UNIVERSITY of RWANDA

COLLEGE OF SCIENCE AND TECHNOLOGY
SCHOOL OF SCIENCES
DEPARTMENT OF BIOLOGY
ACADEMIC YEAR: 2023-2024
MASTER'S PROGRAM IN BIODIVERSITY CONSERVATION AND NATURAL RESOURCES MANAGEMENT

Assessing the impact of lightning strike disturbances on vegetation regeneration in Nyungwe National Park's Tropical Forest Ecosystem

A thesis submitted in partial fulfillment of the requirements for the degree of Master in Biodiversity Conservation and Natural Resources Management By Maniriho Jean d Amour (Reg. No:222022063)

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Kigali, August 2025

I, Maniriho Jean d'Amour, hereby declare that this Master's dissertation entitled " assessing the impact of lightning strikes disturbance on vegetation regeneration in Nyungwe national park's tropical forest ecosystem" is the result of my work in partial fulfilment of the requirements for the award of a Master's degree in Biodiversity Conservation and Natural Resource Management at the University of Rwanda, College of Science and Technology and has not been submitted for any other degree at the University of Rwanda or any other institution. All sources that I have used or quoted have been indicated and acknowledged in the references.

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Acknowledgements

I am profoundly grateful to Almighty God for the strength and perseverance granted to me throughout this academic journey. I extend my deepest gratitude to my supervisors, Prof. Elias Bizuru, Prof. Beth Kaplin, and Prof. Martin Sullivan, for their invaluable guidance and unwavering support throughout this research.

I am sincerely thankful to Dr. Myriam Mujawamariya for her insightful contributions. Special thanks to Dr. Göran Wallin for generously providing the essential rainfall data.

This study would not have been possible without the research permit granted by the Rwanda Development Board (RDB) and the exceptional facilitation provided by the management and staff of Nyungwe National Park (NNP). My sincere appreciation also goes to my dedicated field assistant for their tireless efforts.

Finally, I thank my family and friends for their constant encouragement.

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List of acronyms and abbreviation

NNP: Nyungwe National Park

ANP: Akagera National Park

VNP: Volcanoes National Park

RDB: Rwanda Development Board

TFs: Tropical Forests

NBSAP: National Biodiversity Strategy and Action Plan

KBA: Key Biodiversity Area

LLI: Leaf Loss Index

CFI: Crown Formation Index

LLI: Leaf Loss Index

CG: Canopy Gap

VLD: Visible Lightning Damage

DBH: Diameter at Breast Height

RS: Remote Sensing

GIS: Geographical Information System

GPS: Global Positioning System

NDVI: Normalized Difference Vegetation Index

NH: National Herbarium of Rwanda

UR: University of Rwanda

NMDS: Non-metric multidimensional scaling.

Abstract

Lightning is an often-overlooked yet powerful disturbance shaping tropical forest dynamics. In Nyungwe National Park, Rwanda, where thunderstorms occur on over 220 days annually, lightning is likely to play a critical role in vegetation regeneration and forest structure. This study investigated the ecological impacts of lightning strikes by comparing three disturbance regimes: lightning-damaged patches, non-lightning disturbed patches (caused by landslides, erosion, and other factors), and undisturbed forest controls. A total of 62 plots were surveyed to assess tree, shrubs and seedling density, species composition, and structural attributes such as diameter at breast height, height, canopy cover, crown formation, and leaf loss indices. Microclimate variables (temperature, humidity, rainfall, elevation) were measured alongside remote sensing analyses of vegetation greenness (NDVI). Results revealed that lightning strikes significantly reduced species diversity and community evenness by promoting dense regeneration dominated by a few light-demanding pioneer species, while suppressing shade-tolerant species. In contrast, non-lightning disturbed sites supported higher species richness but exhibited stunted structural development due to chronic abiotic stress. Undisturbed sites maintained the highest canopy cover, cooler temperatures, and more humid microclimates, favoring late-successional species. NDVI time-series analysis showed sharp declines in vegetation greenness immediately following lightning strikes, followed by gradual recovery in subsequent years. These findings demonstrate that lightning functions as an agent of ecological simplification, resetting successional trajectories and altering microclimates within canopy gaps. As climate change is projected to increase lightning frequency, these disturbances may become more significant for montane forest resilience and biodiversity conservation. Integrating lightning ecology into park management strategies is therefore essential for sustaining Nyungwe's unique forest mosaic and guiding adaptive restoration efforts.

Keywords: lightning disturbance, forest regeneration, biodiversity, Nyungwe National Park, microclimate, successional dynamics, microclimate,

CHAPTER 1: INTRODUCTION

1.1 Background

Rwanda boasts rich biodiversity, including montane rainforests (Nyungwe), savannas (Akagera), and volcanic ecosystems (Volcanoes NP), which shelter endangered species like mountain gorillas (Gorilla beringei beringei), golden monkeys (Cercopithecus kandti), and over 700 bird species. However, habitat loss from agriculture, deforestation, and urbanization threatens ecosystems, with forest cover declining sharply before recent restoration efforts. Rwanda has prioritized conservation through expanded protected areas (now 10.3% of land), reforestation, and policies like the National Biodiversity Strategy and Action Plan (NBSAP). Challenges remain, including human-wildlife conflict and climate change impacts, but community-based initiatives and ecotourism offer hope for sustainable preservation (Cazalis et al., 2022).

Nyungwe National Park, situated in Rwanda southwest is one of the most biologically important Afromontane forests of Albertine Rift. This forest ecosystem is renowned for its rich biodiversity and ecological significance. It serves as a sanctuary for vegetation types such as bamboo forests, mountain forests and high-altitude wetlands. Spanning over 1020 Km2 and altitudinal ranging between 1600 m and 2950 m (Seimon, 2012). Nyungwe Forest harbors over 260 documented species of trees and shrubs but the large areas of forest devastated by wildfires have been taken over by ferns, negatively impacting the regrowth of trees and diminishing the ecological value of these regions as habitats for wildlife (Chadri. & Plumptre, 2014). The park is known for its high levels of endemism and diverse array of flora and fauna. As an integral part of the Albertine Rift, Nyungwe plays a crucial role in maintaining regional ecological balance and providing various ecosystem services like biodiversity conservation, research and education, climate regulations and so many others (Plumptre et al., 2006). The tropical forest ecosystems like the one found in Nyungwe, are complex and dynamic due to the disturbances and constantly responding to natural disturbance.

Rwanda's biodiversity, despite its richness, faces severe threats due to rapid environmental degradation. Key pressures include deforestation, soil erosion, landslides, habitat fragmentation, and wildfires, all of which contribute to ecosystem decline (MINIRENA, 2015). These threats stem from human activities (e.g., agricultural expansion, unsustainable land use) and natural factors (e.g., climate extremes). Between 1958 and 1996, Rwanda lost nearly 70% of its forest cover, drastically reducing wildlife habitats (Apuri et al., 2018). Even protected areas have suffered degradation due to encroachment, illegal logging, and climate-related disturbances (Nkundabose et al., 2020). However, conservation initiatives such as the establishment of Nyungwe National Park have helped restore critical ecosystems and safeguard endangered species (Umuziranenge, Gloriose Muhirwa et al., 2021).

The disturbances in Tropical Forests (TFs) have wide role than commonly acknowledged. The distinctive effect of disturbances are due to that Tropical forests (TFs) frequently demonstrate low productivity due to resource constraints, resulting in slow recovery from disturbances (Gora et al., 2021). The forests display considerable environmental variability, creating unique interactions with disturbances (Crausbay & Martin, 2016a). A significant part of TFs often faces high-energy windstorms and landslides. These forests are home to a bio-geographically diverse range of tree species with different evolutionary backgrounds, leading to varied responses to different types of disturbances (Vašíčková et al., 2021).

Disturbances are fundamental drivers of ecosystem dynamics in tropical forests, shaping structure, composition, and function (Poorter et al., 2023). Defined as discrete events that disrupt ecosystems, disturbances range from small-scale treefalls to large-scale cyclones or fires. Disturbances generate patchiness in forests, leading to mosaics of successional stages (Chadwick & Larson, 1996). Canopy gaps (e.g., from treefalls) increase light availability, altering competitive hierarchies and promoting pioneer species (Canham, 1990). Post-disturbance, forests undergo succession, transitioning from fast-growing pioneers to shade-tolerant climax species (Poorter et al., 2024). Light-demanding species dominate early stages, while gap size influences recruitment (Mlambo et al., 2023). Intermediate disturbance hypotheses suggest moderate disturbances maximize species diversity by preventing competitive exclusion (Connell, 1978). Light conditions under small canopy gaps (10–15% full sunlight) and large canopy gaps (40–50% full sunlight) induced greater growth rates for seedlings from early and mid-successional stages than from late-successional stage (Crausbay & Martin, 2016b). Disturbances accelerate nutrient cycling via litter decomposition and soil turnover (Heartsill-Scalley & López-Marrero, 2021).

Among these disturbances, lightning strikes emerge as a powerful force shaping the structure and composition of forested landscapes (Richards et al., 2021). Lightning, a common natural phenomenon, is known for its ability to cause disturbances through ignition of fires, tree mortality, and alterations in vegetation structure. Given that lightning is estimated to strike tropical forests 35–67 million times annually and strikes thousands of trees each day, over 500 million hectares of forest exist in regions with high lightning frequency. Studies in Panama and Brazil examined 2,195 lightning-damaged trees resulting from 93 strikes. They showed that, on average, a single strike damages 23.6 trees and kills 5.3 of them within 13 months contributing to 20.1% of new gap area formulation and 16.1% of woody biomass turnover annually (Gora et al., 2021)(Yanoviak et al., 2024). The ecological impact of a single lightning strike exhibits significant variability. Documented cases in tropical forests show a range of 1 to 116 trees damaged and 0 to 65 trees killed per strike (Gora, Schnitzer, Bitzer, et al., 2023).

Lightning disturbances create canopy gaps by killing large trees, increasing light availability, and altering species composition. These gaps promote pioneer species, enhance biodiversity, accelerate successional processes, and affect carbon dynamics, leading to a more dynamic and continuously evolving forest structure and function (Heartsill-Scalley & López-Marrero, 2021).

In addition to tree mortality, lightning strikes can cause localized branch die-back and damage to the tree crown, which may lead to further structural changes in the forest canopy. For instance, in tropical forests(TFs), lightning-damaged trees often exhibit directionally biased branch mortality, creating specific patterns that can be used to identify lightning strikes (Yanoviak et al., 2024). Research identified that the place in the world with more thunderstorms per day, Uganda experiences the highest number of thunderstorms per day, averaging 242, followed by the Democratic Republic of the Congo with 228 thunderstorms, and Rwanda with 221 thunderstorms per day (Albrecht et al., 2016). Consequently, Nyungwe National Park, situated within this region, is particularly susceptible to these frequent natural disturbances. The high incidence of thunderstorms in Nyungwe National Park significantly affects its ecosystem, influencing various ecological processes and species interactions (Albrecht et al., 2016).

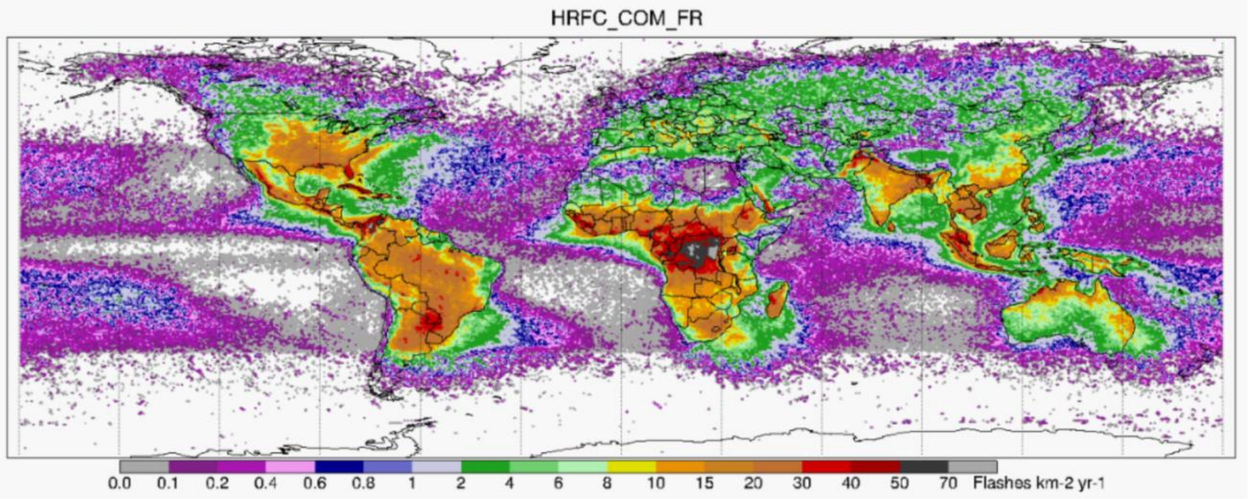

Figure 1: Average number of lightning strikes per km2 per year (resolution 0.5°/ODT and LIS data/satellite-based optical determination for 1995–2010). (© Rachel et al. (2016))

Understanding the consequences of lightning strikes in tropical forest ecosystems is crucial for developing effective management strategies, especially as climate change may increase lightning frequency and associated tree mortality, impacting forest dynamics and resilience (Nsanzurwimo, 2021)

While existing literature provides a foundation for understanding the general effects of lightning on vegetation in tropical forests, specific gaps persist, particularly regarding Nyungwe National Park. Few studies have addressed the complex relationships between lightning and vegetation regeneration in this unique ecosystem. The existing research tends to be generalized, lacking the depth required to inform site-specific conservation strategies. Understanding the gaps in the literature is crucial for shaping the research agenda. A focused investigation into the effects of lightning on vegetation regeneration in Nyungwe National Park will contribute significantly to the broader field of tropical ecology and inform sustainable management practices.

