

What shapes the wild?

Ecological drivers of mammal diversity across forest regrowth stages in Cloudbridge



Research report

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“Ecological drivers of mammal diversity across forest regrowth stages in Cloudbridge”

A research report to answer the question “ Which ecological drivers influence mammal diversity and abundance across old-growth forest, replanted forest, and naturally regrown forest?”

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Foreword

This research report has been written as part of my internship at Cloudbridge Nature Reserve in Costa Rica, in fulfillment of the requirements of the graduation phase of the

Applied Biology program at HAS Green Academy Venlo. The project reflects my interests in conservation and restoration, with a focus of the role of cloud forests in sustaining wildlife populations. I would like to express gratitude to the team at Cloudbridge for granting me the opportunity to conduct research in this kind of ecosystem. I would also like to thank my coach and supervisor, Sam Mulders, for his guidance and feedback throughout the preparation. Lastly, I want to thank Blanca Cejalvo and Greilin Fallas Rodriguez for their support and expertise on site at Cloudbridge Nature Reserve.

I hope this project will not only contribute to my academic development but also will provide useful insights for conservation strategies here at Cloudbridge and worldwide.

Quinten Reuscher

Summary

Cloudbridge is home to old-growth forests, as well as secondary forests that distinguish between natural regrown and planted areas. It is important to understand which ecological drivers influence mammal recovery in these different forest types as mammals are key indicators of ecosystem functioning. Mammal abundance and diversity can reflect whether reforestation efforts are helping forest restore to a complete and resilient system. The aim of the following study was to dive into how mammal abundance and diversity differ between the three forest types and look into which ecological drivers could explain these differences. Mammals have been surveyed with camera traps that were deployed across the three forest types. Mammal diversity, abundance and activity have been assessed using species richness measures, species accumulation, estimation curves, a RAI and diversity indices. The influence of ecological drivers on abundance and diversity has been calculated using Generalized Linear Mixed Models. Key results have shown that species richness has been comparable between forest types. This finding indicates that secondary forests in Cloudbridge support a large part of the mammal community. Ecological drivers that have been associated with mammal abundance and diversity are understory density, leaf litter depth and elevation, indicating that microenvironmental variables have a bigger impact on mammal communities than forest type alone. Overall, these findings suggest that successful mammal recovery in regenerating forests depends on the quality and structure of the habitat at each given site. Continued monitoring and maintaining a diversely structured, well-connected habitat are recommended to support the recovery of mammal communities within Cloudbridge Nature Reserve.

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1. Introduction

In the past couple of hundred years biodiversity and ecosystems around the world were greatly impacted by human activities. Since the beginning of the industrial revolution, many of the untouched ecosystems were on large scale converted to farmlands, cities or exploited in other ways. This has caused many species to be driven to extinction and has caused a lot of natural habitats that could once be found here on earth to disappear (IPBES, N.D.). The rate at which ecosystems are disappearing has rarely ever been seen in geological history (Secretariat of the Convention on Biological Diversity et al., 2019), leading to scientists believing that we are currently experiencing a sixth mass extinction (Carrington, 2021), (WWF, N.D.). According to IPBES, there are approximately one million species that are at risk (CBD.int, N.D.). This loss goes beyond ecological implications, as ecosystem services such as food production and climate regulation are being impacted as well, influencing the lives of numerous people worldwide (CBD.int, N.D.). One of the habitats with the biggest anthropogenic influence are the rainforests and cloud forests.

Cloud forests are among the most important, yet vulnerable ecosystems on earth. They cover only a small fraction of the total land mass; however, they provide a critical habitat for a diversity of species (Jetz, W., 2021). Most of these species are endemic, which means they need the cloud forests to survive. The constant mist and high humidity create unique ecological conditions which sustain rich animal and plant communities (Britannica, 2025). Cloud forests also play a key role in regulating local water cycles by capturing and releasing moisture (Oliveira et. Al, 2014). However, cloud forests are increasingly threatened by factors like deforestation, agriculture and climate change, disrupting the balance they depend on. The loss of these forests not only has a negative impact on the biodiversity but also disrupts ecological connectivity and the movement of species (Kuijpers Et. Al, 2021).

In recent decades, some people have come to the understanding that to live on this earth in a sustainable way, we should protect these vulnerable ecosystems. Conservation efforts have not only been focused on protecting remaining primary forest but have also looked at how to restore degraded areas (Chazdon, 2008), (Benayas et al., 2009). The effects of reforestation as a result of these efforts have been studied over the years, but what drives the ecosystems to restore to their old conditions how biodiversity comes back is still largely unknown (Atkinson et al., 2022). It is known that reforestation helps in carbon fixation, plays a key role in the water cycle and biodiversity restoration (Shimamoto et al., 2018). Information on how resilient these ecosystems really are and on under which circumstances biodiversity will bounce back effectively is still largely unknown (Atkinson et al., 2022b). A world leader in nature conservation is Costa Rica (World Bank Group, 2023).

Costa Rica, despite being a small country, houses approximately 5% of all biodiversity worldwide, despite covering only about 0.03% of the earth's surface (E N V Team et al., 2011). Furthermore, Costa Rica is known worldwide as a country that is actively protecting its nature, including reforestation efforts to restore habitats and stimulate wildlife (Tafoya et al., 2020). Efforts range from national parks backed by

the government to smaller initiatives owned by private parties, aimed at protecting and restoring the nature in various ways (Fabiano et al., 2019). The combination of old primary forest and reforested areas co-existing close to each other makes Costa Rica a great location to conduct research on reforestation and protection efforts and their effectiveness to restore biodiversity (Chazdon et al., 2009), (Chazdon et al., 2006).

