COMPARING THE EFFICACY OF CONVENTIONAL SURVEY METHODS TO EDNA IN A RAPID MULTI-TAXA SURVEY OF A TROPICAL RAINFOREST ECOSYSTEM

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KEYWORDS

conservation ecology; cryptic species detection; metabarcoding; rapid biodiversity assessment

ABSTRACT

Madagascar is globally recognized for its exceptional biodiversity and endemism yet remains severely under-sampled for many taxa. We evaluate the effectiveness of environmental DNA (eDNA) metabarcoding as a rapid, non-invasive method for surveying vertebrate biodiversity in the Makira Forest Protected Area (MFPA), comparing its performance to conventional surveys across a range of vertebrate taxa. eDNA sampling detected 158 OTUs across 18 sites, outperforming conventional surveys in birds (p = 0.000107), mammals (p = 0.000718) amphibians (p = 0.000725), reptiles (p = 0.000877) and ray-finned fish (p = 0.00788). We further examined the result for ray-finned fish by modelling species-accumulation curve asymptotes which supported this result. However, significant primer bias and amplification inconsistencies were observed, particularly in amphibian detections, and a high proportion of OTUs could not be resolved to species level due to taxonomic gaps in reference databases. We demonstrate, using species accumulation curves of our eDNA data and inventoried taxa lists of the MFPA, that the widespread practice of considering only resolved OTUs, rather than all unresolved OTUs, significantly underestimates biodiversity. This study underscores both the promise and current limitations of eDNA as a tool for tropical biodiversity assessment, specifically when compared to conventional sampling techniques. Combining eDNA and conventional survey methods increased species detection rates by 66.4%, highlighting their complementary strengths and reinforcing the value of integrated monitoring strategies for biodiversity-rich, data-deficient regions.

INTRODUCTION

Madagascar is renowned for both its high species richness and high rates of endemism, shaped by the island's complex geological history and continental isolation [1]. Classified as one of the world's 17 megadiverse countries, Madagascar is one of the world's eight 'hottest' biodiversity hotspots [2], with over 300 species of birds [3], 150 species of mammals [4], 600 species of herpetofauna [5], and 100 species of freshwater fish [6]. Madagascar is also unique due to its extremely high levels of endemism, with 50% of bird species, and 98% of reptiles, amphibians and mammals being endemic to the island [7]. While Madagascar has long been recognized as a conservation priority [8], acute deforestation has destroyed over 40% of its original forest cover since the 1950s, resulting in severe biodiversity decline and ecosystem instability [9].

The MFPA, located on the north-east coast of Madagascar, covers more than 372,000 Ha of the one of the largest remaining expanses of intact tropical rainforest on the island. Formally established in 2012, the MFPA forms part of the 98 strategic protected areas in Madagascar, providing connectivity between the Masoala and Marojejy National Parks. The MFPA is estimated to contain 112 bird species, 58 species of mammals including 17 lemurs [10], 68 amphibians [11], 60 reptiles [12], and 18 species of freshwater fish [13]. The MFPA also remains a top conservation priority due to the number of threatened species it contains, 46% of the total Malagasy Red Listed species according to IUCN [14]. Monitoring biodiversity in these forests is essential for assessing conservation priorities

and guiding protection efforts, yet conventional field surveys remain logistically challenging, time-intensive, and expensive, with limited capacity to detect rare or cryptic species.

As a form of non-invasive, high throughput ecological surveillance, eDNA metabarcoding analysis has revolutionized the field of biodiversity research by allowing the identification of invasive, cryptic (both visually and genetically) and undescribed species, with broad applications to understanding ecosystems[15-19]. The detection of DNA persisting in ecosystems can be used to provide information on species, populations, and communities, representing a significant breakthrough as a tool for ecologists and conservation policy making [20]. The benefits over other non-invasive sampling methods; such as cost effectiveness, time efficiency, scalability, and both comprehensiveness and equitability could be significant [21]. However, while the technical capabilities of eDNA are now well-established, less attention has been paid to how these tools can be best deployed to generate accurate ecological baselines datasets essential to informing conservation priorities, allocating resources, and evaluating policy interventions [22, 23]. In regions where biodiversity is both exceptional and understudied, establishing such baselines is critical for preventing extinctions and guiding protected area management.

Despite Madagascar representing a clear conservation priority, it remains a globally significant darkspot of biodiversity across multiple taxa [24, 25]; a point of serious concern for conservation policy in the face of anthropogenic pressures. Although previous research efforts in the MFPA focused on specific taxonomic groups such as carnivores and palms, significant data deficiencies of the park's overall biodiversity persist. In this eDNA metabarcoding study, we compare the efficacy of tetrapod eDNA analysis with conventional surveys completed by specialist taxonomists within the MFPA to produce updated biodiversity baselines. This study was completed as part of the broader "Search for Lost and Undescribed Species: A rapid, multi-taxon biodiversity inventory of Makira Natural Park, Madagascar," conducted from August 29th to September 9th, 2023. This study aims to evaluate and compare the effectiveness of eDNA metabarcoding and conventional surveys for assessing multi-taxa vertebrate biodiversity in a tropical rainforest, while identifying methodological limitations and opportunities to improve future biodiversity inventories.

METHODS

All fieldwork activities were conducted in accordance with the research permits issued by the Malagasy Ministry of Environment and Sustainable Development, outlined in the research permit 273/23/MEDD/SG/DGGE/DAPRNE/SCBE.Re of 09/08/2023, with specimen exports authorized by permit number 39 IN-EA10/MG23 of 10/13/2023.

2.1 Survey Site

All surveys and sampling were conducted from August 29 to September 9, 2023, in the Sahamatreha forest within MFPA, Madagascar (S 15°04'15.2", E 49°34'48.3"), 44 km northwest of Maroantsetra, at altitudes between 250–700 m. Designated as 'Af' under the Köppen climate classification system, the area is characterized by tropical rainforest with consistently high temperatures and significant rainfall throughout the year, with no distinct dry season and extensive humid forest [26]. Locations and survey distances of all survey techniques were recorded using Garmin inReach Explorer+.