This research aims to bridge the knowledge gap by investigating the consequences of lightning strike disturbances in Nyungwe National Park's tropical forest ecosystem, focusing on how these strikes disrupt the forest and influence its capacity to regenerate. By exploring the role of lightning as a driver of forest dynamics, the study seeks to enhance the processes of vegetation recovery, which are crucial for park management. These disturbances have cascading effects on forest ecology, such as creating micro habitats for various species or potential sites for invasive species establishment. Ultimately, the findings will provide valuable insights to anticipate future forest changes and inform effective management strategies in the context of increasing lightning frequency due to climate change

1.2 Problem Statement

Despite the recognized ecological role of lightning as a natural disturbance in tropical forests, its specific impacts on vegetation regeneration in Nyungwe National Park (NNP) remain poorly understood. While studies in the Neotropics (e.g., Panama and Brazil) have quantified lightning-induced tree mortality and gap formation (Gora et al., 2021), similar research is scarce in African montane forests, particularly in the Albertine Rift.

Most lightning ecology studies focus on the Amazon and Southeast Asia, leaving African tropical forests especially montane systems like Nyungwe understudied (Gora, Schnitzer, Yanoviak, et al., 2023). Nyungwe's high thunderstorm frequency 221 days/year; (Albrecht et al., 2016) suggests lightning is a major disturbance, yet its effects on forest structure remain unquantified.

Lightning creates distinct canopy gaps by killing multiple trees simultaneously (avg. 0 to 65 trees killed per strike) (Gora et al., 2021) but it is unclear whether these gaps favor pioneer species or hinder climax species regeneration in Nyungwe. Unlike windstorms or fires, lightning damage is often localized but severe, potentially altering microclimates (temperature/humidity) in ways that affect seedling recruitment a factor unexplored in NNP (Heartsill-Scalley & López-Marrero, 2021)

Rising global temperatures may increase lightning frequency (Romps et al., 2014), yet no studies project show how this will impact Nyungwe's forest resilience. The park's high elevation (1,600–2,950 m) could amplify lightning's effects but empirical evidence is lacking. Nyungwe's management plans prioritize fire and human encroachment but overlook lightning as a disturbance agent (Park, 2014). Without data on lightning magnitude and role, reforestation efforts may fail to account for species-specific vulnerability (e.g., Slow-growing endemics vs. light-demanding pioneers).

Why this matters for conservation

Understanding lightning's impact on vegetation regeneration in Nyungwe National Park (NNP) is critical for conservation due to increasing Lightning Frequency. Climate models predict a 12% rise in lightning strikes per 1°C of global warming (Romps et al., 2014).

Given Rwanda's already high thunderstorm activity of 221 days/year (Albrecht et al., 2016), Nyungwe may face more frequent and severe lightning disturbances, altering forest recovery rates.

Lightning can shifts species composition, if lightning favors fast-growing pioneer species over slow-growing, late-successional climax species (e.g., *Ocotea usambarensis* endemics climate change could accelerate biodiversity loss in NNP (Gora et al., 2021)

Current reforestation efforts primarily address fire and human encroachment while neglecting lightning-induced gaps, but identifying lightning-resilient tree species (e.g., thick-barked or tall canopy species) could significantly improve reforestation planning (Richards et al., 2021).

Lightning kills 0 to 65 trees and damage 1 to 116 trees per strike (Gora et al., 2021), releasing stored carbon. If strikes increase, Nyungwe's role as a carbon sink may weaken requiring proactive management. Nyungwe's endangered species (e.g., Rwenzori colobus monkeys) depend on mature forests. If lightning disrupts canopy continuity, their habitat could fragment further. Lightning gaps may create openings for invasive plants and lianas (e.g., *Sericostachys scandens*), complicating restoration. NNP's current strategies lack lightning-specific protocols. This research can inform revised fire management policies and early detection systems for strike-prone zones.

As a Key Biodiversity Area (KBA), Nyungwe's resilience to disturbances affects regional ecological stability. Data on lightning impacts can attract funding for climate-adaptive conservation.

The research questions for this study are:

Do lightning-disturbed forests recover differently from both undisturbed forests and non-lightning disturbed forests patches?

Do lightning disturbances affect the forest microclimate, and how does the altered microclimate following lightning disturbances influence vegetation recovery?

1.3 Research Objectives

The primary aim of this research is to comprehensively assess the effects of lightning disturbances on vegetation regeneration, vegetation composition and dynamic.

Examine the disparities in regrowth patterns between forest patches affected by lightning strikes, landslides, soil erosion and those unaffected by it.

Gain insights into the factors of ecological and environmental that impact forest regeneration following lightning strikes.

1.3.1 The hypotheses to be tested are:

H_0: There is no significant difference in vegetation regeneration between lightning-disturbed forest patches, non-lightning disturbed patches, and undisturbed forest patches.

H_1: Vegetation regeneration is significantly higher in areas subjected to lightning strike disturbances compared to the undisturbed and non-lightning disturbed forest patches in Nyungwe National Park.

H_0: There is no significant difference in microclimate (temperature, humidity and rainfall) between undisturbed forest patches, non-lightning disturbed patches, and lightning-disturbed patches

H_1: Lightning-disturbed Forest patches have significantly warmer and less humid microclimates compared to both undisturbed forests and non-lightning disturbed patches.

1.4 Overall conservation goal

Our research will provide and enhance the understanding of how natural disturbances, specifically lightning strikes, influence forest dynamics and vegetation regeneration in a tropical forest ecosystem.

By identifying the specific impacts of lightning strikes on vegetation, the research will provide park managers and conservationists with critical information to develop targeted management strategies by understanding which tree species are more resilient or vulnerable to lightning disturbances and will guide reforestation efforts and habitat restoration. The research will help assess whether these disturbances promote or hinder biodiversity by creating opportunities for pioneer species or disrupting the growth of climax species in case of cap created in the forest canopy. This information is vital for maintaining the park's rich biodiversity.

As climate change increases the frequency and intensity of thunderstorms, lightning-induced disturbances may become more common. The research will provide insights into how the forest ecosystem can adapt to such changes, helping conservationists prepare for future scenarios and implement adaptive management practices.

CHAPTER 2. LITERATURE REVIEW

2.1 Lightning as a forest disturbance agent

The effects of lightning on vegetation vary based on factors such as strike intensity, tree species, and local environmental conditions. A comprehensive study by (Yair, 2018) investigated the mechanisms of damage caused by lightning strikes, emphasizing the importance of understanding how different plant species respond to these disturbances. Lightning strikes can lead to both immediate mortality and delayed impacts on vegetation through changes in growth patterns and susceptibility to diseases (Gora et al., 2021). Research in other tropical regions, such as the Amazon rainforest (Yanoviak et al., 2024) has shown that lightning can create canopy gaps, altering the competitive dynamics among plant species. Furthermore, disturbances caused by lightning can provide opportunities for regeneration, influencing the overall structure and composition of the forest (Yanoviak et al., 2017)

Studies in Neotropical forests (e.g., Panama, Brazil) show that lightning preferentially affects large, emergent trees and can account for up to 13% of annual tree mortality (Yanoviak et al., 2017) However, African tropical forests have been underrepresented in such research, despite high thunderstorm activity in the Congo Basin and Albertine Rift.

2.2 Vegetation Regeneration in Tropical Forests

Regeneration following disturbance is a key process in maintaining forest biodiversity and structure. It typically follows a sequence: (1) gap formation, (2) colonization by pioneer species, (3) canopy closure, and (4) return to mature forest (Lasky et al., 2014). In tropical montane forests, regeneration is often slower due to cooler temperatures, lower decomposition rates, and reduced seed dispersal.

Light-demanding species such as *Macaranga spp, hagenia abyssinica* and some lianas like *Sericostachys scandens* are common early colonizers, while shade-tolerant species dominate in later stages (Lasky et al., 2014). The success of regeneration depends on factors including gap size, soil nutrients, seed bank availability, and microclimate.

2.3 Tropical Forest Ecosystems

Nyungwe National Park, as a representative tropical forest ecosystem, is characterized by its high biodiversity and complex ecological interactions. The vulnerability of tropical forests to disturbances like lightning strikes is a critical aspect of their resilience. Studies conducted in similar ecosystems, such as the Congo Basin (Clarke et al., 2021) highlight the intricate relationships between lightning, vegetation, and ecosystem dynamics. Tropical forests play a significant role in global carbon sequestration and climate regulation. The potential impact of increased lightning strikes, possibly linked to climate change (Kurniawan et al., 2021), raises concerns about the long-term stability of tropical forest ecosystems. Therefore, understanding how lightning affects vegetation regeneration in Nyungwe National Park is essential for developing effective conservation strategies (Park, 2014).

2.3 Forest recovery from disturbances

Forest recovery from disturbances, such as fragmentation or any other disturbances, involves complex ecological processes influenced by the size and isolation of forest remnants. As highlighted in the study conducted in Sabah, Malaysian Borneo, fragmentation significantly reduces seedling richness by about 30% compared to undisturbed forests patches (Stride, 2018). Recovery dynamics vary based on disturbance type, severity, and frequency, as well as the adaptive strategies of the resident species. For instance, fire-adapted species may resprout or have seeds that require heat to germinate, thereby facilitating quicker recovery post-fire (Frost, 1984). Small gaps created by disturbance support the gradual regeneration of shade-tolerant climax species, ensuring a stable canopy composition. On the other hand, large gaps encourage a rapid influx of fast-growing pioneer species, resulting in a more dynamic and changing canopy structure (Gora et al., 2021)

2.4 Lightning Strikes in Nyungwe National Park

In June 2022, 23.3 km of trails were surveyed, covering most of the network accessible from Uwinka station in Nyungwe National Park. The survey inspected all canopy disturbances (clusters of dead or damaged trees) found along these trails for signs of flashover damage, which appears as the defoliation of the two nearest branches on neighboring trees in a directional pattern. Trees exhibiting this pattern with two or more neighbors were selected for detailed surveys to confirm lightning as the cause (Sullivan, 2025).

During June 2022 and October 2023, the lighting strikes identified in Nyungwe Nation Park was the first systematic assessment of lightning-caused disturbance in Africa and the study observed that lightning causes disturbance were six times more often on the ridge than in the valleys. However, strikes in valleys result in greater damage to trees compare to on the ridge (Sullivan, 2025).

Although lightning is a known driver of ecological dynamics in tropical forests, its specific effects within Nyungwe National Park are poorly understood. The park's unique assemblage of species and varied topography provide an ideal setting to explore the interactions between lightning disturbances and forest structure. This knowledge is crucial for tailored conservation and management practices in the park. A preliminary study by Nyungwe National Park noted an increase in lightning strikes within the park, raising concerns about potential ecological consequences. However, a comprehensive investigation into the direct and indirect effects on vegetation and subsequent regeneration processes is yet to be undertaken.

2.5 Gaps in existing literature

Despite the well-documented role of lightning as a significant agent of disturbance and driver of forest dynamics in tropical ecosystems (Yanoviak et al., 2017). A critical knowledge gap persists regarding its specific impacts within montane tropical forests such as Nyungwe National Park. While global literature has established patterns of tree mortality, gap formation, and pyrogenic effects in lowland tropics, the effects of lightning in this Afromontane context remain largely unquantified and extrapolated rather than directly studied (Gora et al., 2021).

Key uncertainties include whether the park's unique topography characterized by high elevations and rugged terrain influences strike frequency and distribution, and how its distinct floristic composition, including slow-growing, high-biomass species, affects resilience and recovery pathways post-strike. Furthermore, the scarcity of targeted studies in Nyungwe means the cascading effects on faunal communities, soil biogeochemistry, and the role of lightning in interacting with other disturbances (e.g., windstorms, anthropogenic pressure, landslides) are virtually unknown. Consequently, filling these gaps is imperative to understand this fundamental abiotic process and to integrate it effectively into the park's conservation and management strategies, particularly in an era of changing climate and fire regimes.

CHAPTER 3: METHODOLOGY

3.1 Description of the study area

3.1.1 Nyungwe National Park

The Nyungwe National Park (NNP) and Volcanoes National Park (VNP) exemplify the Afromontane Forest ecosystems along the Nile-Congo Crest in Rwanda. These mountain forests are integral parts of the Albertine Rift's Afromontane forests and represent a crucial habitat for biodiversity. NNP, being the largest protected area in Rwanda, also stands as the most extensive remaining section of Afromontane Forest in Africa, hosting one of the highest levels of biodiversity.

3.1.2 Study area

The study was conducted in Nyungwe National Park (NNP), located in southwestern Rwanda (2°15'–2°55'S, 29°00'–29°30'E). The park is characterized by rugged terrain, montane rainforest, and high biodiversity hotspot spanning 1,020 km². Situated in the Albertine Rift a region renowned for endemis. The park ranges in elevation from 1,600 to 2,950 meters. It forms a contiguous forest block with Burundi's Kibira National Park, collectively representing one of the largest and most intact montane forests in Central Africa (Ayebare et al., 2018). Over 1,050 plant species, including 200+ endemic to the Albertine Rift Habitat for 13 primate species (e.g., endangered Eastern Chimpanzees, Pan troglodytes schweinfurthii), 322 bird species (32 Albertine Rift endemics), and rare amphibians like the Rwenzori turaco (Ingabire et al., 2019). The forest also has designated a UNESCO World Heritage candidate (2023) for its ecological integrity.