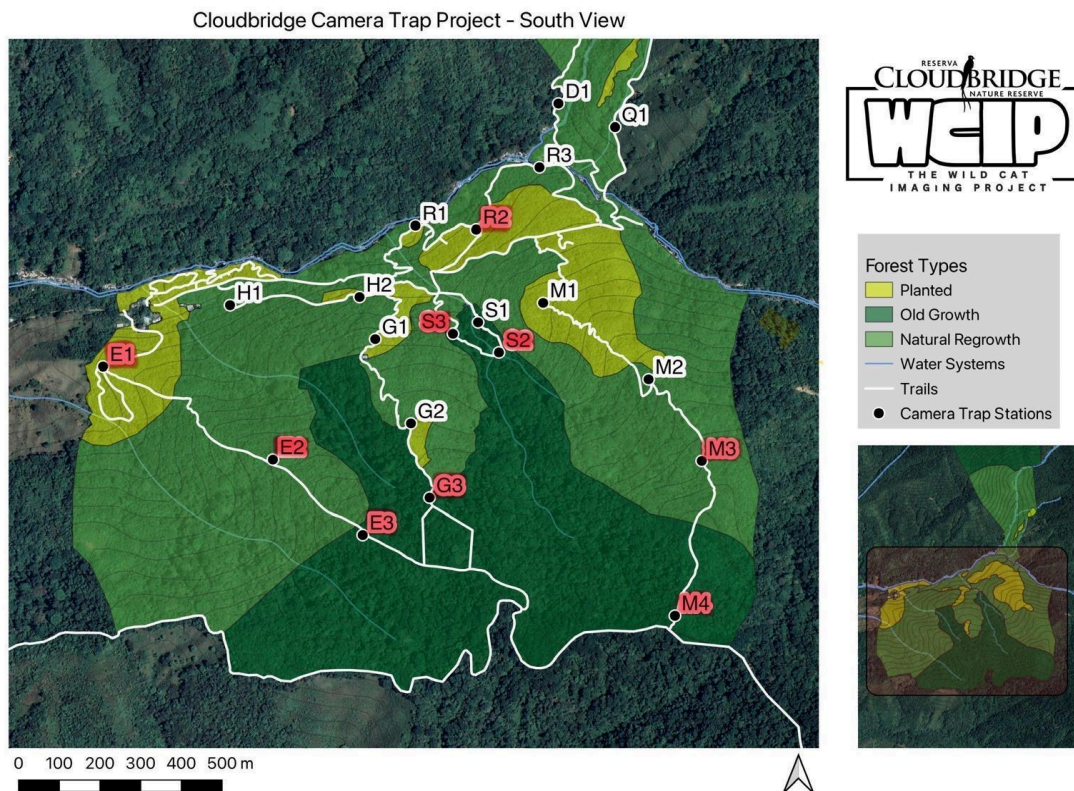
One of these Private Reserves is Cloudbridge. It is located in the Talamanca highlands at the base of the Chirripo mountain. It was created in 2002 by a South-African couple, who saw the destruction that agriculture has brought to the nature in this area. Since then, a lot has changed. Large areas have been reforested or naturally regrown and up to 99% of all the species have returned. They now play a role as both a Nature Reserve which is open to visitors and a research center for volunteers and researchers across the world. It allows for the reserve to be a wildlife refuge while researchers are able to look into the effects of reforestation, enabling future efforts to be more effective.

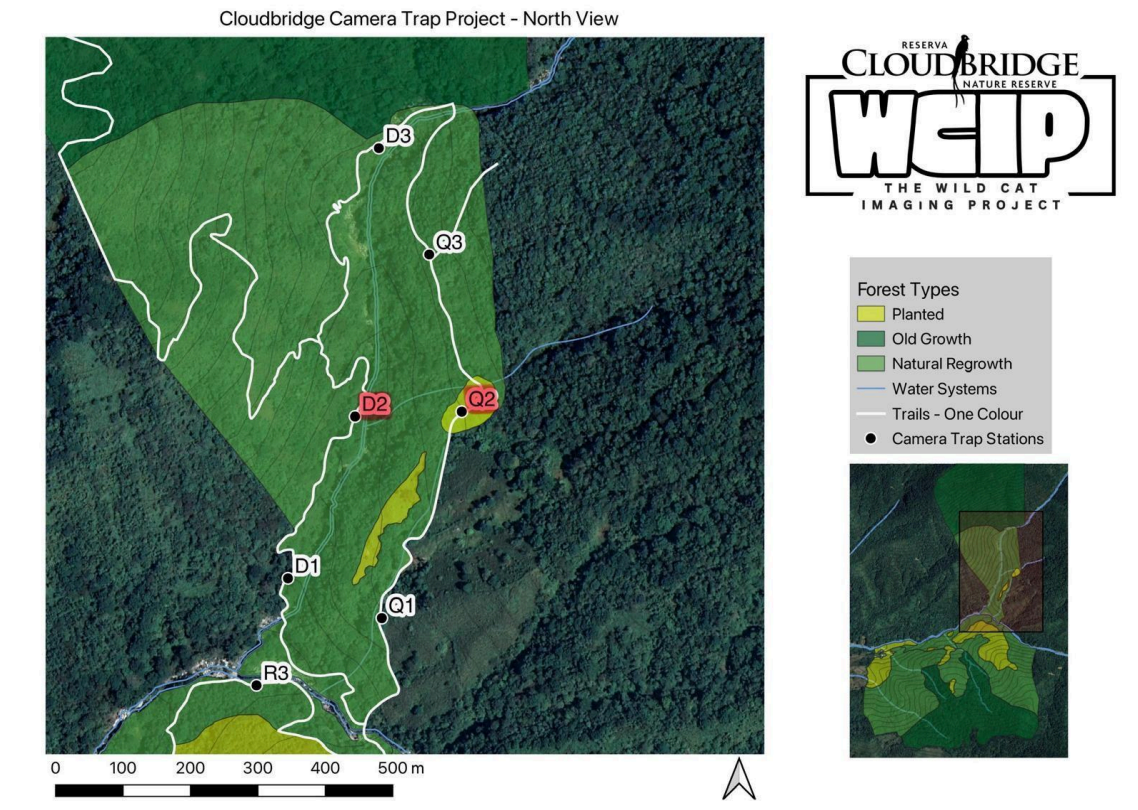
In this context, Cloudbridge offers an opportunity to gain a better understanding of the differences between primary and restored forests, particularly concerning large fauna. While the recovery of flora in reforested areas has been widely studied, less is known about the return of medium-to large sized mammals and the ecological factors that influence this process. This knowledge is essential to assess whether reforested areas can replicate the ecological functions of original ecosystems. Also, this has given an insight on how to best shape these reforested areas in a way that is most effective in regaining lost species. Therefore, this research has answered the question which ecological drivers impact mammal diversity and abundance between old growth forest, replanted forests and natural regrown forest. To be able to answer this question two sub questions have been researched being “Which ecological questions impact mammal diversity and abundance” and “What is the current diversity of mammals between old- growth, planted and natural regrowth forest within Cloudbridge”. This has been done by using the data of 20 weeks of camera trapping, combined with historical data and comparing them with ecological factors found in each forest type. By answering this question, the research has contributed to a broader understanding of ecological restoration in tropical rainforests and provide practical insights for improving conservation and rewilding strategies globally. This has been done by comparing the biodiversity between primary forest, naturally regenerated forest and replanted forest, while finding which ecological factors cause the possible difference.

