping points and the potentially devastating effects of temperature increases. Implementing this improvement might require adjustments to the design of the tipping point indicators and the timeline within the simulation.

It could also be valuable for users to observe how CO_2 levels and temperature have evolved in the past, how they have developed until the present, and how they are projected to change in the future. To facilitate this, a diagram could be incorporated, either on a global scale or for individual countries, providing a clear visual representation of historical and projected trends.

Another aspect that is currently not contained in the simulation is the strong positive impact of reforestation on biodiversity. It could be particularly valuable to illustrate which specific biodiversity benefits can be achieved through reforestation efforts. For instance, users could select a country, especially one of the ten countries identified as having high reforestation potential and receive detailed insights into the possible biodiversity gains, such as habitat restoration or species preservation.

A final conceptual addition could be the inclusion of predefined scenarios, rather than requiring users to adjust emissions and reforestation manually. This would allow participants to more easily explore and understand the effects of different emission and reforestation strategies. For example, one scenario could implement the goals of the Paris Climate Agreement, automatically adjusting the simulation controls to reflect these targets. Alternatively, users could select from standardized scenarios, such as -3%,-1.5% ,0%, 1.5%, or +3% changes in emissions, making it easier to compare and comprehend the impacts of different policy or mitigation strategies.

6 Conclusion

This thesis investigated how an interactive, simulation-based climate model can support the understanding of the long-term impacts and limitations of reforestation and emission reduction strategies on global climate change. To address this research question, a climate simulation was developed and evaluated using a pre-test/post-test questionnaire. The results indicate that interaction with the simulation led to a statistically significant improvement in participants' understanding, as reflected by higher post-test scores and a large effect size. These findings suggest that interactive simulations can effectively convey both factual knowledge and conceptual insights into complex climate processes, including the delayed effects of emissions and the limitations of reforestation as a mitigation strategy.

Overall, the study demonstrates the potential of simulation-based tools to enhance climate change education by making abstract, long-term dynamics more tangible and accessible. While the evaluation was limited by a small sample size, the results provide a promising foundation for future work, including larger-scale studies and further extensions of the simulation's functionality.

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