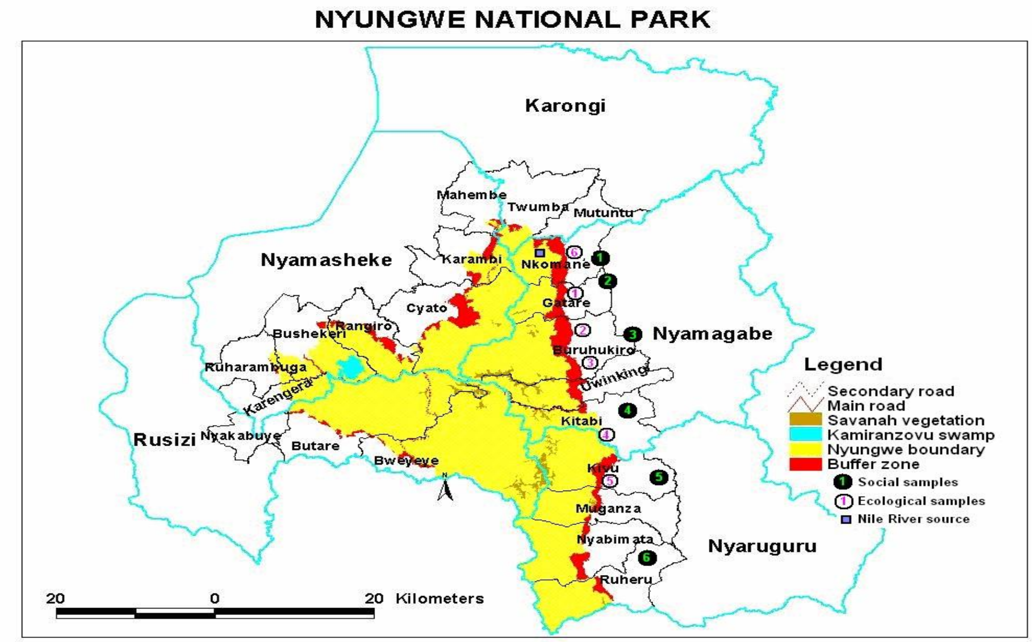

Figure 2:Nyungwe National Park. Source: Jean Rwihaniza Gapusi book, 2007

3.4 Materials

Duning the field activities, we have used a couple of material which helped us to obtain the accuracy data. We have used Field notebooks which helped us to record each data we obtained and the observation on the plot that were surveyed, and data sheets for recording observations, data loggers, GPS device for recording the geographic coordinates of study sites and plots, and camera to document the visual aspects of lightning damage, canopy, vegetation recovery, and hemispherical photos Tree diameter tape DBH measuring tape, meter tape to measure height of samplings, data loggers and clinometer to measure slope, and a panga. Other field equipment will include protective clothes, boots, sleeping bags.

The success of this ecological study on lightning damage and forest recovery hinges on a suite of specialized tools, each fulfilling a critical role in data collection, researcher safety, and operational efficiency. For precise geospatial documentation, a GPS device was indispensable; this handheld satellite receiver records the exact geographic coordinates of each study plot and damaged tree, enabling accurate mapping, spatial analysis, and the ability to return to the exact same locations for long-term monitoring. To capture comprehensive visual evidence, a high-resolution digital phone camera was employed to meticulously document the visual aspects of lightning disturbed area, landslides and control sites, canopy gaps, and subsequent vegetation regrowth; this includes taking hemispherical photos. All qualitative observations and methodological notes are recorded in real-time within durable, weatherproof field notebooks, which serve as the primary, irreplaceable record, while standardized data sheets ensure consistent, error-free, and systematic collection of quantitative metrics across all sites.

For forest mensuration, a diameter tape (D-tape), which is uniquely calibrated in units of meters was used to accurately measure tree trunk circumference and directly convert it to Diameter at Breast Height (DBH), a fundamental metric for assessing tree size and biomass. A standard metric tape measures other plot dimensions and distances between samples. To monitor the microclimatic changes caused by a new canopy gap, data loggers are deployed; these automated electronic devices continuously record environmental data like temperature, humidity, and light levels at set intervals over long periods. The weekly precipitation data from mid-2011 to mid-2021 were obtained from the data recorded at weather station located in the forest by Göran Wallin.

For field access and safety, a panga (machete) is essential for clearing dense undergrowth to reach remote sites and carefully manage vegetation around study trees. Finally, researcher welfare is ensured through protective clothing like cut-resistant trousers to guard against tools and thorns, sturdy waterproof boots for safety and traction on uneven ground, and appropriate sleeping bags to provide rest and warmth during multi-day expeditions in remote locations.

3.1.3 Climate

Nyungwe National Park exhibits a classic montane forest climate, characterized by minimal seasonal temperature variation and a pronounced wet season lasting from September to May, followed by relatively drier conditions during the mid-year months (June-August). The annual precipitation in NNP ranges between 1500 mm and 2500 mm. Temperatures remain cool but stable, averaging 11–20°C annually, with rare extremes below 5°C or above 25°C even at high elevations (Seimon, 2012). allowed collection of data related to the regeneration of woody species and site characteristics in the forest. Data collection on temperature and humidity, and rainfall data was carried out in the period between May-July 2025. During that time, data loggers were placed in four different regions within the park specifically on the region data were collected to measure the temperature and humidity and the weekly precipitation data from mid-2011 to mid-2021 were obtained from the data recorded at weather station located in the forest by Göran Wallin.

3.2 Site Selection

The field study was conducted with sampling focused along trails near the Uwinka where lightning strike frequency is highest as identified in the previous research conducted in NNP. A total of 62 study sites were surveyed and categorized into three distinct disturbance types: (1) lightning-disturbed sites (n=21), selected based on documented lightning damage in 2022 and 2023 surveys and characterized by visible evidence of recent lightning impacts such as scorched trees, dried, and sudden canopy gaps; (2) non-lightning disturbed sites (n=20), identified by alternative disturbance agents including windthrow events, soil erosion features, landslide scars, and fire-affected zones, located in the forest; and (3) undisturbed control sites (n=21), selected within a 200m radius of lightning-disturbed sites and carefully matched for similar ecological conditions like elevation, slope aspect, forest type composition, and canopy closure to ensure valid comparisons across disturbance regimes.

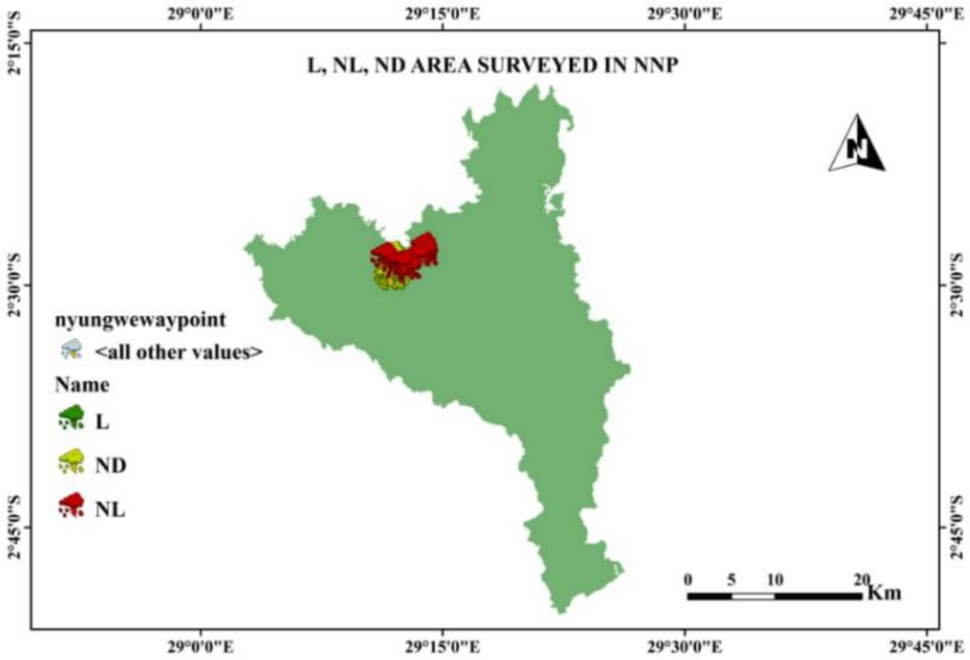

Figure 3: Map of surveyed area

3.3 Research design and data collection

Field data collection was conducted by a research team consisting of the lead researcher, a local technician (field assistant) with extensive knowledge of forest flora, and a park ranger from Nyungwe National Park. Data collection utilized standardized ecological methods across 62 study plots (21 lightning-affected, 20 non-lightning disturbed, and 21 control sites), each consisting of a 10m × 10m main plot with three nested 2m × 2m subplots for regeneration assessment.

Within each subplot, all trees greater than 5 cm in diameter at breast height (DBH) were measured. For each tree, we recorded the DBH, total height, and health status. Health was assessed using visual indicators, including a leaf loss index. This index was estimated as the percentage of leaf volume lost due to broken branches and was grouped into five categories: 0%, 1–25%, 25–50%, 50–75%, and 75–100% loss. Crow formation index was estimated by evaluating the foliage density (eg., gaps, sparse area) on cales of one to four where 1: Very sparse (≤25% foliage), 2: Moderate (25%-50%), 3: Moderate (50-75%). 4: Dense (75%-100%). Canopy gap was also evaluated by looking up at multiple points beneath the canopy and estimated according to the canopy cover.

Crown Formation Index (CFI), Leaf Loss Index (LLI), Canopy Gap (CG), Visible Lightning Damage (VLD). Stress symptoms (e.g., wilting, chlorosis, necrosis) and biotic factors (pathogens, pests) were identified. Regeneration was assessed in subplots by counting all seedlings (defined as individuals with <5 cm DBH) and shrubs. All individuals were identified to species, and their heights were measured and recorded on data sheets.

Canopy structure was documented using hemispherical photography, while microclimate data (temperature, humidity) were collected hourly using installed data loggers. Weather data were obtained from installed datasets in NNP at Uwinka station, this data were weekly precipitation data from mid-2011 to mid-2021 by Göran Wallin. At Uwinka research station, located in the center of the park at an elevation of 2,465 m, received 1,900 mm of annual rainfall and had average daytime and nighttime temperatures of 15.7 °C and 13.5 °C (Sullivan, 2025).

Topographic variables (elevation, slope) were measured for each plot using GPS. Unidentified plant specimens were collected as vouchers and verified at the National Herbarium (NH) of Rwanda (University of Rwanda (UR), Huye Campus), with additional taxonomic support provided by park botanists. Field equipment included measuring tapes, GPS units, digital phone cameras for canopy imaging and light measurements, and data loggers for environmental monitoring. The survey was carried at different trails in NNP Which include Umuyove, Umugote, Imbaraga, Main Road, Rukuzi, Igishigishigi, Chimpanzee, and Nyabishwati trail sites.

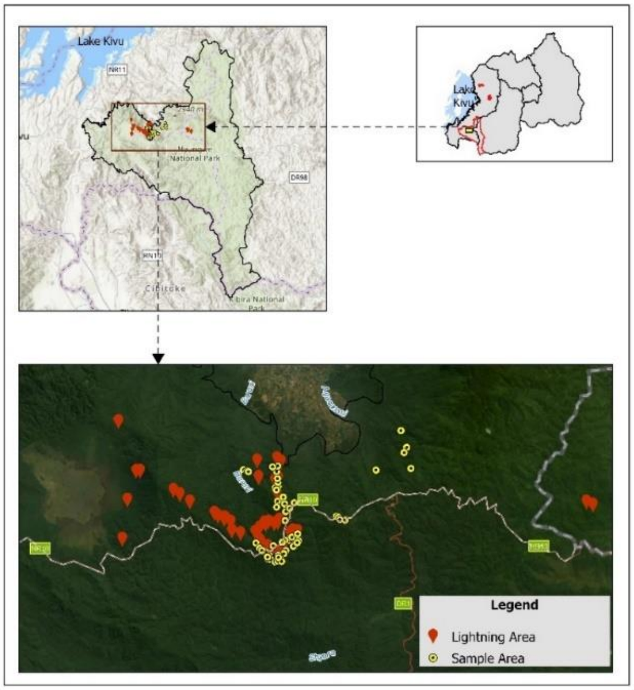

Figure 4: Map of surveyed forest patches including lighting strike

Figure 5: Lightning strikes patch (Left) and Non-Lighting strikes patch (Right)

3.4 Remote Sensing, GIS, and NDVI analysis for regrowth patterns.

GPS coordinates recorded within lightning strike areas of Nyungwe National Park in June 2022 and October 2023 were used as reference points to analyze changes in NDVI over time.

3.4.1 Normalized Vegetation Index Analysis.

This research employed a time-series analysis on a harmonized dataset of atmospherically corrected surface reflectance imagery, sourced from the United State Geological Survey (USGS) and the European Union's Copernicus Programme using the Google Earth Engine (GEE) cloud computing platform. The study utilized the Landsat 8 Collection 1 Tier 1 Surface Reflectance (LANDSAT/LC08/C01/T1_SR) product for the period of 2016-2018, and the Sentinel-2 Level-2A (COPERNICUS/S2_SR_HARMONIZED) product for 2019-2025. Imagery was filtered to a specific area of interest (AOI), with a preliminary scene filter applied to exclude images with a CLOUDY_PIXEL_PERCENTAGE exceeding 30%. Further quality control was achieved through the application of per-pixel cloud and cloud-shadow masks derived from the Landsat pixel_qa and Sentinel-2 QA60 metadata bands. For each year, a median composite was generated to mitigate seasonal variability and fill data gaps, followed by the calculation of the Normalized Difference Vegetation Index (NDVI). The final time series of annual NDVI composites was exported in both tabular (CSV) and raster (GeoTIFF) formats for subsequent analysis.

3.5 Data Analysis

In data analysis, we employed descriptive statistical analysis to summarize and understand the data. For further analysis, we used R software version 4.3.2, which enabled us to analyze the information clearly and visually. Independent t-tests and ANOVA were used to compare seedling density, species richness, and microclimate between lightning disturbed non lightning disturbed and control forest patches. Non-metric multidimensional scaling (NMDS) was used to analyze species composition. Regression models tested the effect of elevation, gap size, and microclimate on regeneration and all analyses were performed in R (v4.3.2).

CHAPTER 4: RESULTS

4.1 Site characteristics

The 62 site were selected stratified into (1)lightning-disturbed sites (n=21), selected based on documented lightning damage in 2022 and 2023 surveys and characterized by visible evidence of recent lightning impacts such as scorched trees, dried, and sudden canopy gaps; (2) non-lightning disturbed sites (n=20), and (3) undisturbed control sites (n=21), selected within a 200m radius of lightning-disturbed sites and carefully matched for similar ecological conditions like elevation, slope aspect, forest type composition, and canopy closure to ensure valid comparisons across disturbance regimes. The longitude and latitude of the sampled area differed (2°15'–2°55'S, to 29°00'–29°30'E) at and near Uwinka. The average GPS points and altitudes, tree surveyed, plant types and pieces, aspect, slope, crown and ground leaf Loss Index, crown Formation Index and canopy covers are given in Appendix 1.