2. Method

2.1 Research area

This research has taken place at the reserve of Cloudbridge Nature Reserve, Perez Zeledon, Costa Rica. The reserve lies on the southern flank of the Chirripo National Park in the Talamanca Mountain range. It has a surface area of around 200 hectares of forest (primary forest, old-growth, young growth/restored forest) the habitat of the area can be described as a cloud forest with high humidity, steep hills and diverse tree- and shrub layers. The area has an elevation of 1550-2600m above sea level. Annual precipitation exceeds 4.000mm with a distinct wet season ranging from May to November. The area provides an important habitat for a wide variety of fauna, including several species of medium-to large-sized mammals. A map of the reserve with forest types, trails and camera trap locations can be found below in figure 1 and 2.





2.1 Camera trap survey and data collection

For this study, medium- to large-sized mammals have been monitored using camera traps. The camera traps were already installed as they are part of the long-term monitoring project within the reserve. The camera traps are distributed across the trails of both the primary and regenerating forest areas within the reserve. This makes it possible to monitor animal movements across old growth forest, reforested areas and areas that are naturally regenerating. To assess species richness and abundance of mammals, a standardized camera trapping protocol has been implemented. The cameras are installed at a height of 40-50cm above ground level. They are placed along the trails of the reserve and are checked upon once every two weeks to be cleaned, change the batteries or change the SD-cards. The infra-red camera traps are set to run 24 hours a day, programmed to capture 10-second videos when activated by movement. Each week consisted of 2-3 days of checking camera status (battery life, memory and placement), the other 2-3 days of the week were used to download and interpret the collected data. For each observation made by the camera traps, metadata is recorded including time, date, species identification by using the Costa Rica mammal guide, number of individuals and activity type when observed. Independent events have been considered when a detection of the same species is made at least 5 minutes from each other, to prevent counting the same individuals twice. Data has been collected and added to the Cloudbridge camera trapping database. Data used during this research consisted of data collected during the 20-week research period and historic data since the 1st of January 2025 with a total of 50 weeks' worth of data. The Cloudbridge camera trapping manual has been used for data collection (Appendix 1).

2.3 Habitat and environmental varieties

To investigate the potential ecological drivers of differences in mammal diversity and abundance between the two forest types, different environmental variables have been measured. These variables have been measured systematically at each camera location. Variables measured are listed down below.

- Canopy coverage in percents, this has been estimated using a spherical densiometer (Appendix 2). It has been measured at four points around the camera trap (North, East, South and West). This data will give an insight on light penetration and vertical forest structure.
- Understory density: a 1,5-meter vegetation profile board has been used to assess the understory vegetation density at five meters distance from the camera location, following standard visual obstruction scoring methods. Higher understory density might affect mammal movement patterns and detectability.
- Forest type and age: Forest classification (primary, replanted or naturally regrown) and the estimated age of secondary forest plots. This information has been obtained through GIS maps and planting records provided by Cloudbridge. Secondary forest plots have been further classified by regeneration methods.
- Elevation (in meters above sea level) recorded by using a GPS unit. Elevation affects temperature and species distribution and is a key gradient in cloud forests.
- Slope and aspect: Slope angle (in degrees) and direction of the slope are measured using a clinometer (Appendix 3) and a compass at every camera location. These topographic features have been measured to look into the influence microclimate and vegetation type.
- Leaf litter depths: the depths of the leaf litter have been measured at five random points within each plot, measured with a ruler. This substrate variable has been measured to see the possible impact on foraging opportunities and cover for mostly medium size mammals.

Ecological variables have been measured once during this research, in December at the end of rainy season.

2.4 Data-analysis

Data processing and statistical analysis has been done using RStudio 2026.01.0-392 to ensure significance of this research. Datasheets have been made by using Excel. Mammals' species richness, relative abundance and community composition have been compared across forest types using the following approach:

- Relative abundance index (RAI) was calculated as the number of independent detections per 100- trap-nights per species
- Diversity indices: Shannon and Simpson indices have been computed for forest type.
- Rarefaction curves and species accumulation curves have been generated using the INEXT package to assess sampling completeness.
- Generalized linear mixed models have been used to test the effects of forest type and environmental variables on mammals diversity and abundance.

3. Results

This results section will present the main results of the camera trap survey. It shows the composition of mammal communities between old-growth, natural regrowth and planted forest found within Cloudbridge Nature Reserve. Notable patterns in species richness, abundance and community diversity are described. Lastly, the outcomes of the statistical models that predict the influence of ecological variables on mammal diversity and abundance are presented.

3.1 Sampling completeness and species counts

Species accumulation curves were made using the observed data. All three forest type curves showed increased species richness with an increased sampling effort. Neither of the curves reached a full asymptote during sampling period. The combined forest type curve shows the biggest increase in species during given sampling period.