2.2 eDNA Analysis

2.2.1 Sampling

The 20 eDNA sampling locations were selected in river or stream environments (precise locations being determined by water flow dynamics) [27] (Figure 1). At each site, three independent samples were collected from the left bank, centre, and right bank. Sampling progressed upstream, starting from

the most downstream location, with all waterways accessed on foot. Water was collected at the surface using a dedicated sampling bag held upstream, with the sampler downstream to avoid contamination. Gloves were worn, and sediment disturbance was minimized. The bag was sealed and shaken for 30 seconds. For sediment-heavy samples, water was allowed to settle for one minute. 60 mL of water was drawn into a syringe, attached to a filter, and pushed through. This was repeated until the filter clogged or the entire sample was processed. Air was then used to expel residual water. A preservative syringe was attached to the filter inlet, and Longmire's solution was slowly injected. Both ends of the filter were capped with Luer Lock caps, and the filter was sealed in a specimen bag. Each sample's Barcode, ID, date, GPS coordinates, volume filtered, habitat characteristics, and sampler information were logged. A field negative control was included at the site. This control consisted of purified tap water, processed identically to field samples. Site photographs and observations on flow, sedimentation, and weather were also recorded.

Figure 1: Survey design and preparation of eDNA sampling in the MFPA. Map of eDNA survey sites (A) with map of Madagascar (inset). eDNA sampling equipment (B). Sample sites (C-E) showing range of lotic ecosystems sampled. MAK#2 (C), MAK#8 (D), MAK#19 (E)

2.2.2 OTU Extraction & Amplification

DNA was extracted from 0.8 µm filters using the DNeasy Blood and Tissue Kit (Qiagen, 1001 Marshall St, Redwood City, CA 94063; https://www.qiagen.com/us), with proteinase K added directly to filter housings. Extracts were purified with the DNeasy PowerClean Pro Cleanup Kit (Qiagen, 1001 Marshall St, Redwood City, CA 94063; https://www.qiagen.com/us). Negative controls (molecular-grade water) were included to monitor contamination. DNA concentration was measured using a Qubit fluorometer (Thermo Fisher Scientific 340 El Pueblo Rd, Scotts Valley, CA 95066, https://www.thermofisher.com/us). Replicate PCRs targeted the 12S rRNA gene of freshwater vertebrates using primers F1 (5'-ACTGGGATTAGATACCCC-3') and R1 (5'-TAGAACAGGCTCCTCTAG-3') and 16Smam1 5'- CGGTTGGGGTGACCTCGGA-3' and 16Smam2 5'- GCTGTTATCCCTAGGGTAACT-3' primers [28]. A blocking primer minimized non-target human DNA amplification (12S_V5_blkhum; [29]). Positive and negative controls (synthetic sequences and PCR-grade water) accompanied each plate. Amplification was visualized using gel electrophoresis.

2.2.3 Sequencing

Amplified PCR replicates were pooled, purified with magnetic beads, and prepared for sequencing using Illumina's dual-index protocol (Illumina, Inc., 5200 Illumina Way, San Diego, CA 92122; https://www.illumina.com). Libraries were sequenced on an Illumina MiSeq using a V3 600-cycle kit. Demultiplexing used bcl2fastq based on index tags. Paired-end reads were merged with USEARCH [30], requiring 80% overlap agreement. Primers were trimmed with cutadapt [31], and sequences were quality-filtered with USEARCH (error rate ≤0.01). Unique sequences were dereplicated and denoised with UNOISE to identify zOTUs [32]. Taxonomic assignments were made via blastn searches against the NCBI nucleotide database, with thresholds of 99%, 97%, and 95% for species, genus, and higher-level identifications. Assignments were cross-checked with GBIF occurrence data to ensure local relevance, adjusting taxonomy as necessary. zOTUs were clustered into OTUs using USEARCH UPARSE and custom pipelines to reduce intra-specific variants while preventing over-clustering [33]. Chimeras were removed, and OTU tables were generated at a 97% identity threshold. OTUs were annotated with IUCN Red List status and GRIIS invasive status. Low-abundance OTUs (<20 reads per sample) and those assigned to humans or domesticated mammals were excluded.

2.3 Ornithological Surveys

A range of standard ornithological survey techniques were used. Data collection coincided with the pre-breeding period for most Malagasy forest birds and included direct observations using eBird Mobile and mist-netting (Figure 2). Observers completed point counts along non-standardized transects from 6:00–11:00 when birds were most vocally active and least mobile, for seven days. This reduced the chance of repeated contact [34, 35].Twenty mist nets (5 of 12m and 15 of 6m) were installed near streams and dense vegetation [36]. Nets were deployed from 5:30–17:30 daily, monitored every 30 minutes, and captured birds were photographed, weighed, banded with numbered aluminium rings, and released. Bird calls and photographs were recorded for threatened or notable species and uploaded to the eBird and Macaulay Library platforms.

2.4 Mammals Surveys

Mammal surveys were conducted using a combination of diurnal and nocturnal Visual Encounter Surveys (VES) along line transects as well as systematic searches, following methods adapted from Goodman et al. (1997) [37] and tailored for the terrain and target taxa. The primary transect was a pre-existing footpath that followed the altitudinal gradient of a canyon. Transects were surveyed twice daily 07:30–11:00 and 14:30–17:00 and again at night between 18:00–21:00. Nocturnal surveys utilized low-intensity torches to detect eyeshine, particularly for lemurs. Observers recorded all visual and auditory detections, including species ID, number of individuals, behavior, distance, height, and GPS location. In addition to transects, systematic searches were carried out in habitat features likely to harbor lemurs, such as areas with abundant fruiting trees, signs of feeding, or recent vocalizations using flexible routes based on topographic and ecological cues. Mist netting was conducted at two sites for *Chiroptera spp*. detection. Nets were set from 16:00–21:00 and 3:00–5:30.