A total number of 1949 individuals tree species were measured. This included the standing trees in plantation and the regeneration trees including young trees regenerating seedlings and shrubs in the site that have been sampled which occupied 84% of the total population sampled. For each species the number (density) and performance (diameter and height) varied from stand to another and site. Species are distributed in the different sites and differed in densities, growth and the number of standing trees.

Figs. 6-8 explain how the number of individuals, diameter at breast height (dbh) and height varied from stand to another. This is done separately for stands of lightning-disturbed sites, non-lightning disturbed sites and undisturbed control sites.

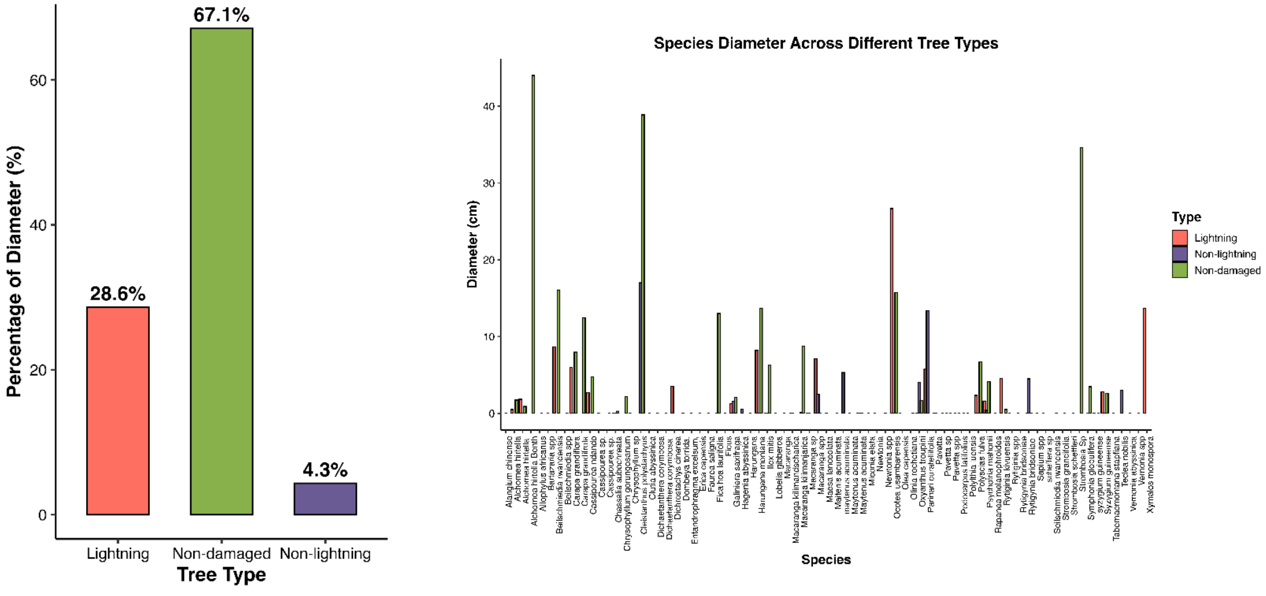

Figure 6:Species and Diameter of the trees across L, NL, and ND

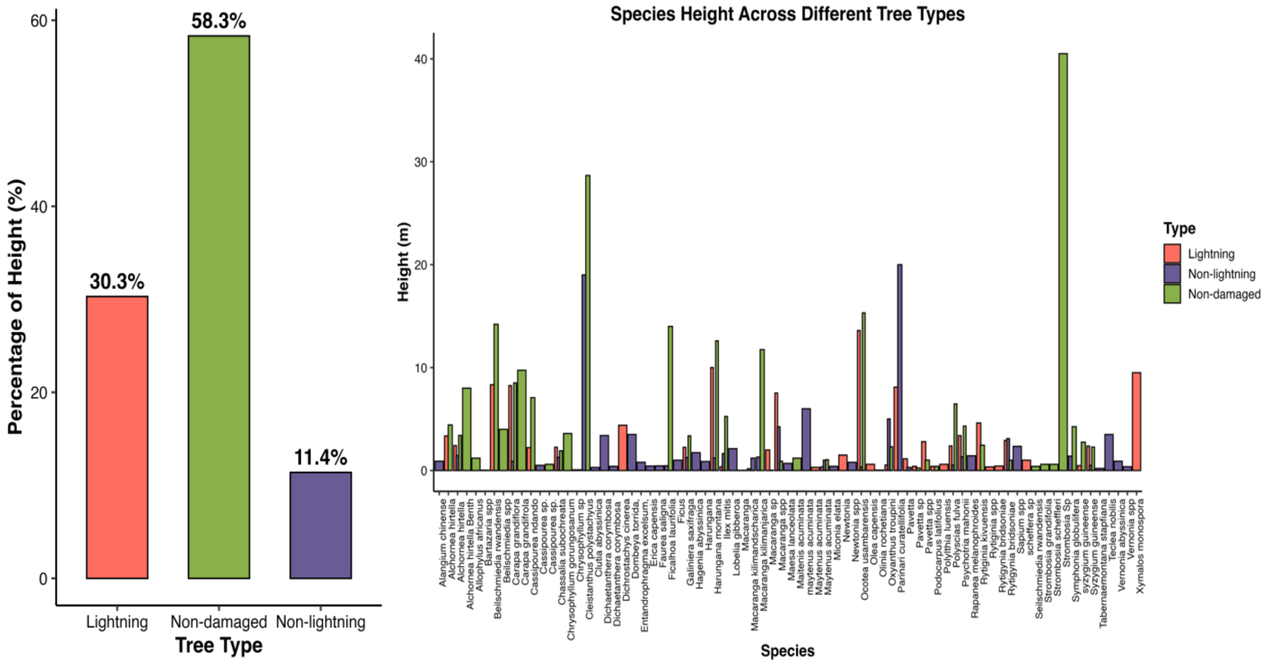

Figure 7:Species and Height measures of the trees across L, NL, and ND

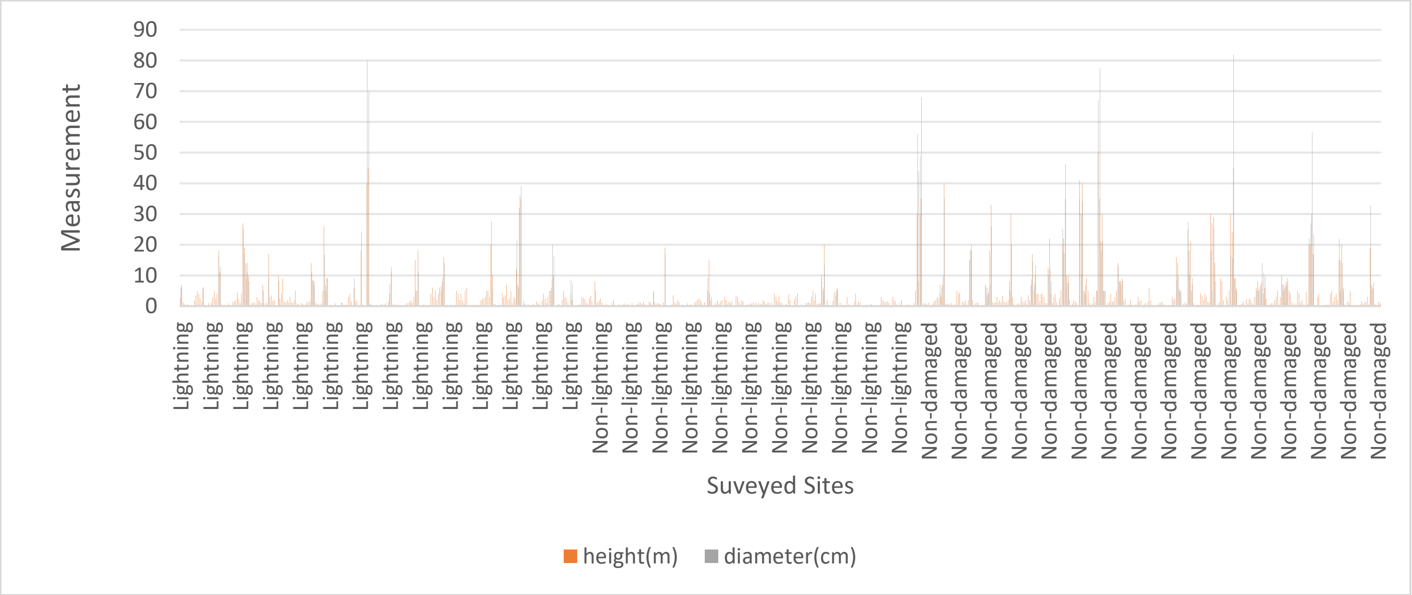

Figure 8: Height and Diameter changes in L,NL, and ND

Figure 6-8 displays tree diameter and Height distributions across forest patches. Non-damaged patches had the highest frequency of large-diameter and height trees, indicating a mature stand structure with minimal disturbance. Lightning gaps displayed a broader size distribution, whereas non-lightning disturbed sites were dominated by small-diameter and height trees, consistent with chronic growth suppression.