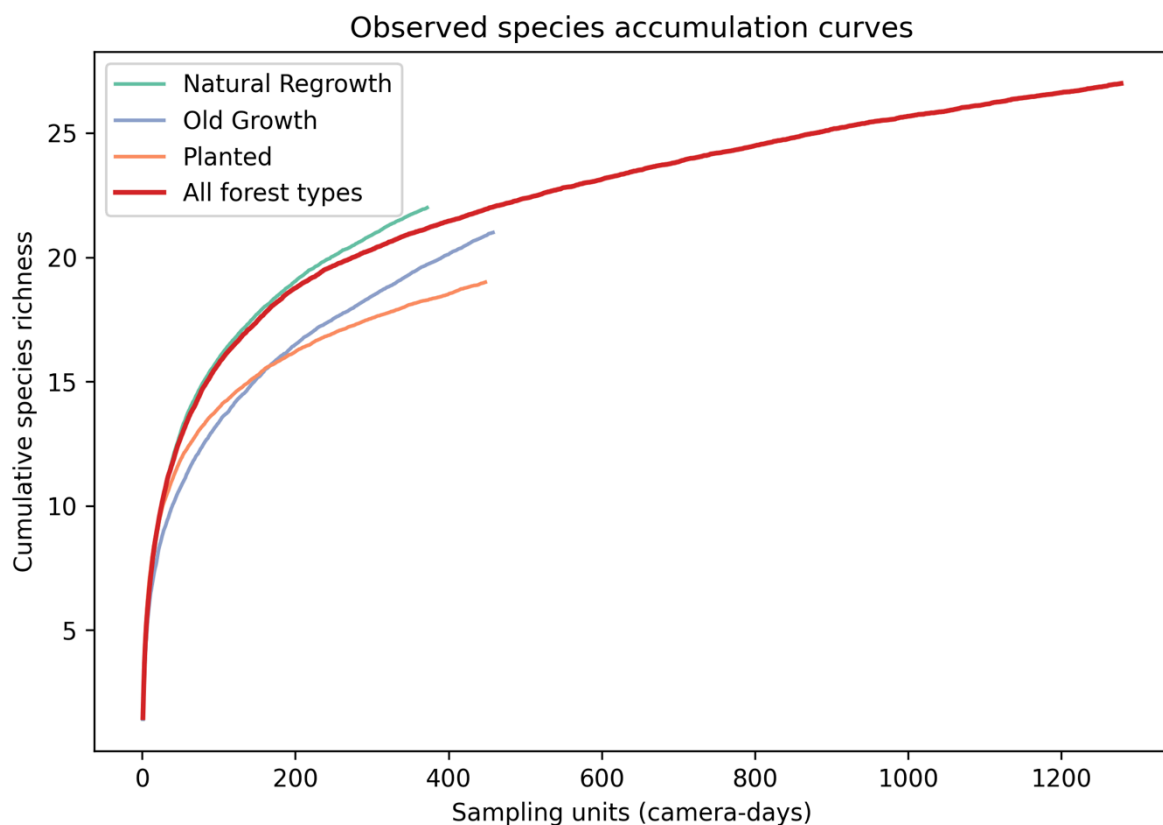


Figure 3: Observed species accumulation curves, showing the increase in cumulative mammal species as a function of increased sampling effort (Camera-days) between natural regrowth, old-growth and planted forest. In addition, a curve for all forest types combined

The Chao1-estimated accumulation curves gave an indication for higher estimated total species richness. All curves scored higher than the observed species accumulation curves. Old growth showed the highest estimated species richness, followed by natural regrowth and planted forest. Combined species curve showed highest richness overall.

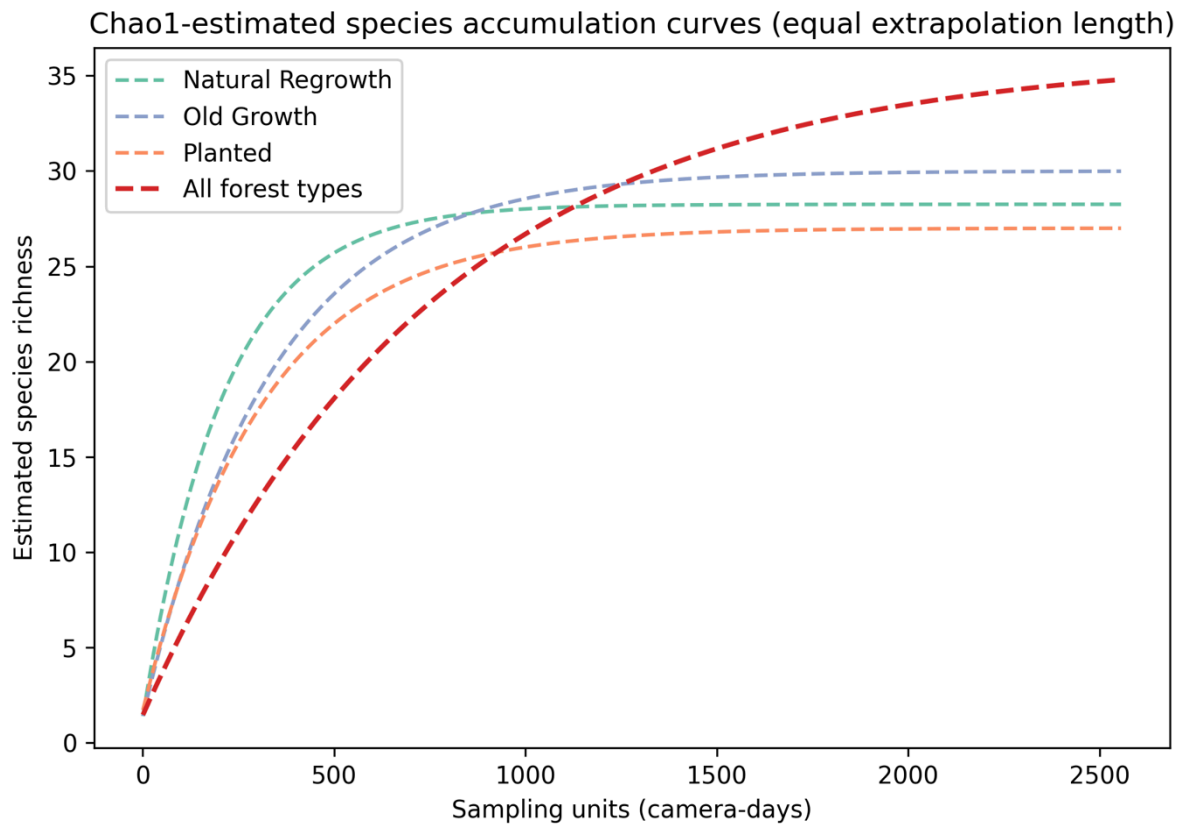


Figure 4: Chao1-estimated accumulation curves, showing the increase in cumulative mammal species as a function of increased sampling effort (Camera-days) between natural regrowth, old-growth and planted forest. In addition, a curve for all forest types combined