2.5 Ichthyological Surveys:

Ichthyological survey sampling sites were chosen based on accessibility, proximity to the Sahamatreha River and its tributaries, and historical records of target species. Additional considerations included habitat diversity, hydrological features, and input from local fishers on species presence. Seine netting was completed in areas of low depth and velocity, additionally shrimp traps were deployed and repurposed to capture fish (Figure 2). A microprocessor SUM unit (Electro Fisher Company Co. Ltd., 15 Bialostoczek St, Bialystock, BIA 15869, Poland; https://www.electro-

fisher.net) was used in fluvial stretches of high turbidity, high velocity and areas of deeper bathymetry to induce "electronarcosis" and enabling capture of immobilized fish [38].

2.6 Herpetological Surveys

Surveys followed standard protocols [39] and included pitfall traps, standardized transects, and opportunistic searches. Eleven pitfall traps were installed 10m apart, connected by a 50cm high plastic barrier to guide animals into the traps. Traps were checked twice daily, at 05:30 and 16:30. Standardized transects were between 200m and 250m and were designed to cover diverse habitats. Point counts were conducted at regular intervals of 10m, during both day (8:00–15:00) and night (18:30 onwards) using headlamps. Transect surveys were supplemented with opportunistic searches which were completed at likely refuges, such as under bark, in leaf axils, and inside hollow logs. Species were identified according to the taxonomy proposed by Glaw & Vences [40].

Figure 2: Selection of conventional survey techniques employed. Electrofishing (A), camera trapping of Eulemur albifrons (f.) (B), herpetofaunal pitfall trapping (C); *Athene superciliaris* in a mist net (D).

2.7 Inferential Statistical Analysis

Statistical analysis was conducted in R (Version 4.4.1)[41]. To standardize results, sample sites across both categories (eDNA and Visual) were grouped according to their GPS coordinates to allow paired comparisons. Data was cleaned, with species repeats at sites by either sampling type removed and eDNA classifications of monotypic genera assumed to be the respective species, with all subsequent eDNA analysis completed using distinct OTUs, rather than species classifications to avoid unjustifiable merging of OTUs that mask cryptic species detections, primer-specific biases, and errors in reference databases. We employed this protocol throughout the analysis unless otherwise stated.

To evaluate the species richness at each of the 17 sampled sites, we chose the Shannon Diversity Index, instead of other metrics for α-diversity, and used read-count frequencies of distinct OTUs as a

proxy for abundance [42], given our data was zero-inflated and contained taxonomically unresolved read counts which may be non-mutually exclusive. OTU read-count was pooled across both the 12S and 16S primers to generate a conservative estimate of species richness, and OTUs detected by both primers were deduplicated to avoid artificial inflation of species richness estimates. Prior to analysis, the dataset was also cleaned to remove ambiguous or non-target sequences, and samples with zero read-counts were excluded. The Shannon Diversity Index (H') for each sample was computed manually using the formula $H' = -\Sigma(p_i * \ln p_i)$ where p_i is the proportional OTU abundance in each sample [43].

To explore taxonomic primer biases for both the 12S vertebrate and 16S mammal specific primers, we computed the mean detections by both primers across the 17 sample sites for taxa that were detected by both; amphibians, mammals and ray-finned fish. We used distinct OTUs rather than solely sequences resolved to species level to reduce the influence of reference database limitations and to more accurately capture primer-specific amplification bias. Prior to analysis, statistical testing for normality visualised using a Q-Q plot suggested our dataset was non-parametric, therefore we used non-parametric tests for significance in this analysis. Wilcoxon's Signed Rank tests were used for each taxon to evaluate the significance in differences in detection frequencies between the two primers, which was conducted using the "stats" package in R.

We further analysed the data to visualise the proportion of OTUs resolved to species-level and those that were unresolved to evaluate the effect of GenBank library coverage on effective eDNA detection. Total OTU detections by taxa were computed using both unresolved and resolved sequences and pooled across both the 12S vertebrate and 16S mammal-specific primers, whilst unresolved OTUs were meaned for taxa identified by both primers to provide a conservative estimate of unresolved OTUs, with error bars computed using standard error by the "stats" package in R.

We used a similar approach in defining OTUs by site, to evaluate the efficacy of eDNA in comparison to visual surveying techniques across all taxa. Data cleaning occurred to remove duplicated species at sites detected across both 12S vertebrate and 16S mammal primers, and occasionally by the same primer. The MAK#17 eDNA sample was removed from the analysis due to its exclusion from sequencing, and across taxa the MAK#1 sample was included due to its sequencing by the 16S mammal primer. The total number of OTUs detected by eDNA were calculated as above, as the total number of resolved OTUs and the meaned number of unresolved primers across both the 12S and 16S primers. For both eDNA and visual data, the 'expected' number of detections was calculated as the proportion of focal taxa constituting the total inventoried species in the MFPA (n = 316), scaled to the sample size for eDNA (n = 83) and visual (n = 125) surveys. The difference to which is displayed in Figure 6. Prior to analysis, statistical testing for normality visualised using a Q-Q plot indicated our dataset was non-parametric, therefore we used the non-parametric Wilcoxon's Signed Rank test to evaluate levels of significance in difference between our eDNA and visual datasets, conducted by the "stats" package in R.

To estimate total taxon richness in the survey area, and compare the efficacy of eDNA as a survey method compared to conventional techniques, we used Michaelis-Menten functions to fit asymptotes on the species and OTU accumulation curves using the "vegan" package in R. Two case studies were used. First, we selected amphibian detections to evaluate the number of taxa/OTUs in the survey area incorporating both resolved and unresolved OTUs. A Michaelis-Menten model was fitted to the SAC which incorporated 1,000 bootstrapping permutations to generate confidence intervals and estimate asymptotic richness. Secondly, to evaluate the efficacy of eDNA as a survey method in comparison to conventional techniques we used ray-finned fish detections resolved to species-level in both datasets. As before, we used a Michaelis-Menton model to fit an asymptote to the SAC which incorporated 1,000 bootstrapping permutations for both datasets to generate confidence intervals. To quantify the

survey effort required to achieve a given proportion of asymptotes, we extracted the predicted number of survey hours detecting 95% of the asymptotes.