4.1.1 Trees Density in lightning-disturbed, non-lightning disturbed, and undisturbed forest patches.

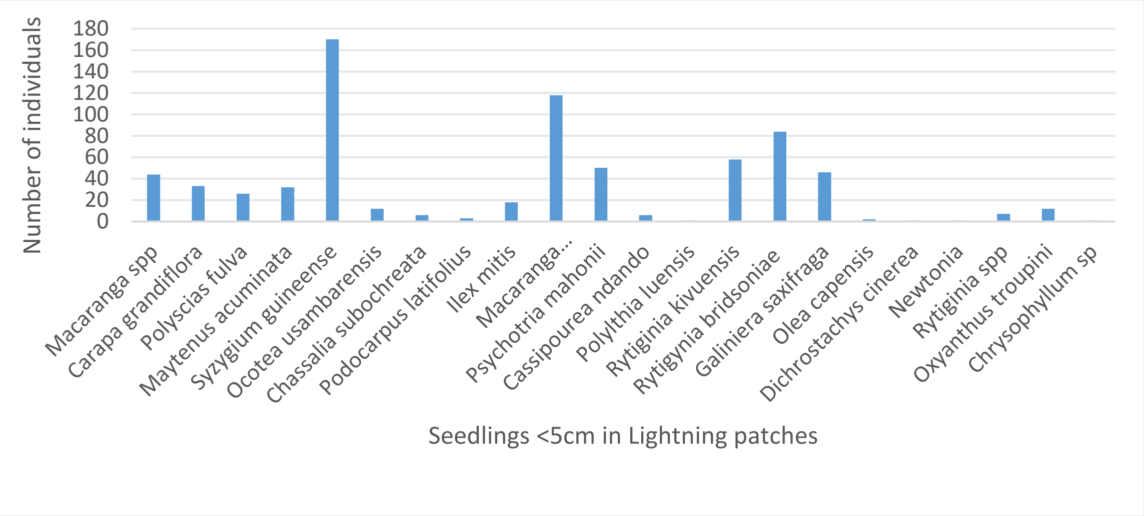

Figure 9:Seedling Density in Lightning-Disturbed Patches

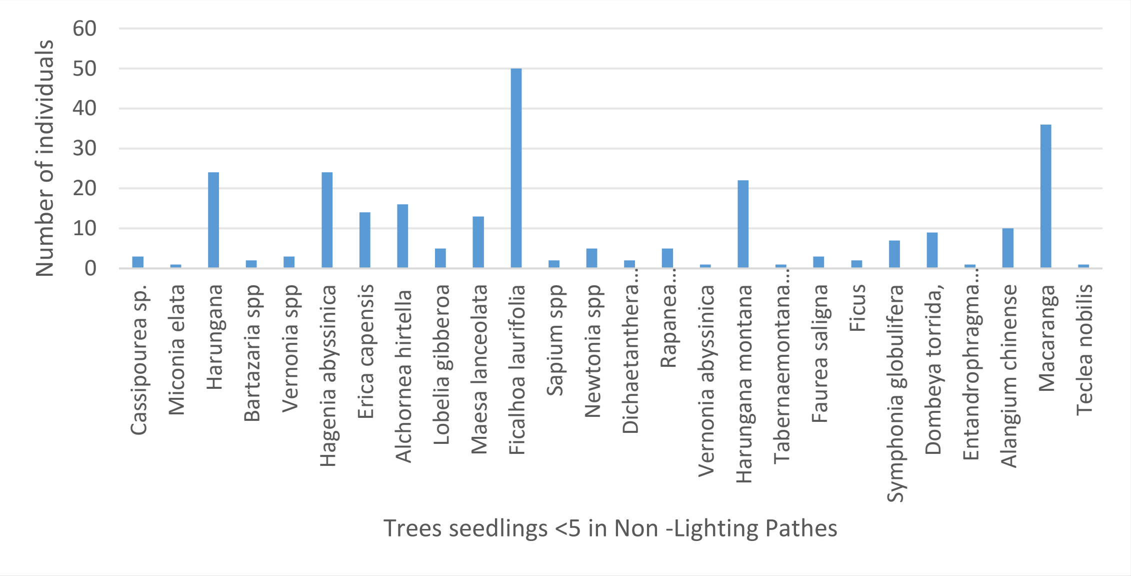

Figure 10:Seedling Density in non- Lightning-Disturbed Patches

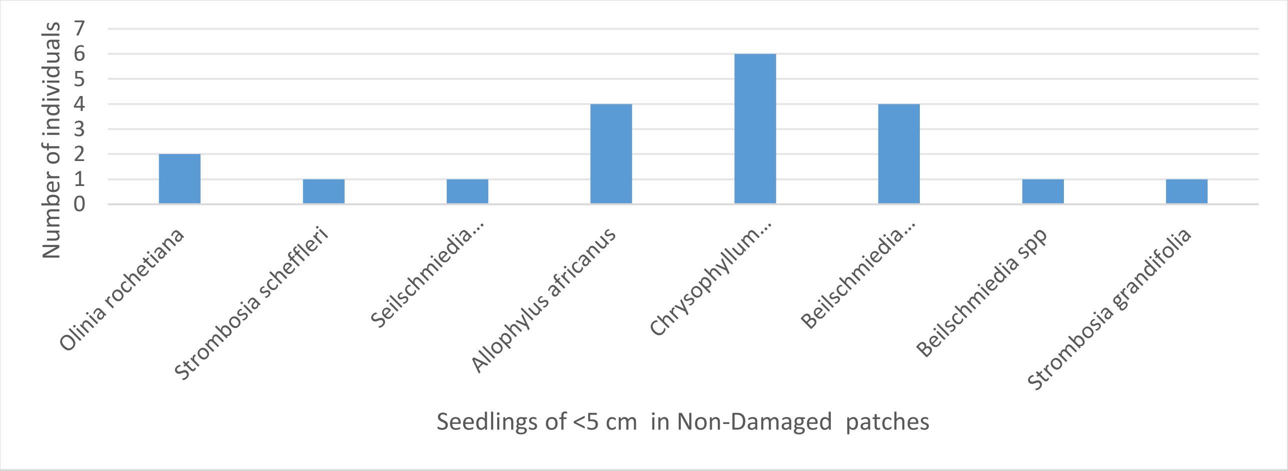

Figure 11: Seedling Density in non - damage Patches

The density of regenerating seedlings (DBH < 5 cm) differed among disturbance regimes (Figs. 9-11). Non-Lightning-Disturbed Patches: Exhibited the highest seedling density, which was strongly dominated by *Ficalhoa laurifolia*, with *Macaranga kilimandscharica*. Non-Damaged Patches was supported the lowest seedling density. The few seedlings present were primarily the shade-tolerant species those include *Macaranga kilimandscharica, Rytigynia bridsoniae* and Syzygium guineense. Lightning strikes disturbe patches eshibit few number of young seedling germinating including Syzygium guineense and *Carapa grandiflora,* and *Macaranga kilimandscharica*

A total number of 1949 individuals tree species were measured and identified. This included the standing trees in plantation and the regeneration trees including young trees regenerating seedlings and shrubs in the site that have been sampled which occupied 84% of the total population sampled. Some species occur in all the diameter classes. The tree species recorded as regenerating were categorized in three diameter classes, taken at less than five centimeters, greater than five centimeters of diameter at breast height, shrubs, and height were measured for every individual. In all 62 surveyed sites, 63 tree species were recorded and identified.

The diameter class of all individual less than five centimeters has more individuals (Seedlings) than the other two diameter classes. The young seedlings identified (<5cm) were significantly low in lighting strikes sites (L) compared to Non-Lightning (NL) and non-damaged (ND). There is no statistically significant difference in vegetation regeneration among lightning-disturbed (L), non-lightning disturbed (NL), and undisturbed (ND) forest patches in Nyungwe National Park (F(2,158) = 2.29, p = 0.104). (P>0.05; one-way ANOVA was conducted). We failed to reject the null hypothesis. There was insufficient evidence to conclude that a significant difference in vegetation regeneration exists among the three forest patch types.

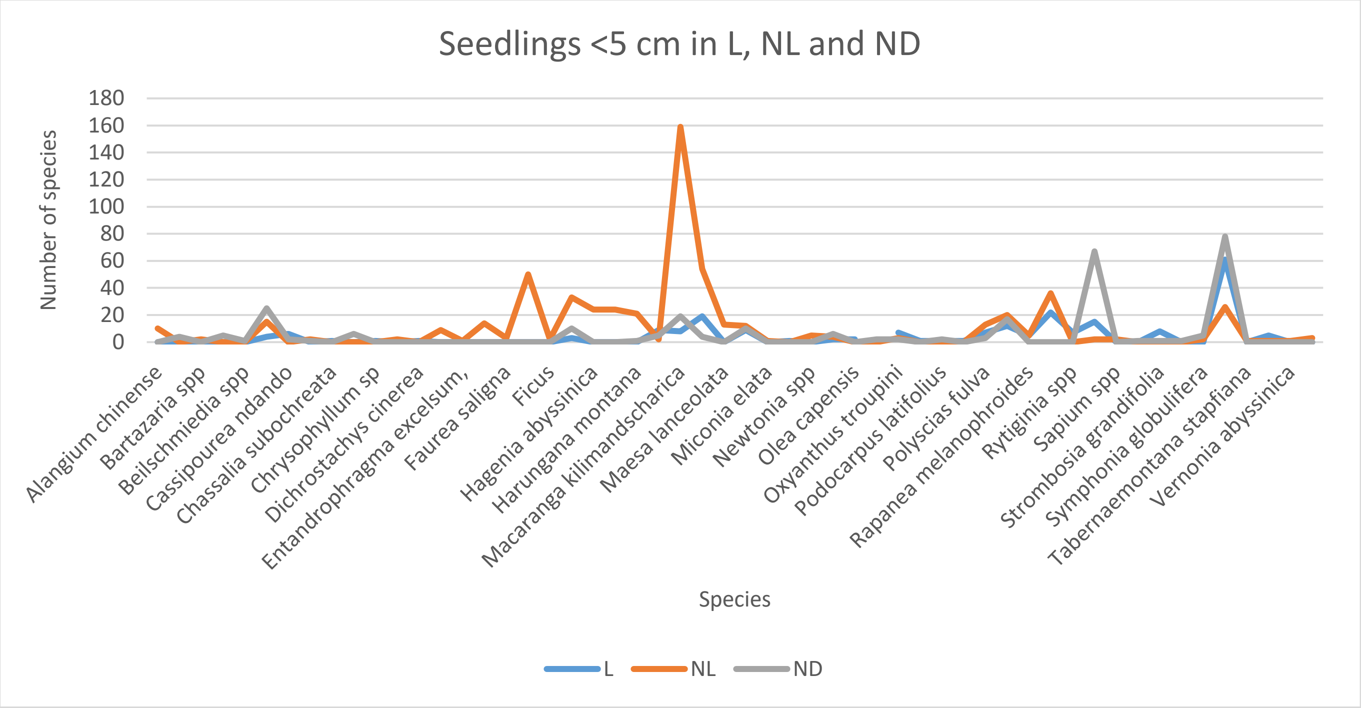

Figure 12:Seedlings <5cm in L,NL,ND forest patches

4.2 Analysis of tree species diversity across sites surveyed.

The analysis of tree species diversity across the lightning-affected, non-lightning, and non-damaged areas of Nyungwe National Park revealed a clear gradient among the eight sampled sites (Figure 3). The Shannon-Wiener Diversity Index (H') was highest at the Umugote site (H' = 2.7), followed closely by Umuyove (H' = 2.6) sites and Main Road (H' = 2.5) indicating these areas support the most species-rich and balanced tree communities. Moderately high diversity was recorded at Rukuzi (H' = 2.5) and Imbaraga (H' = 2.2). In contrast, significantly lower diversity values were found at Chimpanzee (H' = 0.6), and Nyabishwati (H' = 0.7) sites, suggesting a community structure potentially dominated by fewer species or influenced by factors that reduce ecological balance.

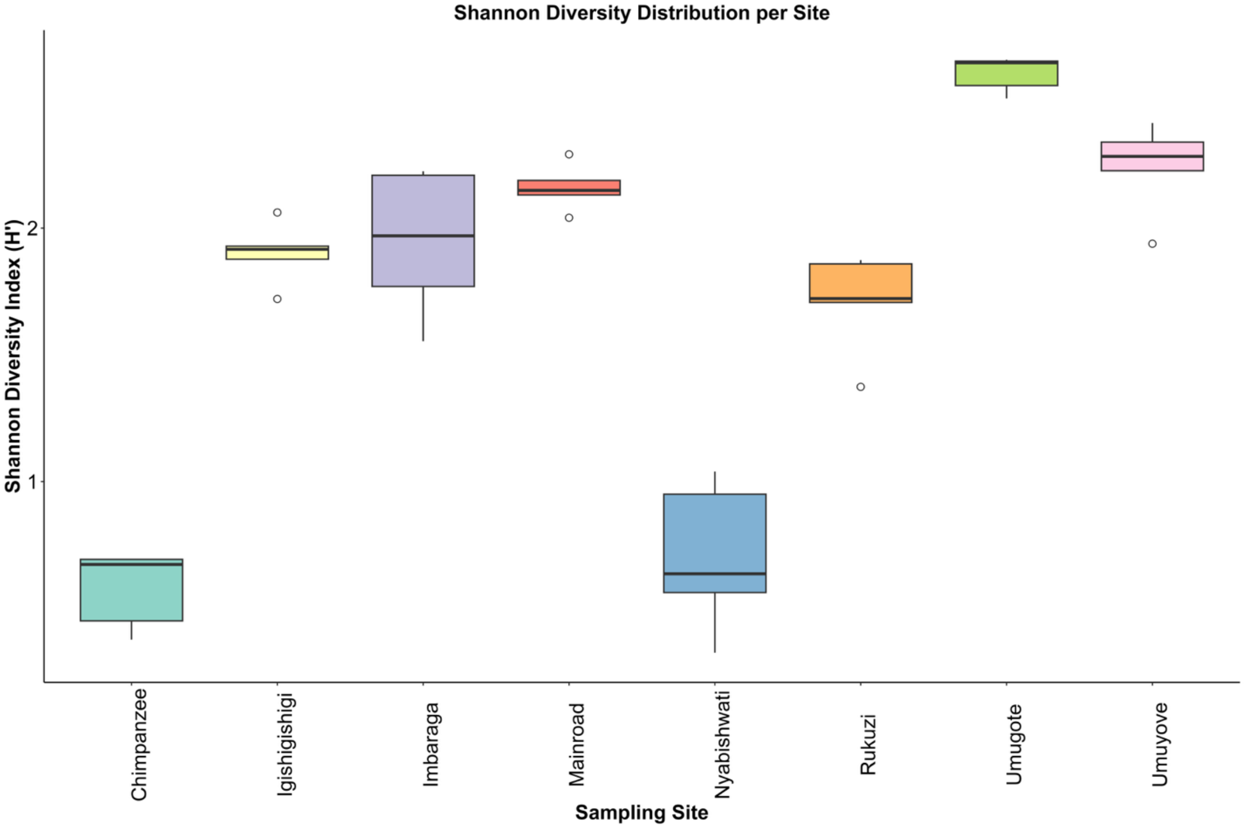

Figure 13:The Shannon diversity of plants found across the sites

4.2 Analysis of species richness and diversity in response to lightning disturbance

The analysis of tree communities across different disturbance regimes reveals a clear impact of lightning strikes on forest structure (Fig. 14). The non-lightning affected area exhibited the highest levels of tree diversity, followed by the non-damaged area, with the lightning-damaged area showing significantly reduced diversity (Fig 14. Right).

Regarding species richness, we used rarefaction analysis to standardize species count data. The estimated asymptotic species richness for the lightning-damaged area is closer to that of the non-damaged area than the overall diversity indices might suggest. However, the non-lightning area consistently demonstrates the highest species richness.

This pattern indicates a critical ecological distinction: while the lightning and non-damaged areas may host a somewhat similar number of species (richness), the distribution of individuals among those species (evenness) is fundamentally different. The significantly lower diversity in the lightning zone is not solely due to a loss of species, but rather to a dramatic shift in community structure.

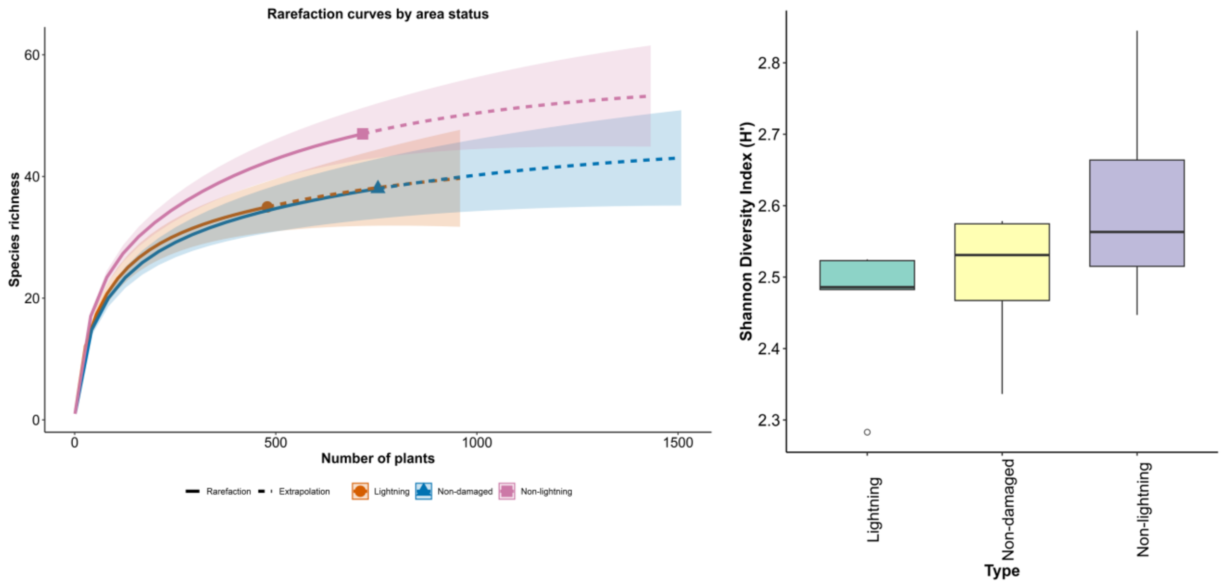

Figure 14:Illustration of the diversity (right), abundance, and species present across (left) the habitat type

The destruction of canopy trees by lightning creates large gaps, increasing light availability on the forest floor. This sudden change inhibits shade-tolerant understory species while aggressively promoting the rapid growth and dominance of a few light-demanding pioneer species. Consequently, the plant community becomes heavily dominated by these few pioneers, leading to a drop in evenness and thus a lower overall Shannon diversity index, even if the total count of species remains moderately high.