3.2 Observed species richness and abundance per forest type

The total number of mammal individuals recorded was different per forest type. Planted forests showed the highest number of individuals recorded during given sampling period. Old-growth forests showed intermediate values while natural regrowth forests showed lowest recorded individuals

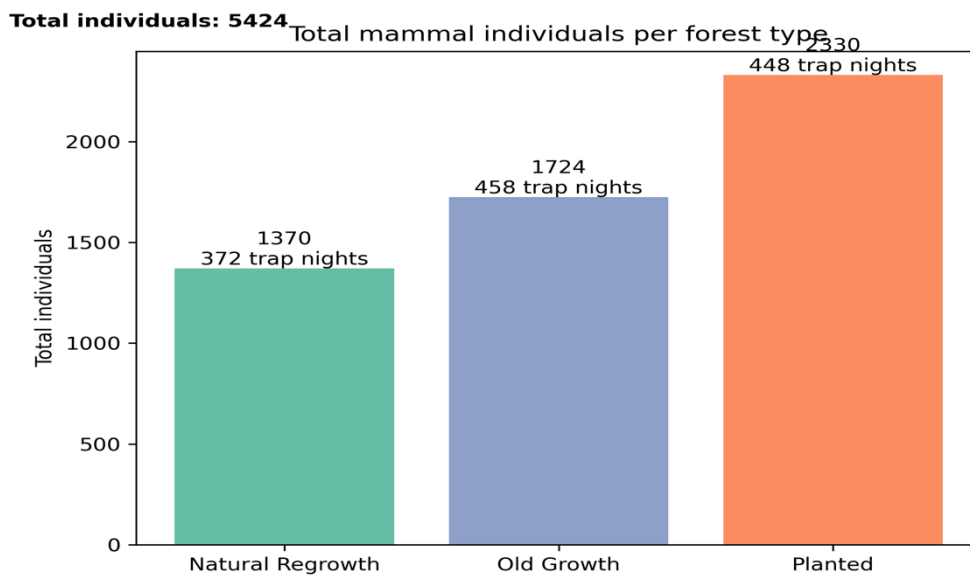


Figure 5: Total number of mammal individuals detected in natural regrowth, old growth and planted forests. Numbers are based on camera-trap observations with total individuals recorded and total camera trap days highlighted above the bars.

The total number of species detected between the three different forest types was also different for each forest type. Natural regrowth forest showed highest number of total species recorded. Old growth forests showed intermediate values with planted forests having the lowest amount of recorded species.

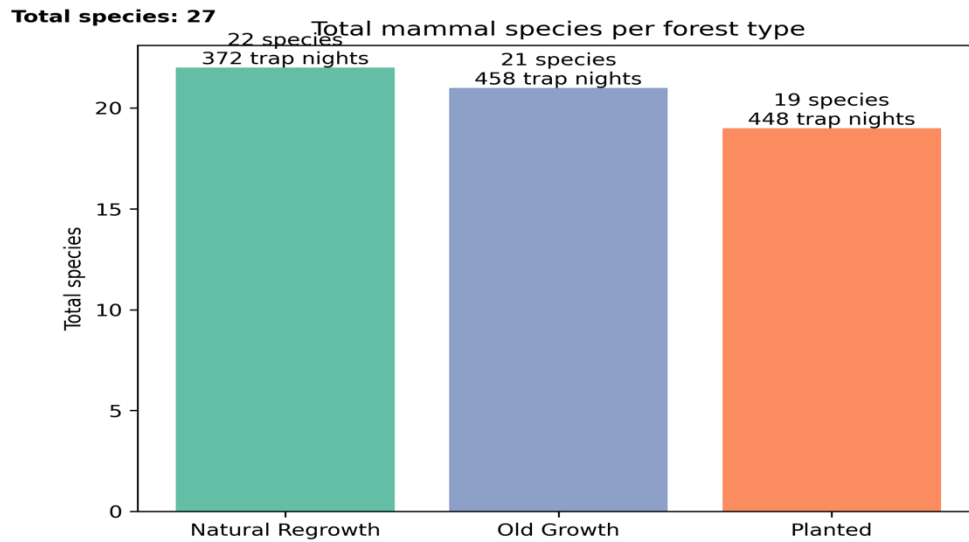


Figure 6: Total number of mammal species detected in natural regrowth, old-growth and planted forests. Numbers are based on camera-trap observations with total species recorded and total camera trap days highlighted above the bars.

3.3 Mammal activity

The relative abundance index (RAI) has different values between the three forest types. Planted forest showed highest RAI values. Old growth forest and natural regrowth followed and showed similar values. These values show the differences in mammal detection rates between the different types of forest.