RESULTS

eDNA analysis of three water samples for each of the 19 sites sampled in the MFPA detected a total of 158 distinct Operational Taxonomic Units (OTUs) and 265,154 reads, using amplification by the vertebrate specific primers: F1 5'- ACTGGGATTAGATACCCC-3' and R1 5'- TAGAACAGGCTCCTCTAG-3' [28]. A comparison of the alpha diversity of each site was inferred using the Shannon Diversity Index calculated from the vertebrate OTU dataset and is visualised in Figure 3 [43]. eDNA metabarcoding analysis detected a mean Shannon Index (*H'*)across sites of 1.58 ± 0.178 with significant variation in species diversity across the 19 sites, with a range of Shannon Index values (*H'*) between 0.379 (MAK#18) to 2.83 (MAK#3), with OTU evenness inferred from the read counts of OTU's identified to species or genera level. Figure 4 indicates a significant difference in the mean number of species detected using the two primers, with a difference approaching statistical significance for detection of ray-finned fish ($W = 19$, $N = 17$, $p = 0.0890$). Wilcoxon's Signed Rank tests on the other classes report no significant difference in detections by the vertebrate and mammal primers in both amphibians ($W = 42$, $N = 17$, $p = 0.187$) and mammals ($W = 28$, $N = 17$, $p = 1.00$), however we observed a large difference in mean detections of amphibians by the vertebrate primer (3.82 ± 0.456) and the mammal primer (6.44 ± 1.34). However, the lack of significance in efficacy differences by both primers across taxa suggests that differences in taxa-specific amplification have resulted from a lack of primer specificity.

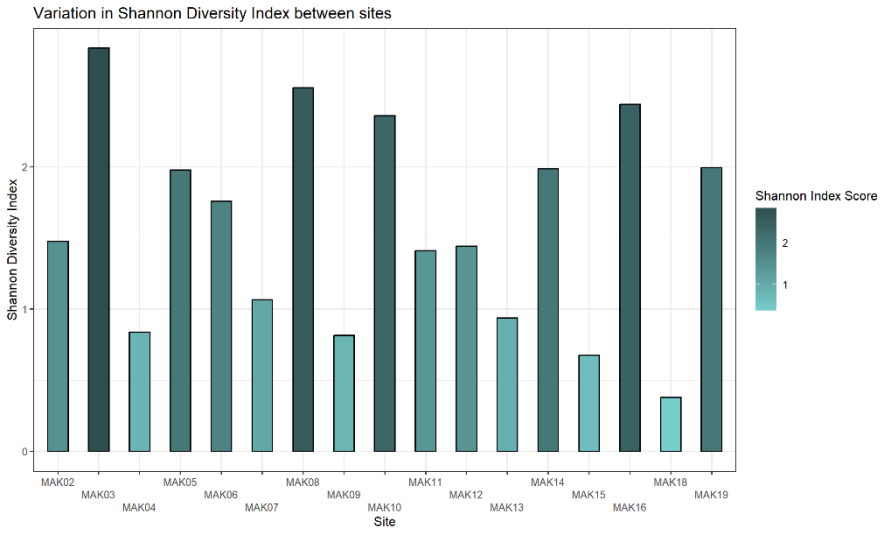

Figure 3: Variation in Shannon Index (H') between sites detected by eDNA. OUT read-count was used as a proxy for abundance, and distinct (resolved & unresolved) OTUs were pooled across both primers.

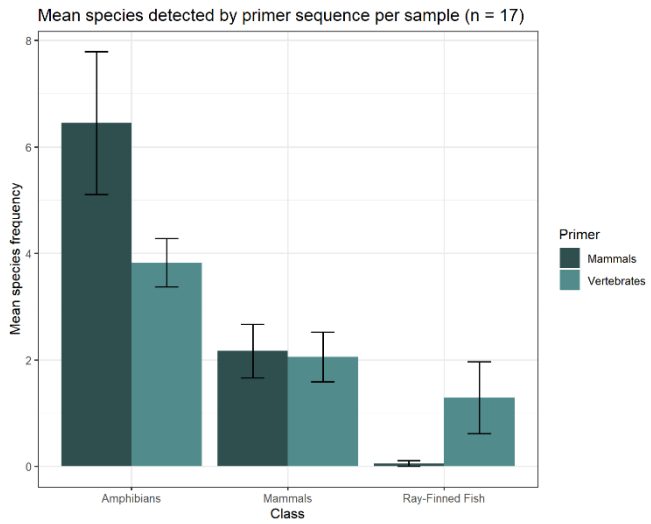

Figure 4: Mean species detected by each primer used, by taxa. Wilcoxon Signed Rank: Amphibians ($p > 0.05$), Mammals ($p > 0.05$), Ray-Finned Fish ($p > 0.05$). Error bars are standard error.

We also found that eDNA analysis of samples detected a significant number of OTUs that were unable to be identified to species level, particularly within amphibians, as displayed in Figure 5. A total of 41 unidentified 12S fragments were detected by the vertebrate primer, and 27 unidentified 16S fragments were detected by the mammal primer. A mean of 20.5 ± 2.5 unidentified amphibian OTUs were observed, alongside 13 unidentified bird OTUs, 3.5 ± 0.5 unidentified mammal OTUs, 3.5 ± 3.5 unidentified ray-finned fish OTUs and 0 unidentified reptile OTUs, averaged across the use of both

primers, indicating that there remain significant unidentified taxa in this dataset, possibly due to poor quality GenBank library coverage across these Malagasy taxa.