In essence, lightning disturbance acts as an agent of simplification, reducing ecosystem complexity by favoring a subset of species better adapted to disturbed conditions, thereby decreasing overall tree diversity

Table 1: Number of species and individuals for the families represented in diameter class (<5cm)

		Number of species			
No	**Seedling Species <5 cm**	**L**	**NL**	**ND**	**Total**
1	*Alangium chinense*	0	10	0	10
2	*Allophylus africanus*	0	0	4	4
3	*Bartazaria spp*	0	2	0	2
4	*Beilschmiedia rwandensis*	0	0	5	5
5	*Beilschmiedia spp*	0	0	1	1
6	*Carapa grandiflora*	4	15	25	44
7	*Cassipourea ndando*	6	0	2	8
8	*Cassipourea sp.*	0	2	1	3
9	*Chassalia subochreata*	1	0	0	1
10	*Chrysophyllum gorungosanum*	0	0	6	6
11	*Chrysophyllum sp*	1	0	0	1
12	*Dichaetanthera corymbosa*	0	2	0	2
13	*Dichrostachys cinerea*	1	0	0	1
14	*Dombeya torrida,*	0	9	0	9
15	*Entandrophragma excelsum,*	0	1	0	1
16	*Erica capensis*	0	14	0	14
17	*Faurea saligna*	0	3	0	3
18	*Ficalhoa laurifolia*	0	50	0	50
19	*Ficus*	0	2	0	2
20	*Galiniera saxifraga*	3	33	10	46
21	*Hagenia abyssinica*	0	24	0	24
22	*Harungana*	0	24	0	24
23	*Harungana montana*	0	21	1	22
24	*Ilex mitis*	9	2	5	16
25	*Macaranga kilimandscharica*	8	159	19	186
26	*Macaranga spp*	19	54	4	77
27	*Maesa lanceolata*	0	13	0	13
28	*Maytenus acuminata*	9	12	10	31
29	*Miconia elata*	0	1	0	1
30	*Newtonia*	1	0	0	1
31	*Newtonia spp*	0	5	0	5
32	*Ocotea usambarensis*	2	4	6	12
33	*Olea capensis*	2	0	0	2
34	*Olinia rochetiana*		0	2	2
35	*Oxyanthus troupini*	7	3	2	12
36	*Parinari curatellifolia*	1	0	0	1
37	*Podocarpus latifolius*	1	0	2	3
38	*Polylthia luensis*	1	0	0	1
39	*Polyscias fulva*	7	13	3	23
40	*Psychotria mahonii*	12	20	17	49
41	*Rapanea melanophroides*	5	5	0	10
42	*Rytiginia kivuensis*	22	36	0	58

43	*Rytiginia spp*	7	0	0	7
44	*Rytigynia bridsoniae*	15	2	67	84
45	*Sapium spp*	0	2	0	2
46	*Seilschmiedia rwandensis*	0	0	1	1
47	*Strombosia grandifolia*	8	0	1	9
48	*Strombosia scheffleri*	0	0	1	1
49	*Symphonia globulifera*	0	2	5	7
50	*Syzygium guineense*	61	26	78	165
51	*Tabernaemontana stapfiana*	0	1	0	1
52	*Teclea nobilis*	5	1	0	6
53	*Vernonia abyssinica*	0	1	0	1
54	*Vernonia spp*	0	3	0	3
		218	577	278	1073

4.5 Microclimate differences (temperature, Elevation, Canopy Cover, humidity and rain fall).

Microclimatic conditions were monitored over a one-month period (June-July 2025) using data loggers that recorded temperature and humidity. These loggers were strategically placed in four different forest regions, corresponding to the survey areas. For each of the three surveyed sites, geographic coordinates and elevation were recorded. Rainfall data were data from mid-2011 to mid-2021 were obtained from the data recorded at weather station located in the forest by Göran Wallin.

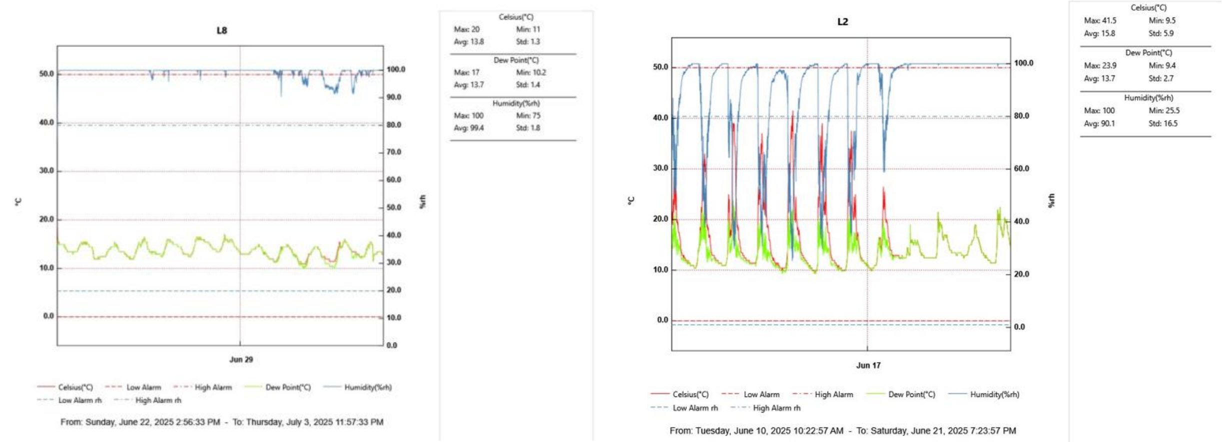

Figure 15:Temperature and humidity measurements in the forest

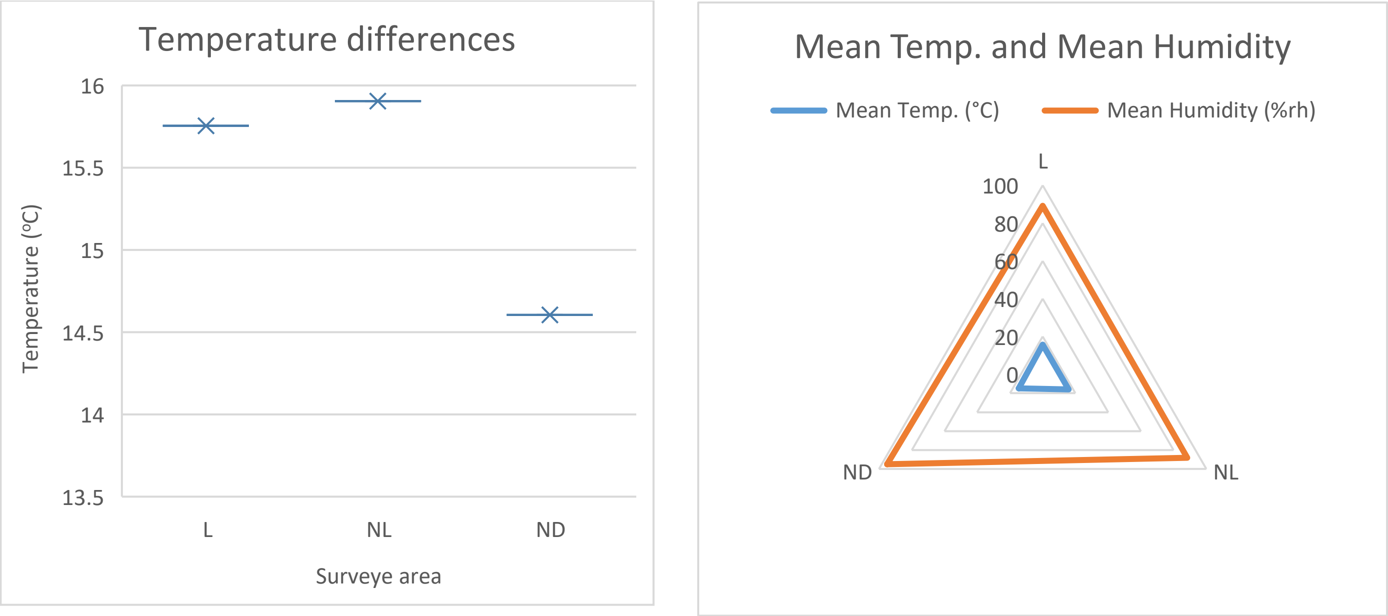

Figure 16: Temperature increase (Left) and Humidity (Right) in L,NL and ND

Surface air temperature is higher in the lightning and non-lightning patches (open canopy) due to direct exposure to solar radiation. In contrast, the Non damaged forest patches (closed canopy) exhibit lower temperatures and higher humidity. The dense canopy shade limits light penetration, reducing solar heating and facilitating moisture retention near the forest floor. The results showed that no significant difference in temperature between Lightning and non-Lightning Forest patches $p = 0.307$. Lightning Forest patches has significantly higher temperature than non-damaged and p value was equally to 1.05×10^{-27}. Non lightning patches has significantly higher temperature than non-damaged forest patches with the Adjusted $p = 2.17\times10^{-38}$

As relative humidity (RH) rises in cooler temperatures, the difference in water vapor between the inside of the leaf (saturated) and the outside air (now also more saturated) decreases. This gradient is the driving force for water loss. With less pressure to lose water, the tree's stomata (pores on leaves) can remain open for longer periods without risk of dehydration. Open stomata allow for the uptake of carbon dioxide (CO_2), which is the essential ingredient for photosynthesis. More CO_2 uptake means more sugar production, which fuels all growth.

Table 2:Table shows the mean Temperature, Humidity, canopy cover and rainfall

	Mean Temp. (°C)	**Mean Humidity (%rh)**	**Elevation (m)**	**Canopy Cover (%)**	**Rainfall (mm/yr)**
L	15.75437956	89.17773723	2380.175182	6.923076923	1561.436
NL	15.90337423	88.33773006	2394.819018	1.557377049	1561.436
ND	14.61393443	94.98770492	2311.909836	13.33333333	1561.436

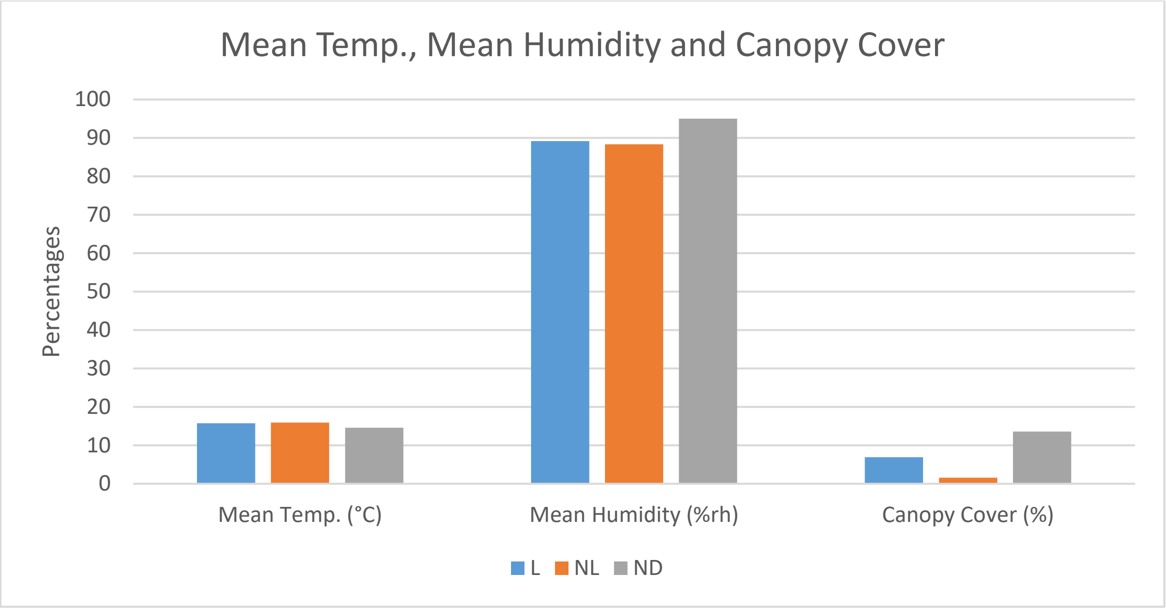

Figure 17: Mean Temp., Humidity and canopy cover in both three sites

4.5.1 Trees distribution across the temperature and humidity

The redundancy analysis (RDA) revealed that humidity was a significant environmental factor influencing species composition within the study area. The ordination biplot (Fig. 18) showed that species such as *Harungana montana*, *Hagenia abyssinica*, *Lobelia gibberoa*, and *Symphonia globulifera* were positively associated with higher humidity levels, clustering along the direction of the humidity vector. In contrast, species including *Chassalia subochreata*, *Alchornea hirtella*, and *Rytiginia kivuensis* were positioned opposite to the humidity gradient, suggesting a stronger association with drier conditions. Species located near the origin, such as *Polyscias fulva* and *Ocotea usambensis*, exhibited weak correlations, indicating broader ecological tolerance. These findings highlight humidity as a primary driver structuring plant community composition, with clear differentiation between moisture-adapted and dry-tolerant species.