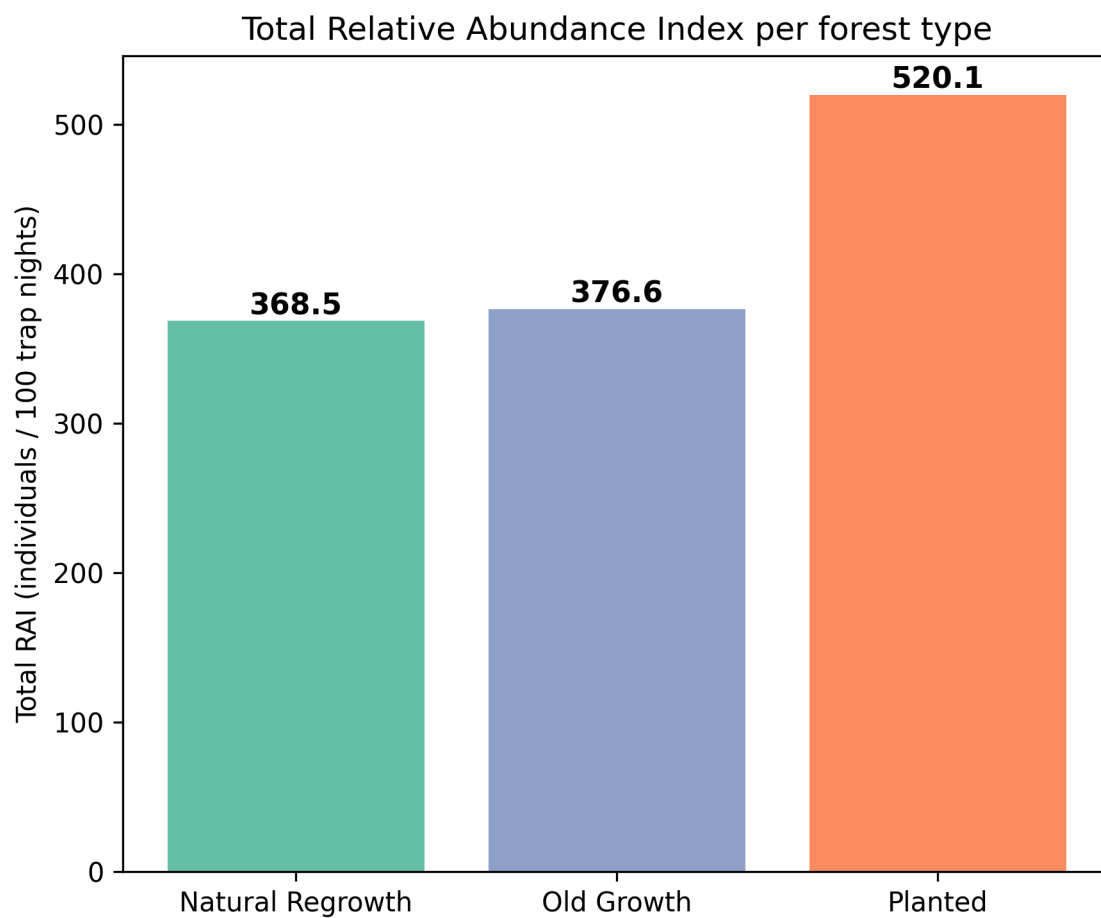
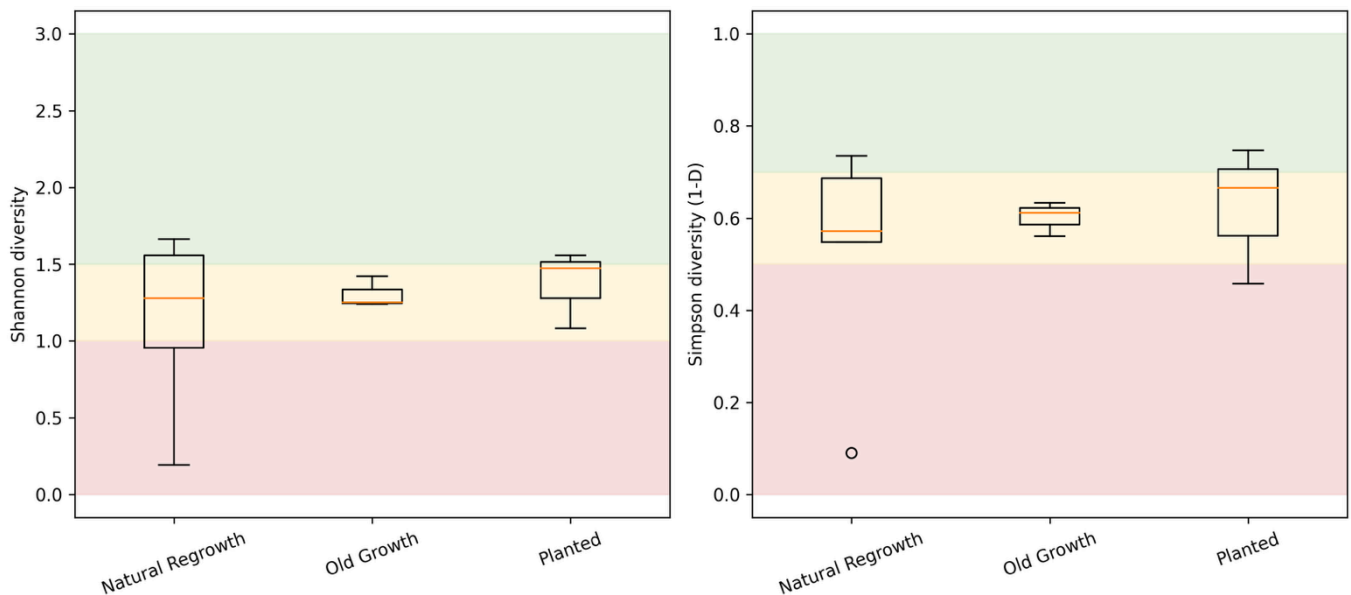


Figure 7: Total Relative Abundance Index (per 100 trap nights) for mammal detections in natural regrowth, old-growth and planted forest based on camera-trap data.

3.4 Community diversity and dominance

Shannon and Simpson indices varied between forest types. Planted forests showed relatively consistent values for both indices. Natural regrown forests showed more variability between sides. Old growth forests showed intermediate values with minimal variability between sites. Differences between forest types have been tested but showed no significant differences ($P < 0.05$).



3.5 Statistical analysis on ecological variables

Generalized Linear Mixed Models showed that understory had a significant effect on both richness and abundance. Also, elevation showed a positive effect on mammal abundance and richness. Leaf litter depth both on and off trail showed an effect on abundance, with off trail leaf litter depth showing a small effect on richness too. Furthermore, site level random effects showed to have a big effect on both abundance and richness.