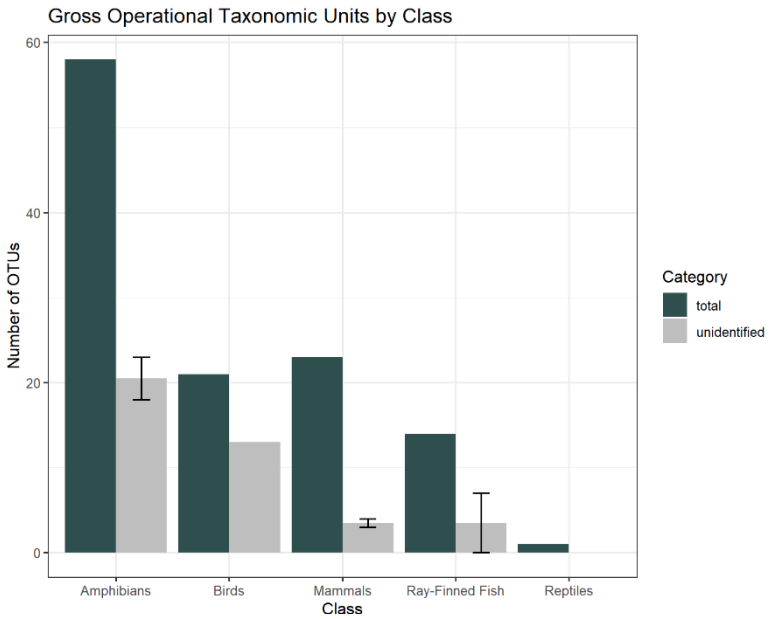

Figure 5: total OTUs (blue), and those unidentified to species level (grey). Error bars are standard error (calculated using both primer datasets for amphibians, mammals, and ray-finned fish).

Figure 6 depicts the mean adjusted difference in species identifications by eDNA sampling and visual techniques from published inventories of the MFPA (n_{total} = 316)[10-13, 44] Expected observations were calculated using taxonomic ratios of published data (visual n_{total} = 125, eDNA n_{total} = 83), and the difference between observed observations is presented by taxa in Figure 6 with the zero line indicating 100% efficacy. Sample sites are treated as pseudo-repeats. Analysis using the Wilcoxon Signed Rank test indicate that eDNA metabarcoding is therefore significantly more effective at detecting all taxa analysed in this study. eDNA was more effective at detecting amphibian taxa (W = 0, N = 15, p = 0.000725); with eDNA detecting a mean difference of -11.5 ± 1.03 species, whilst visual surveys detected a mean difference of -24.9 ± 0.696 species in comparison to the scaled inventoried taxa ratios for the MFPA. eDNA sampling was also more effective at detecting reptile taxa (W = 0, N = 14, p = 0.000877), with eDNA a mean difference of -15.6 ± 0.0762, in comparison to visual surveys (-21.9 ± 0.294), from published inventories. Ray-finned fish detections were also significantly higher for eDNA than conventional surveys (W = 1.00, N = 10, p = 0.00788), with eDNA detecting a mean difference of -3.84 ± 0.405 species, in comparison to visual surveys (-6.42 ± 0.3). eDNA was also significantly more effective at detecting birds than visual surveys were (W = 6, N = 18, p = 0.000107). eDNA surveys detected a mean difference of -27.9 ± 0.448 species, compared to -34.5 ± 1.34 species by visual surveys, from the scaled inventoried taxa of Makira. eDNA was also significantly more effective at detecting mammals than visual surveys were (W = 0, N = 15, p = 0.000718). eDNA detected a lower mean difference of -12.8 ± 0.48 in comparison to visual surveys (-21.9 ± 0.00). When considered together, the use of eDNA increased overall species detection rates by 66.4% in comparison to the use of visual surveys alone, underscoring the complementarity of the two methods.

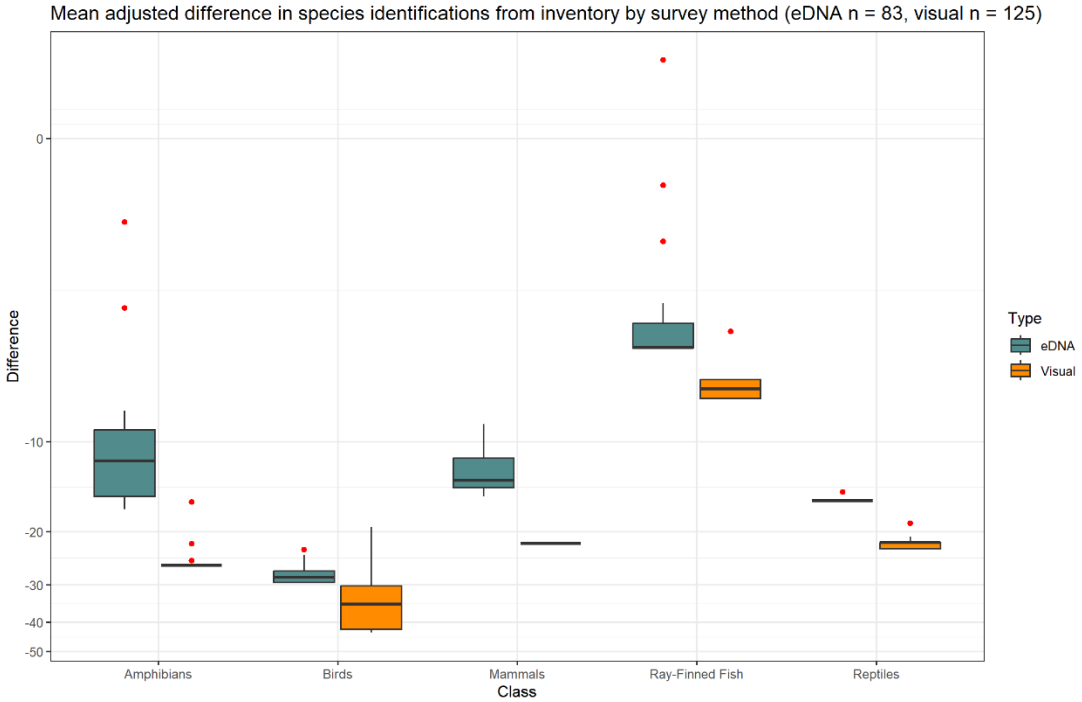

Figure 6: Mean difference between observed and expected species identifications, standardized to sample size, by survey method. Wilcoxon Signed Rank: Mammals ($p < 0.01$), Amphibians ($p < 0.001$), Reptiles ($p < 0.001$) Ray-Finned Fish ($p < 0.01$) Birds ($p < 0.001$); Y axis is pseudo log transformed with outliers in red.