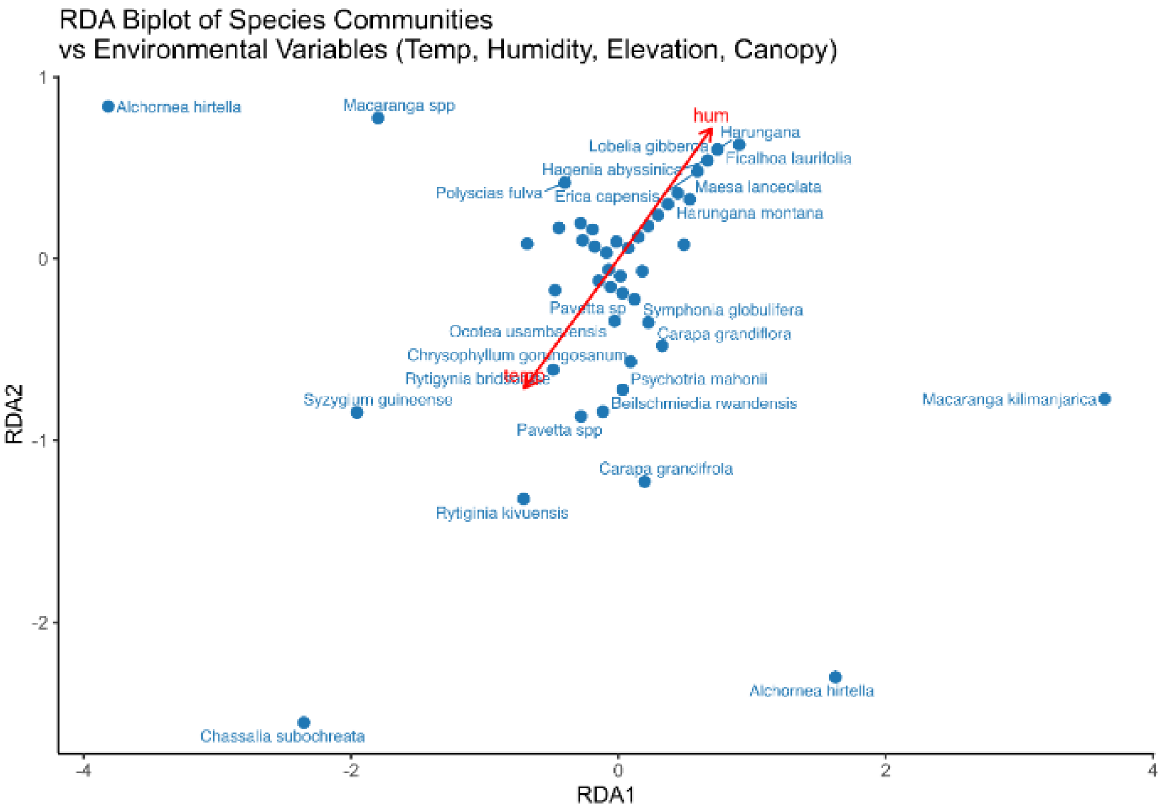

Figure 18:Species communities Vs Environmental Variability(Tem, Hum, Elev, and Canopy)

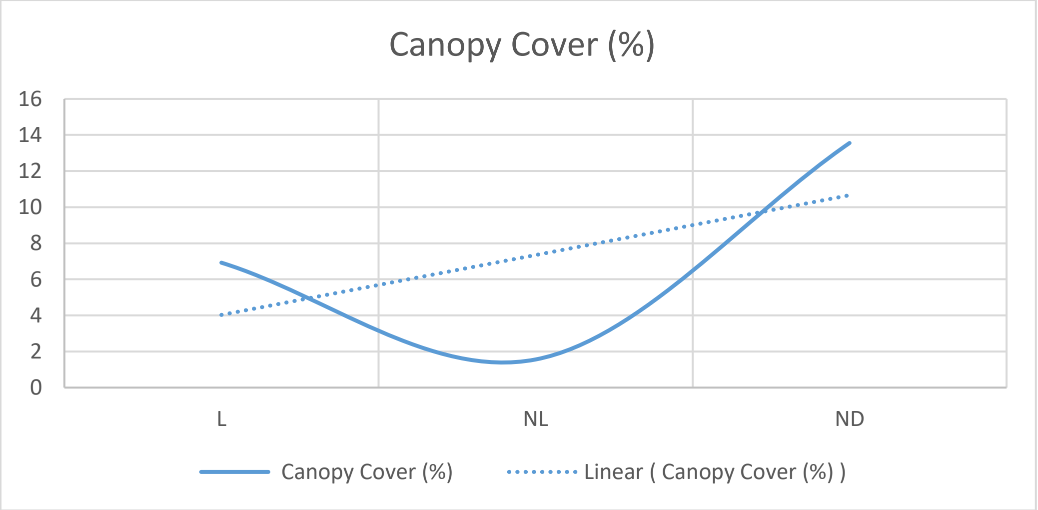

Figure 19:Canopy cover across three surveyed area

A dense canopy observed in non-damaged forest patches severely limits the amount of sunlight reaching the forest floor, creating a competitive environment where only shade-tolerant seedling species can survive and persist. This suppression of light-demanding species shapes the future composition of the forest. Conversely, gaps in the canopy, created by treefalls, allow light to penetrate, triggering a burst of growth and enabling light-loving pioneers and saplings to establish, driving forest dynamics and diversity.

4.5.2 Abiotic Environmental Heterogeneity

Analysis of key environmental variables revealed significant heterogeneity across the eight study sites (Chimpanzee, Rukuzi, main road Nyabishwati, Umuyove, Imbaraga, Umugote, and Igishigishigi) in both the lightning-disturbed area, non-lightning disturbed area and undisturbed area). A clear microclimatic gradient was observed, primarily driven by differences in elevation, temperature, humidity, and canopy cover.

Table 3:Summary of mean environmental variables measured across the eight study sites. Climatic data of rainfall were obtained from on-site weather stations, a local meteorological station installed in Nyungwe National Park for the calendar year of 2011 to 2021

Site Name	**Mean Temp. (°C)**	**Mean Humidity (%rh)**	**Elevation (m)**	**Canopy Cover (%)**	**Rainfall (mm/yr)**
Chimpanzee	13.6	99.3	2,265.00	-	1,561.44
Igishigishigi	15.8	90.1	2,378.09	13.91	1,561.44
Imbaraga	15.86	89.32	2,169.83	3	1,561.44
Mainroad	13.75	99.38	2,452.13	1.45	1,561.44
Nyabishwati	13.8	99.4	2,430.00	20.42	1,561.44
Rukuzi	13.6	99.3	2,309.29	1.25	1,561.44
Umugote	15.84	88.2	2,410.70	8.14	1,561.44
Umuyove	15.94	89.07	2,320.33	12.84	1,561.44
p-value	<0.001	<0.001	<0.001	<0.001	0.129

Mean annual temperature and relative humidity differed significantly among sites ($p < 0.001$). Sites clustered into two distinct groups, Cooler, more humid sites: Chimpanzee, Rukuzi, and Nyabishwati and main road and warmer, less humid sites: Umuyove, Imbaraga, Igishigishigi and Umugote. Elevation varied significantly across the study area ($p < 0.001$) with a measurable negative correlation between elevation and temperature. Higher elevation sites were consistently associated with cooler temperatures. In contrast, cumulative annual rainfall did not differ significantly among sites $p = 0.129$ Precipitation was uniform across the study area, indicating that rainfall is not a primary driver of the observed environmental differences between sites. The observed variation in tree diversity across surveyed sites appears to be influenced by localized microclimatic conditions, particularly temperature and humidity. This relationship, however, is complex and not unidirectional.

Contrary to what might be expected, sites with higher temperatures, such as the Igishigishigi trail and Imbaraga, exhibited moderate tree diversity. In contrast, cooler sites like Nyabishwati and Chimpanzee, which are also affected by other disturbances like erosion and primate activity, recorded lower diversity. This suggests that while temperature plays a role, its effect is likely mediated by other compounding factors.

Furthermore, a clear pattern emerged regarding humidity: sites characterized by higher humidity levels consistently showed lower tree diversity. This counterintuitive result may be explained by the underlying causes of the humidity. In these montane ecosystems, persistently high humidity is often associated with waterlogged soils, valley bottoms prone to cold air pooling, or frequent cloud immersion. These conditions create abiotic stress that can inhibit germination, root respiration, and nutrient uptake, ultimately limiting the number of species that can thrive and leading to a less diverse plant community.

4.5.3 Vegetation Structure and Light Availability.

Canopy cover was a major source of structural heterogeneity, varying significantly among sites p < 0.001). This created a gradient of light availability at the forest floor: Sites such as the historical lightning-disturbance zone and landslide areas were characterized by open canopies or gaps, resulting in higher light penetration and exposure. Other sites maintained partial to complete tree cover, creating shaded understory conditions. The interplay between elevation and canopy structure was a key factor in defining local microclimates, influencing ground-level temperature, humidity, and light regimes.

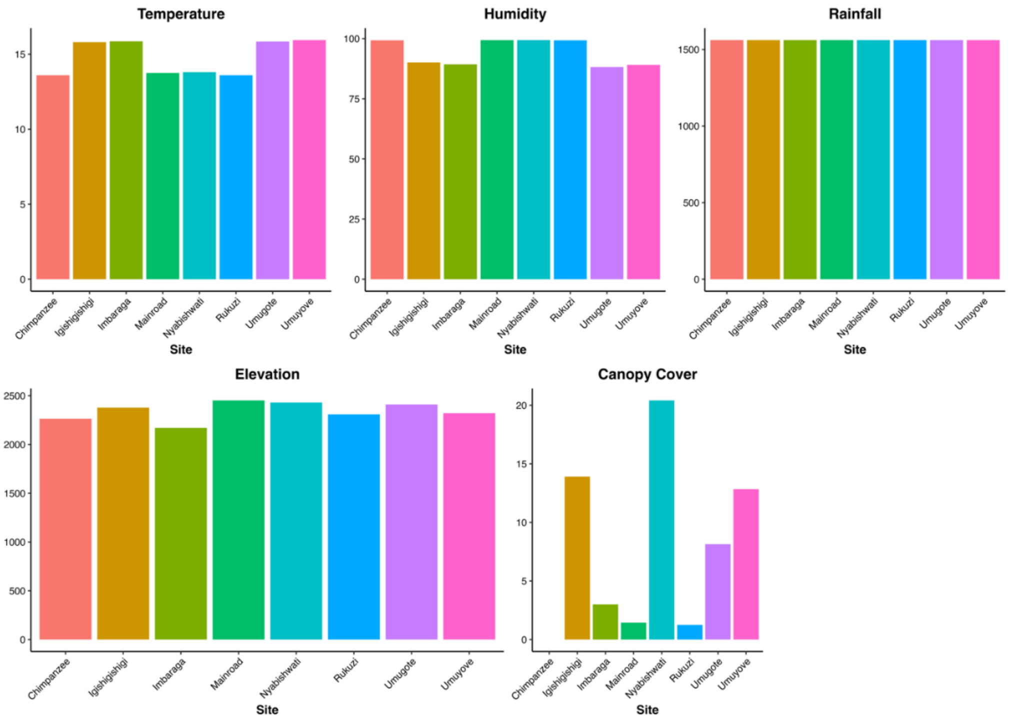

Figure 20: Environmental variables recorded at each site

4.5.3 NDVI Time series analysis

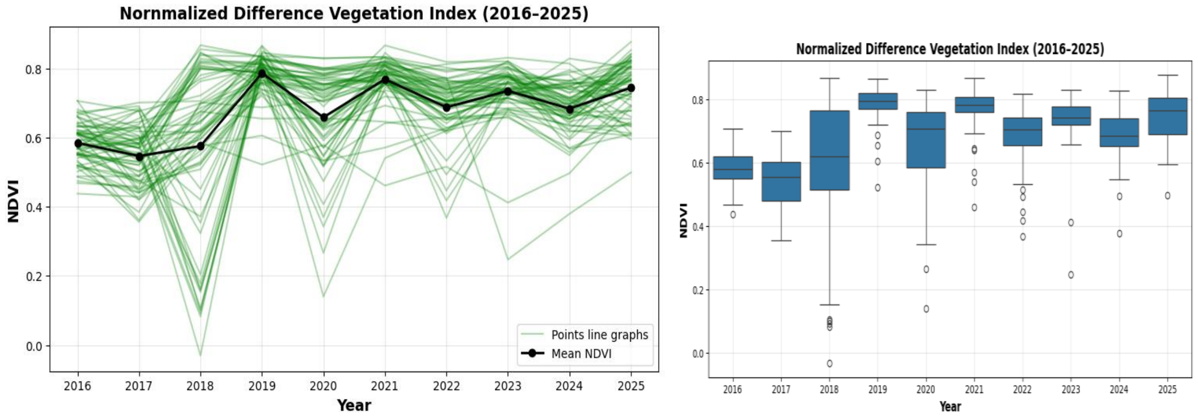

Figure 21:NDVI Time series Analysis.

Each green line represents NDVI at a sampled point; the black line shows the mean NDVI trend. From 2016–2017, NDVI values are relatively stable but modest (~0.55–0.6), indicating average vegetation greenness. In 2018, there is a sharp decline in NDVI, likely linked to major disturbance (lightning strikes). Some points dropped close to 0, indicating severe canopy damage. By 2019, NDVI rebounded strongly (mean ~0.8), showing clear signs of vegetation recovery. After 2020, NDVI stabilizes, with fluctuations but maintaining high greenness (0.7–0.8), suggesting the forest recovered resilience.

The 2018 boxplot has a wide spread with many low outliers (some near 0), confirming severe disturbance from lightning strikes at the sampled locations. From 2019 onward, the distribution shifts upward, with the median consistently above 0.7, reflecting healthy canopy regrowth and recovery. Variability reduces after 2020, indicating that most points returned to stable vegetation cover.

CHAPTER 5: DISCUSSIONS

5.1 Discussion

The regeneration of woody species is a vital component of forest ecosystem dynamics and recovery (PHILIP R, 2020). The findings in this study revealed that the number of regenerating species with less than five centimeters represented 57% of the number of standing young seedlings. The highest number of individuals were more in the forest patches which have been destructed by other disturbances like erosion, landslides, etc where they were more than 577seedlings on the 20 sites of 10*10 m sample size.