GLMM Results: Mammal Abundance and Species Richness

Predictor	Mammal abundance	Species richness	Direction of effect
Understory density	*** (moderate), ** (high)	* (moderate)	Moderate density most favorable
Forest type (Planted vs Natural)	***	n.s.	Higher abundance in planted forest
Forest type (Old growth vs Natural)	n.s.	n.s.	No difference
Canopy cover	n.s.	n.s.	No effect
Elevation	***	*	Positive
Leaf litter depth (on trail)	***	n.s.	Positive
Leaf litter depth (off trail)	***	*	Negative
Random effect (site)	Significant	Significant	Strong site variability

*** $p < 0.001$ ** $p < 0.01$ * $p < 0.05$ n.s. = not significant

Figure 9: Summary of GLMM results showing the effects of ecological variables as predictors on mammal abundance and species richness. Significance levels are indicated as seen at the bottom of the figure

4 Discussions and conclusions

This research has looked at the composition, diversity and activity of mammals across old growth, natural regrowth and planted forests within Cloudbridge Nature Reserve. Camera trap data has been used to form species accumulation analyses, diversity indices and GLMM's. Together with the ecological variables that have been measured these give an insight on sampling completeness, species richness and abundance, mammal activity patterns and answer the main question about the influence of ecological variables on species richness and abundance, between the three different forest types found within the reserve.

The study shows that species richness is comparable between three different forest types. Mammal activity however was strongly different between forest types, showing notably higher values in planted forests. The overlap in observed and estimated species richness, seen in the species accumulation curve and the Chao1-estimated curve, indicate that Cloudbridge's secondary forests support a big portion of the mammal communities present in the old growth forests. This pattern is consistent with other tropical forest regeneration studies (Dunn, 2004). None of the curves showed to reach a full asymptote during the sampling period. However, continued increase and the higher values shown in the estimated species curves indicate that rare or low-detectability species remain under sampled (Colwell & Coddington, 1994; Gotelli & Colwell, 2001). Especially in the old-growth forests complex structure may restrict mammal movement and detectability (Mashintonio et al., 2022). Planted forests showed highest activity despite natural regrown forest showed highest number of species, indicating that reforestation strategies might influence how and which animals use the habitat (Sosibo et al., 2024). Furthermore, Shannon and Simpson indices were both calculated for each individual forest type and differences in diversity indices per forest type have been statistically tested for significant differences. No significant differences were found ($P=0.359$). This indicates that the secondary forest types are comparable in diversity with no significant differences found at this sample size (Chazdon et al., 2009).

Understory density showed to be a strong indicator of mammal abundance and richness. This might be an indication that habitat structure plays a key role in shaping mammal communities. Intermediate understory conditions showed higher diversity and activity. This finding aligns with the habitat heterogeneity hypothesis. It predicts that structural variability provides more niches and supports more species (Tews et al., 2003). The pattern is also consistent with the intermediate disturbance hypothesis. It predicts higher diversity under intermediate disturbance because early and late succession species coexist. (Bongers et al., 2009)

Elevation showed a positive effect on both abundance and diversity. This effect might be due to the higher elevation trails receiving less human disturbance and being closer to undisturbed primary forest. Elevation gradients in montane ecosystems are known to influence mammal communities due to differences in climate and habitat along gradients. (Bateman et al., 2010). Leaf litter depth showed mixed results, with off and on trail litter depth both showing positive effect on abundance. Only off trail litter depth indicated a small influence on species richness. These findings support

other studies that suggest leaf litter depth and its influence on structural complexity can influence mammal communities and behavior (Tews et al., 2003b; Cepeda-Duque et al., 2023).

Several limitations and errors may have had their influence on mostly the data collection part of this research. This influence ultimately has shaped outcomes. Firstly, camera traps were only placed on trails, leaving the possibility for trail avoiding species to be underrepresented. Also, the difference between public trails and research trails have not been taken into account, leaving room for human disturbance to have an influence on results. Secondly, a total of more than 10 people, at different times, were involved in the data collection, leaving room for errors and differences in methods resulting in possibly different numbers. Thirdly, differences in uptime of different cameras and technical and human errors regarding the cameras, made for uneven sampling sizes between forest types and individual sites which may have influenced results. Different structures in habitat between forest types may have limited detectability which can influence RAI values. Sampling period and ultimately size were insufficient leaving room for rare and elusive species to remain undetected, indicated by the accumulation curves not reaching a full asymptote. Lastly, environmental variables were measured once which means they may rule out seasonal variation.

Overall, the results show that mammal recovery within Cloudbridge is influenced more by habitat quality rather than forest regrowth stage alone, being influenced by small scale variables. This highlights the importance of maintaining structurally diverse habitats that are well connected to support mammal diversity and activity. Furthermore, these results indicate that secondary forest types within Cloudbridge are able to support mammal communities similar in richness to the old growth parts. However, habitat structure strongly influences how these mammals use their habitat. Maintaining a mosaic in forest structure with intermediate understory structure is likely to positively influence on diverse and active mammal communities. Retaining connectivity to old growth forest parts is important, especially at higher elevations. For monitoring, longer term, standardized camera-trapping with off trail sampling being added will increase understanding for these communities and how they recover. Including seasonal habitat variables would further increase the certainty of effects on abundance and richness. Future studies should increase sampling effort to improve detection of rare species, make use of off-trail camera sites to include trail avoiding species and reduce the influence of human disturbance. Long-term monitoring across forest types will provide stronger evidence of recovery and dynamics of mammal communities.

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6. Appendix

6.1 Appendix 1 Camera trapping protocol

Camera Trapping Best Practices (Video Mode)

1. Camera Setup & Handling

- Always power **OFF** the camera before inserting or removing **SD cards or batteries**.
- Mount cameras at 50 cm above ground level, aimed perpendicular to animal trails.
- Angle camera slightly **downward** to frame animals fully and **avoid sky exposure**.
- **Ensure** the camera is extremely **stable** - any wobble will ruin video quality.
- **Avoid** placing cameras facing **direct sunrise or sunset** to prevent glare or washout.
- Use video settings appropriate for your species (e.g., 20-30 sec clips, with short delay, medium-high sensitivity).
- Enable audio if animal vocalizations or ambient sounds are relevant to your research.

2. SD Card & File Management

- Power **OFF** before **removing** SD cards - hot-swapping can **corrupt** files.
- Use high-capacity, high-speed SD cards (**Class 10 / UHS-I or II**) - video files are large and demand fast write speeds.
- **Format SD cards** in-camera **before** each deployment to avoid errors and ensure compatibility.
- **Label** SD cards clearly (e.g., "CAM07_Aug04_2025") and keep a log for each.
- Back up data **promptly** - video files are more prone to corruption due to size.
- Handle cards with **care** - avoid moisture, static, or touching the **gold contacts**.