Figure 7 evaluates the efficacy of eDNA versus conventional ichthyological surveys in detecting ray-finned fish in the MFPA. eDNA detections were conservatively defined as OTUs identified to species level, and Figure 7 presents the bootstrapped species accumulation curves of both eDNA and conventional methods. When standardised to cumulative person hours, eDNA methods detected species at a rate of 0.41/hour compared to 0.03/hour using conventional survey techniques, indicating an almost 15-fold increase in efficiency from our sampling. The modelled asymptote of the eDNA sampling reached 23.3 species, a value close (129%) to the known inventoried ray-finned fish of the MFPA (18) [13]. On the other hand, the modelled asymptote of the conventional survey reached 9.2, just 51% of the inventoried species list. We additionally report that the extrapolated SAC model for eDNA had a K-value of 7.05, and that 134 cumulative person hours would be required to detect 95% of asymptotic richness, whilst the extrapolated SAC model for conventional surveying had a *K*-value of 69.8, and would require 1,327 cumulative person hours to detect 95% of the asymptotic richness, itself just 51% of the known richness of the MFPA, indicating eDNA's 10.0 fold increase in efficiency in detecting ray-finned fish in comparison to conventional methods in this survey.

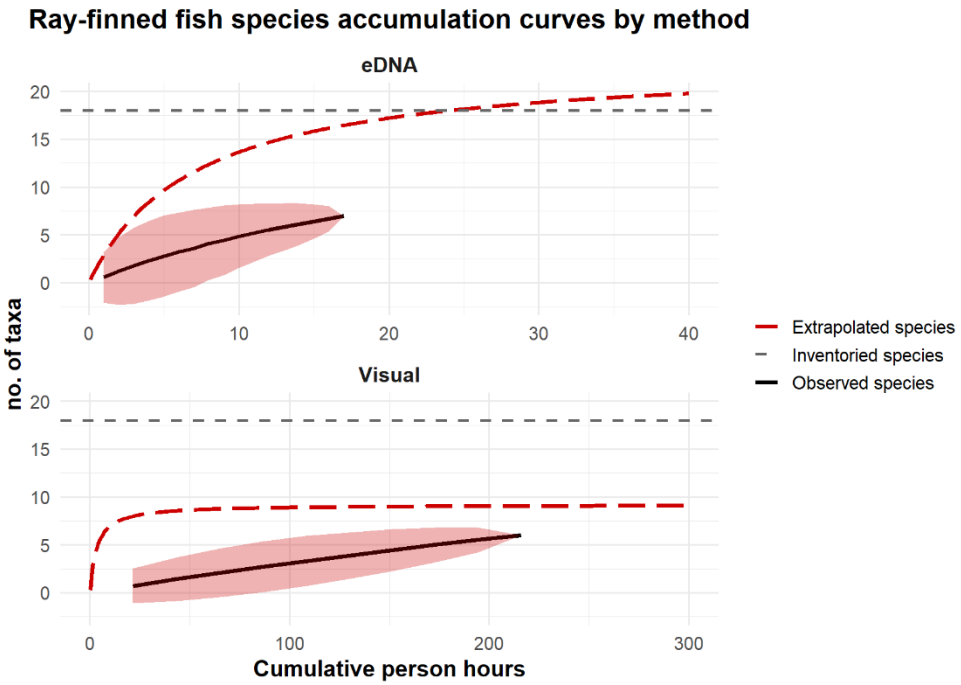

Figure 7: Accumulation curves for eDNA (top) and conventional surveys (bottom) of ray-finned fish. The detections of species were randomised 1000 times to generate confidence intervals (red shading). Asymptotes were modelled using a Michaelis-Menten model (red). Total inventoried ray-finned fish species of the MFPA (18) displayed for comparison (grey).

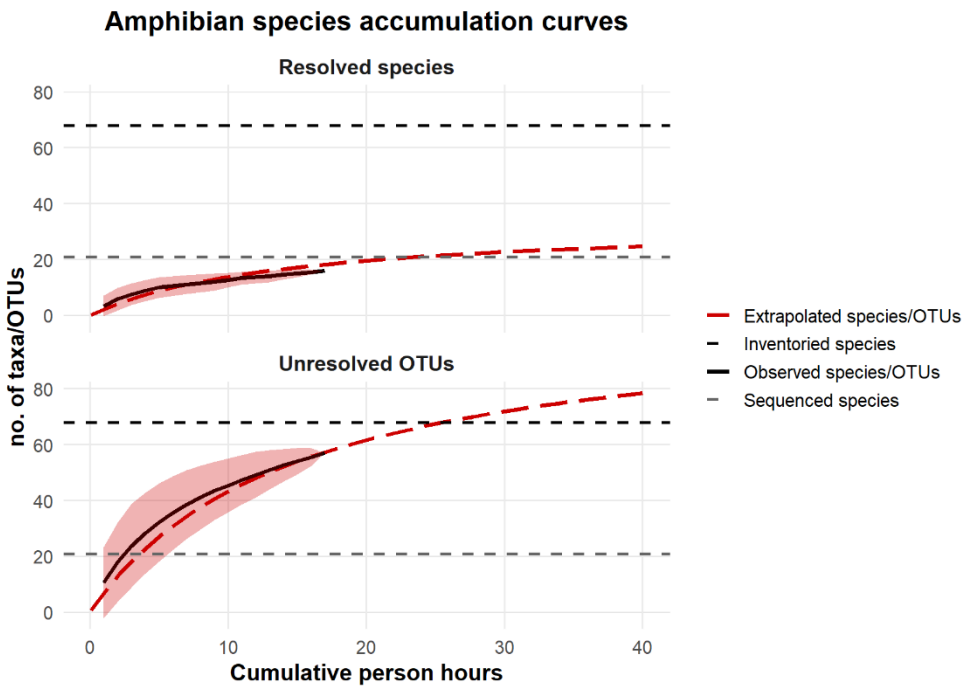

Figure 8: Accumulation curves for eDNA amphibian detections. Detections resolved to species (top) and unresolved total OTUs (bottom). The detections of species and OTUs (black) were randomised 1000 times to generate confidence intervals (red shading). The asymptotes (red) were modelled using a Michaelis-Menten model. Total inventoried amphibian species (68) from MFPA (black), and amphibian species sequenced and available in GenBank (21) from MFPA (grey) for comparison.