The surveyed forest patches display tree diameter and height distributions across forest patches. Non-damaged patches had the highest frequency of large-diameter and height trees, indicating a mature stand structure with minimal disturbance. Lightning gaps display a broader size distribution, whereas non-lightning disturbed sites dominated by small-diameter and height trees, consistent with chronic growth suppression.

Species richness

The number of 54 species for the surveyed area of 62 plots which was equally to around to 0.6 ha is approximated to 90 species/ha. One reason of having denser populations under forest patches affected by disturbances other than lightning may be explained by increased canopy openness which have been destructed by other disturbance which are not lightning strikes could be the openness of the canopy. The canopies of trees can exert protective functions and have a nurse structure that facilitate natural forest recovery, largely through their influence on light availability. This may mainly be depending on light intensity (Fahrig, 2003). The factors like quality and quantity of light penetrating through the canopy, microclimatic conditions, composition of the seed bank in the soil, and availability of recent seed sources in the vicinity of the plantation are also important for regeneration (Stride, 2018). Thus, light in the understory remains a key driver of natural forest regrowth. (Fig 14. Right).

The analysis of tree communities across different disturbance regimes reveals a clear impact of lightning strikes on forest structure (Fig. 14). This pattern is consistent with the intermediate disturbance hypothesis, where periodic disturbances create gaps that allow light-demanding pioneer species to coexist with more established species, increasing overall diversity at the local scale.

The overall species richness was highest in non-damaged area due to the crossed canopy of trees in those area, and followed by the Non lighting disturbed site due to the high number of seedlings which germinate due to the accessibility of the light and lastly the lightening disturbed site which shows the trees which have been died due to the ignition of fire

The highest species richness was also found in the warmer, mid-elevation sites (e.g., Umuyove, Imbaraga), which is a common pattern known as the mid-domain effect. The open, disturbed sites hosted a different suite of pioneer and generalist species, contributing to beta diversity (differences in species composition between sites). The high-elevation, closed-canopy sites had the lowest richness but contained several specialist and endemic species not found elsewhere.

The results of this study provide clear empirical evidence that lightning strikes are a significant driver of forest structure and diversity in the montane forests of Nyungwe National Park. The data strongly support the hypothesis that lightning disturbance reduces tree species diversity and alters community composition by creating gaps that favor pioneer species.

The formation of a canopy gap following a lightning strike fundamentally alters the understory environment. The sudden exposure to high light levels inhibits the regeneration of shade-adapted understory tree species. Concurrently, the abundance of light and space promotes the rapid proliferation of lianas. These fast-growing vines create a physical barrier that smothers emerging seedlings and intensifies competition for vital resources, significantly impeding the recruitment and growth of young trees. where single-tree or large-scale disturbances reset successional processes. The significantly lower Shannon Diversity Index (H') in lightning-damaged sites compared to non-damaged and non-lightning sites demonstrates a loss of ecological complexity following a strike. This finding aligns with the established paradigm of gap dynamics, where single-tree or large-scale disturbances reset successional processes (Gora et al., 2021)

The rarefaction analysis further refined this understanding, suggesting that while asymptotic species richness in damaged areas may be moderately high, the community is dominated by a few species, leading to low evenness. This is a classic signature of recent disturbance. The diameter and height class distributions provide the structural evidence: lightning sites held a mix of a few surviving large trees and a high proportion of small-diameter, short-stature regeneration. This indicates a rapid recolonization by light-demanding, fast-growing pioneer species, a process directly observed in Neotropical forests following lightning disturbance (Yanoviak et al., 2024). Therefore, this study confirms that lightning is a key natural disturbance agent in Afromontane forests, creating heterogeneity in the forest mosaic by generating patches of early successional habitat within the mature forest matrix.

Similarly, the results support the second alternative hypothesis (H1) regarding microclimate. Lightning-disturbed patches, with their open canopies, experience significantly warmer and less humid conditions due to increased solar radiation and airflow. This altered microclimate is the primary driver inhibiting shade-tolerant species and promoting the light-demanding pioneers that came to dominate these sites.

5.1.2 Lightning as an Agent of Ecological Simplification

The significantly lower Shannon Diversity Index (H') in lightning-damaged sites, coupled with the rarefaction analysis, confirms that lightning acts as an agent of simplification. The destruction of canopy trees creates gaps that reset succession, favoring a suite of fast-growing, light-demanding pioneer species. This finding aligns with global literature on gap dynamics, including recent work by (Yanoviak et al., 2024) in tropical forests, which highlights how such disturbances reduce community evenness. The structure of these sites a mix of a few surviving mature trees and a dense layer of small-diameter, short-stature regeneration is classic for a forest in an early successional state. This demonstrates that lightning is a key natural process creating heterogeneity in the forest mosaic.

5.1.2 The complex role of microclimate

The significantly lower Shannon Diversity Index (H') in lightning-damaged sites, coupled with the rarefaction analysis, confirms that lightning acts as an agent of simplification. The destruction of canopy trees creates gaps that reset succession, favoring a suite of fast-growing, light-demanding pioneer species. This finding aligns with global literature on gap dynamics, including recent work by (Yanoviak et al., 2024), in tropical forests, which highlights how such disturbances reduce community evenness. The structure of these sites a mix of a few surviving mature trees and a dense layer of small-diameter, short-stature regeneration is classic for a forest in an early successional state. This demonstrates that lightning is a key natural process creating heterogeneity in the forest mosaic.

CHAPTER 6: CONCLUSION, AND RECOMMENDATIONS

6.1 Conclusion

This study successfully elucidated the distinct impacts of different disturbance regimes on the montane forests of Nyungwe National Park, achieving its primary aim of assessing effects on vegetation regeneration, composition, and dynamics. The findings conclusively demonstrate that disturbance type dictates ecological response: lightning strikes create gaps that catalyze a successional sequence, leading to regeneration characterized by high stem density of a few light-demanding pioneer species, albeit at a temporary cost to overall diversity. This shift is primarily driven by the altered microclimate of increased temperature and decreased humidity within gaps. In contrast, areas affected by chronic erosion exhibit a stunted, yet species-rich, community structure. Ultimately, this research confirms that the park's resilience and biodiversity are underpinned by a mosaic of habitat types including undisturbed old-growth forest, lightning gaps, and erosion-disturbed patches each contributing unique and essential value to the ecosystem's overall integrity.

6.2 Recommendations

Based on the findings of this research, a multi-faceted management approach is recommended for Nyungwe National Park. Firstly, active interventions should be considered in lightning-disturbed gaps where natural succession is being impeded; specifically, the manual reduction of dense liana thickets (particularly *Sericostachys scandens* and *Mechaniopsis spp*.) and competitive shrubs (*Alchornea* spp.) could release young seedlings from competition and aid forest recovery.

Concurrently, the protection of undisturbed old-growth forests must be prioritized as core conservation zones for their irreplaceable carbon storage and biodiversity value. Furthermore, the erosion-prone non-lightning disturbed sites, such as Nyabishwati and Chimpanzee, require targeted restoration through soil stabilization and the planting of resilient native species to break the cycle of chronic disturbance. Finally, given projections of increased lightning frequency under climate change, this study should serve as a baseline for developing long-term adaptive management strategies to safeguard the park's ecological integrity against future disturbances.

2.3.1 Recommendations for future researches

Long-Term Monitoring: Establish permanent plots in the studied sites to monitor long-term successional trends, specifically to determine the time required for lightning gaps to regain pre-disturbance diversity and structure.

Functional Trait Analysis: Move beyond taxonomic diversity to study the functional traits (e.g., wood density, seed mass, specific leaf area) of species in different disturbance regimes to better predict ecosystem recovery.

Soil and Seed Bank Studies: Investigate how lightning fires and soil disturbances affect the soil seed bank nutrient cycling compared to erosion-prone sites.

Faunal Studies: Research how these different disturbance types affect animal communities (birds, insects, mammals) to gain a full ecosystem perspective.

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Appendix 1. Data collection form

Zones	type	plotid	site	lat	long	el	vld	temp	hum	rain	plantType	species	dbh	count	height	diameter	lli	cfi	cg	desc
1																				
1																				
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2																				
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Appendix 2. List of tree species identified

No	***Species***	***No***	***Species***
1	*Alchornea hirtella*	*36*	*Clutia abyssinica*
2	*Macaranga spp*	*37*	*Harungana*
3	*Carapa grandiflora*	*38*	*Bartazaria spp*
4	*Polyscias fulva*	*39*	*Vernonia spp*
5	*Maytenus acuminata*	*40*	*Hagenia abyssinica*
6	*Syzygium guineense*	*41*	*Erica capensis*
7	*Ocotea usambarensis*	*42*	*Maesa lanceolata*
8	*Chassalia subochreata*	*43*	*Ficalhoa laurifolia*
9	*Podocarpus latifolius*	*44*	*Cleistanthus polystachyus*
10	*Ilex mitis*	*45*	*Sapium spp*
11	*Macaranga kilimandscharica*	*46*	*Newtonia spp*
12	*Psychotria mahonii*	*47*	*Dichaetanthera corymbosa*
13	*Pavetta spp*	*48*	*Rapanea melanophroides*
14	*Rytiginia kivuensis*	*49*	*Vernonia abyssinica*
15	*Parinari curatellifolia*	*50*	*Tabernaemontana stapfiana*
16	*Beilschmiedia rwandensis*	*51*	*Faurea saligna*
17	*Cassipourea ndando*	*52*	*Ficus*
18	*scheffera sp*	*53*	*Symphonia globulifera*
19	*Galiniera saxifraga*	*54*	*Dombeya torrida,*
20	*Polylthia luensis*	*55*	*Entandrophragma excelsum,*
21	*Rytigynia bridsoniae*	*56*	*Alangium chinense*
22	*Harungana montana*	*57*	*Teclea nobilis*
23	*Dichrostachys cinerea*	*58*	*Dichaetanthera corymbosa*
24	*Olea capensis*	*59*	*Alchornea hirtella Benth*
25	*Alchornea hirtella*	*60*	*Olinia rochetiana*
26	*Ocotea usambarensis*	*61*	*Strombosia scheffleri*
27	*Newtonia*	*62*	*Seilschmiedia rwandensis*
28	*Rytigynia bridsoniae*	*63*	*Allophylus africanus*
29	*Rytiginia spp*	*64*	*Cassipourea sp.*
30	*Oxyanthus troupini*	*65*	*Chrysophyllum gorungosanum*
31	*Chrysophyllum sp*	*66*	*Beilschmiedia spp*
32	*Xymalos monospora*	*67*	*Carapa grandifrola*
33	*Cassipourea sp.*	*68*	*Strombosia Sp*

34	*Miconia elata*	*69*	*Strombosia grandifolia*
35	*Lobelia gibberoa*		

Appendix 4: Reaearch Permit

	Top Species (by record count)	
No	**Species**	**Count**
1	Chassalia subochreata	90
2	Syzygium guineense	82
3	Macaranga kilimandscharica	81
4	Alchornea hirtella	64
5	Alchornea hirtella	51
6	Psychotria mahonii	48
7	Carapa grandiflora	34
8	Rytiginia kivuensis	29
9	Macaranga spp	28
10	Pavetta spp	26

RWANDA
DEVELOPMENT BOARD

RESEARCH CONTRACT

This agreement is made between the Rwanda Development Board (hereinafter referred to as "The Authority") on one part and MANIRIHO Jean d Amour (Hereinafter referred to as "the researcher")

WHEREAS the researcher is the desirous of carrying out the research in the protected area called Nyungwe National Park

And WHEREAS the authority has agreed to the said research to be carried out in the said protected areas, under the terms and conditions herein stipulated,

IT IS NOW AGREED AS FOLLOWS:

1. The authority has authorized the researcher to carry out the research described herein below, in Nyungwe National Park
2. The research shall be restricted to the impact of lightning strike disturbances on vegetation regeneration
3. The said research shall be commenced one day after execution of this agreement and shall have a duration of one Month after which the said research shall cease to be carried out,
4. The researcher or the group of researchers as Foreign Citizen will pay the research application project fee of 50$ nonrefundable paid once as consideration for the permission to carry out the research above described.
5. The researcher as a Foreign student will pay the research application project fee of 30$ nonrefundable paid once as consideration for the permission to carry out the research above described.
6. Each of the researchers as Foreign Citizen shall pay 120 $ monthly research fee non-refundable
7. Each of the researchers as Foreign Student shall pay 50 $ monthly research fee non-refundable

8. The researcher or the group of researchers as Rwandan Citizen shall pay 5000 Rwf monthly research fee nonrefundable and 5000 Rwf of application paid once.

9. Each of the researchers as Rwandan Students who is doing undergraduate courses shall pay 5000 Rwf of application.

10. For non-Rwandans before commencement of any field work, the researcher shall pay a report/security deposit of 300$ refundable within 15 days following the submission of his/her final report.

11. The researcher shall produce a progress report in on the activities covered under the research to the authority and shall at the completion of the research submit a final report on the research which shall include analyzed data, findings and recommendations.

12. The researcher shall where necessary make an application for permission to collect, take and/or use any specimens for the carrying out of the said research. Such application shall be made to the Chief Executive Officer and shall indicate the exact need for the specimens and the number and the number and categories of specimens required.

13. The researcher shall not hunt, collect take, kill or injure any wild plant or animal or any part or derivative thereof and shall not collect, take or use any specimen without prior written approval of the Chief Executive Officer such approval shall bear a stamp of the authority.

14. The authority shall at all times have absolute discretion in deciding on whether or not to grant permission to collect, take or use any specimen and on whether or not to grant permission to hunt, collect, take, kill, or injure any wild plant or animal.

15. The authority shall have a right to stop the research from commencing or continuing with the research herein above described, for good cause

16. This agreement shall be governed by and be subject to Rwanda laws.

IN witness whereof, the duly authorized representatives of the parties hereto have set their hands hereunto on the day and year below mentioned.

For Rwanda Development Board
Eugene MUTANGANA
Managing Director

For the Researcher
MANIRIHO Jean d'Amour

Signature

RWANDA DEVELOPMENT BOARD

Date 05/02/2025

Signature Date: 17/12/2024