Figure 10: Page 1 of the camera trapping protocol

Camera Trapping Best Practices (Video Mode)

3. Camera Maintenance & Care

- **Clean** the lens and PIR sensor **gently** with microfiber cloth before deployment.
- **Inspect** housing seals and battery compartments for ants, mold, or rust - especially in humid/tropical environments.
- Use silica gel packs or moisture absorbers inside the camera housing where possible.
- **Check** for spider webs or debris on the lens and sensor area that could **obscure** video.
- Store cameras in a **dry**, shaded place when not in use.

4. Deployment Strategy (for Video)

- Target known trails, scent posts, or clearings where animal movement is **predictable**. (**Study dependant**)
- **Avoid** placing cameras near highly **reflective** surfaces, water, or constantly **moving** vegetation.
- Conduct a field **test** - trigger the camera yourself to check framing, focus, lighting, and motion detection.
- Record metadata: Camera ID, GPS location, Orientation (e.g., "facing SE")
Date/time, Deployment purpose, Video settings (resolution, length, delay)



Figure 11: Page 2 of the camera trapping protocol

Camera Trapping Best Practices (Video Mode)

5. Ethics & Safety in the Field

- **Avoid** disturbing animal behavior - no cameras directly at nests, dens, or water sources unless essential.
- Use no attractants or bait unless **permitted** by research protocols and local regulations.
- Be **discreet** and **respectful** of local people and property - seek permissions where necessary.
- **Secure** cameras with **locks** or camo cases in high-risk areas. - Bring gloves, rain gear, and a **basic repair kit** to **maintain** cameras in the field.

6. Before Leaving a Camera Site (Checklist)

- ☐ **Camera** is **stable** and **aimed correctly**
- ☐ Batteries are **full** or recently changed
- ☐ SD card is **inserted, formatted**, and verified
- ☐ Camera is powered **ON** and **LED** indicator confirms readiness
- ☐ A **test** video has been **recorded** and **checked**
- ☐ Field log **updated** with all **relevant info**



Figure 12: Page 3 of the camera trapping protocol

6.2 Appendix 2 Densiometer



Figure 13: Densiometer, used to measure canopy density at every camera location

6.3 Appendix 3 Clinometer

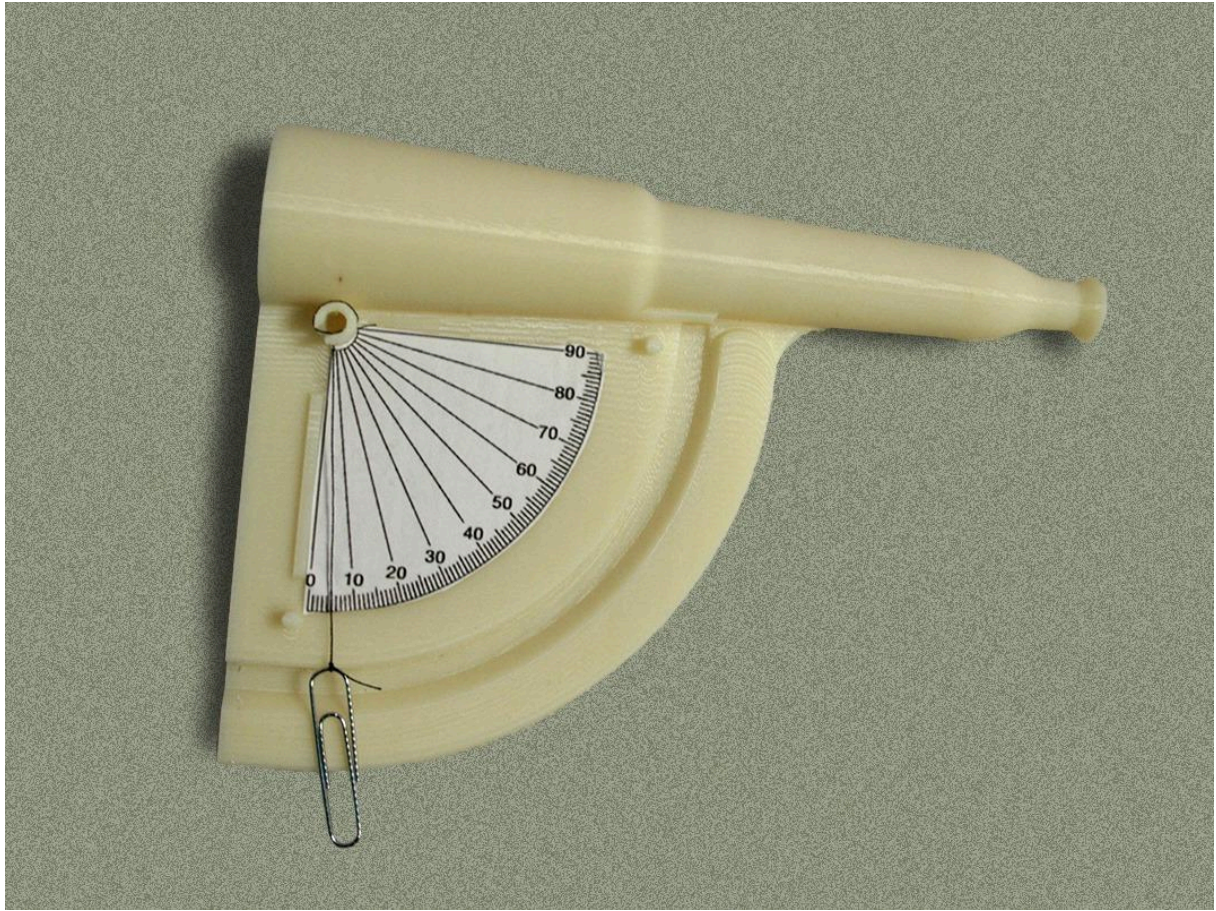


Figure 14: Clinometer, used to measure slope at every camera trap location