The result presented in Figure 5 is further supported by Figure 8 which presents bootstrapped species accumulation curves for the eDNA detection of amphibians, across our 17 samples, comparing the efficacy of defining taxa using a resolved-to-species approach, or an unresolved OTU approach. The modelled asymptote of the assigned species reached 33.5, a value close to the 21 sequenced species present in the MFPA, but 2.0 times lower than the MFPA amphibian species checklist [11]. On the other hand, when treating all OTUs detected by both primers as independent, the modelled asymptote was much higher than the regional checklist (68) at 107.7 species, indicating that a substantial proportion of amphibian diversity in the MFPA remains taxonomically unresolved in current GenBank databases, and conservatively defining eDNA detections as resolved-to-species OTUs, will significantly underestimate taxonomic diversity. However, we report that both extrapolated SAC models had similar *K*-values of 14.1 and 14.9 hours, with estimated effort to reach 95% of asymptotic richness being 269 hours and 284 hours for assigned species and un-assigned OTUs respectively, indicating significant survey effort is required for full species richness detection.

DISCUSSION

Comparative Effectiveness of eDNA vs. Conventional Surveys

Efficacy evaluation of our eDNA metabarcoding protocol in direct comparison to conventional survey methods, quantified using gross species detections, observed significant taxa-specific efficacy variation, with eDNA displaying a higher efficacy than conventional survey techniques across all taxa (Figure 6). The analysis revealed that eDNA metabarcoding was significantly more effective than traditional transect surveys at capturing bird, amphibian, reptile, fish and mammal biodiversity. The higher efficacy result for ray-finned fish was further supported by extrapolations of species accumulation curves (Figure 7), which highlighted a much more accurate reflection of inventoried species in the MFPA by the extrapolated asymptotes of eDNA analysis in comparison to conventional electrofishing and seine netting. Our finding that eDNA metabarcoding is more effective at detecting herpetofauna and ray-finned fish specifically is consistent with previous research [45-47], although our result for other taxa such as birds and mammals may be due to weaknesses in conventional survey design on this project. These findings highlight the particular strength of eDNA in sampling cryptic or elusive taxa, especially in environments where conventional techniques are likely to under-detect true species presence.

Additionally, we observed sampling bias in conventional sampling techniques due to variation in sampling effort. However, this outperformance in capturing diversity by eDNA is due to a number of issues with conventional survey techniques, primarily a high frequency of false negatives. False negatives in conventional survey techniques are elevated by a number of environment-level and species-level characteristics. Environment-level challenges include habitat accessibility, weather variability, and climatic variables [48], whilst species-level challenges associated with conventional survey techniques include behavioural attributes, difficulty in identifying genetically and visual cryptic species, and low population densities, all of which eDNA metabarcoding analysis is more robust to detect [22, 49, 50]. Integrating eDNA with conventional survey techniques increased species detection rates by 66.4%, demonstrating that these methods are not necessarily interchangeable but highly complementary. Together, they provide a more comprehensive picture of biodiversity, particularly in complex, under-sampled ecosystems like the MFPA.

Species accumulation curves for ray-finned fishes showed that both our eDNA and visual sampling did not reach an asymptote suggesting that additional effort would yield new species detections. This finding reinforces the value of continued sampling for tropical freshwater fishes in complex environments like the Makira plateau. We were unable to generate comparable curves for other taxa due to insufficient site-specific data on conventional survey effort, which was not tracked at the level of robust individual sites. As this was a multi-taxa rapid inventory, we nonetheless used all available detection data from these groups to assess relative survey effectiveness and biodiversity patterns.

However, our species accumulation curves of amphibians presented in Figure 8, indicate that treating unresolved OTUs as distinct taxons, yielded a more accurate approximation of the total described species in the national park. Conversely, evaluating resolved OTUs significantly underestimated the total alpha richness of the site. This conclusion suggests that whilst many papers conservatively exclude unresolved OTUs for ecological analyses, such approaches may acutely underestimate and potentially compromise the accuracy of biodiversity assessments, that feed conservation planning. Therefore, whilst eDNA may in some cases outperform conventional survey methods, the treatment of unresolved or resolved OTUs may skew richness estimates, with current conservative practices being inherently flawed.

Site-Specific Variation in Species Diversity

Detected differences in alpha diversity of almost ten-fold, quantified using the Shannon Diversity Index, supported our expectation of significant site-specific differences in diversity. Given sample sites were located within the same watershed system, differences in alpha diversity are unlikely to be due to high true beta diversity. In lotic environments, eDNA concentrations exhibit high spatiotemporal variability as eDNA moves downstream from the point source in a complex plume [51, 52]. Our finding suggests eDNA's sensitivity to a number of biotic and abiotic environmental variables and possible sampling bias. Spatial eDNA heterogeneity in lotic environments is linked to factors affecting eDNA dispersion including water flow conditions, temporal variation, and vegetation structure [53, 54] which varied considerably across the 19 sites we sampled (see Figure 1C-E). Additionally, eDNA degradation is a major factor affecting detectability at the spatial and temporal scale and curtails the power of spatial and temporal inferences drawn from analysis [55]. Degradation is affected by a number of spatially heterogenous variables including UV-B levels, water pH, and temperature [56], measurements of which should be incorporated into reporting of eDNA sampling to allow environmentally driven variation to be evaluated. Furthermore, the presence of naturally occurring proteases and compounds that reduce the accuracy of eDNA analysis by interfering with PCR analysis, that includes tannins, humic acids, heme, and other enzymatic inhibitors significantly impact eDNA detection efficacy [57, 58]. We used an inhibitor removal kit to purify samples prior to PCR amplification and minimise inhibition in our samples, alongside a blocking primer to minimise non-target DNA amplification, and would encourage incorporation of inhibitor and non-target nucleotide removal techniques during eDNA refinement processes. Our finding of significant unexplained variation in alpha diversity across sites with similar macro-ecological characteristics suggest that understanding variables leading to spatial heterogeneity in eDNA dispersion and degradation are essential in refining models for upstream species localisation and abundance estimation, particularly in the context of cryptic and rare species.

Taxonomic Resolution and Data Gaps in Reference Libraries

A key limitation observed in this study was the high number of unidentified OTUs, particularly in amphibians. While eDNA metabarcoding offers a promising approach for species detection, its efficacy is ultimately constrained by the completeness and quality of reference databases [59]. In this study, a substantial proportion of OTUs could not be assigned beyond higher taxonomic levels, due to poor representation of Malagasy taxa in GenBank. Such gaps in reference libraries hinder the resolving power of PCR analysis, and additionally the identification of potentially new species. For example, we detected two distinct sequences belonging to the monotypic *Galidia* mongoose genus, with the unresolved sequence containing two point mutations in the target region, suggesting issues with reference libraries or a possible undescribed species detection. In comparison, the 16S mammal-specific primer duplicated detections of both *Boophis englaenderi* and *Guibemantis liber* with small point-mutation differences between the sequences and resolved them to species level. Evaluating

possible undescribed species detections and duplicated resolved species detections is made significantly more challenging by poor reference libraries.

Addressing these challenges will require targeted efforts to expand reference libraries, including voucher-based sequencing of Malagasy vertebrates. Historically, extracting DNA from museum specimens has been challenging due to degradation over time. However, recent advancements in DNA extraction and sequencing technologies have significantly improved the recovery of genetic material from such samples [60, 61]. These developments enhance the potential to enrich reference databases with sequences from archived specimens, thereby reducing the number of unidentified OTUs in understudied regions and taxa. Taxonomic verification using integrative approaches - such as combining eDNA with conventional morphological identification and targeted sequencing will also be critical to improving the accuracy and reliability of future biodiversity assessments [62].

Further comparative analyses of OTU assignment across primers could have provided additional insights into amplification bias and taxonomic resolution [63]. However, logistical and capacity constraints prevented these analyses from being conducted during the study period, limiting our ability to assess primer-specific performance comprehensively. As noted in prior studies, primer selection significantly affects detection accuracy, particularly in taxa with poor reference representation [64]. Pre-collection agreement of appropriate primers, aligned with the goals and outputs of a study, is critical to maximizing detection success and ensuring comprehensive taxonomic coverage and interpretable results.

Primer Specificity and Amplification Bias

We found significant differences in mean species detection by taxonomic group between the 12S vertebrate specific and 16S mammal specific primers used for amplification of OTUs across all the samples analysed (Figure 4) (see [65] for primer design). Both primers displayed a significantly higher mean species per site detection in Amphibia, followed by Mammalia and finally Actinopterygii, likely due to a combination of differences in intrinsic taxa diversity between classes, and taxa-specific differences in behavioural interactions with lotic habitats. Evaluating the efficacy of eDNA metabarcoding of freshwater sampling in lotic environments for non-aquatic taxa should therefore be a future research priority as detection of non-aquatic target taxa may suffer from disproportionate reduced detection efficacy with ramifications for survey outputs, specifically abundance estimates. Our findings also suggest that differences in taxa-specific amplification are as a direct result of issues with primer specificity and design. We found no significant difference observed in mean species detection across Amphibia, Mammalia and Actinopterygii between the vertebrate and mammal-specific primers. Specifically, a higher mean detection of amphibians across sites by the mammal-specific primer rather than the vertebrate primer raises significant concerns of amplification of non-target OTUs and PCR bias. Primer refinement and redesign clearly needs to occur to mitigate PCR bias which is commonly a result of PCR drift, interspecific variation in gene copy, denaturation efficiency and primer binding affinity [66-68]. Amplification using two primers here suggests primer binding affinity as the most significant factor driving taxa-specific amplification differences, therefore we suggest the inclusion of positive controls with known OTU fragments to examine primer-specific variation in amplification. Moreover, downstream PCR replicate sequencing reported two duplicate OTUs assigned to species level. *Boophis englaenderi* was recorded as separate OTUs by the mammal-specific primer, whilst *Guibemantis liber* was recorded as separate OTUs with a difference of one single nucleotide polymorphism by the vertebrate primer. These records indicate flaws in the post-sequencing workflow which included demultiplexing, denoising and dereplication. Combined with issues of primer specificity and PCR bias, which together pose significant challenges in reliably surveying taxonomic groups, the importance of combining OTUs detected by more than one primer into a meaningful single value for species detections cannot be overstated, and whilst having precedent often over or under-estimates species richness, the robustness of which increases with improved coverage in reference databases [63].

Challenges and Considerations in eDNA Sampling

Rainfall's impact on eDNA sampling in MFPA was evident in our results, particularly in the variation of species detections and the proportion of unidentified OTUs. During our expedition, we encountered rainfall on nine of the eleven sampling days, with several days experiencing heavy and continuous downpours lasting up to 44 hours. Given that the Makira plateau receives substantial annual rainfall-ranging from approximately 1,200 mm on the west side to 3,500 mm on the east -the timing of our survey during a typically drier season still presented significant precipitation challenges. Prior studies have demonstrated that high precipitation can reduce the relative abundance of freshwater fish eDNA sequences while increasing the detection of terrestrial taxa due to runoff [53]. Our results align with this, as amphibians - often associated with terrestrial habitats during rain events-were significantly better detected by eDNA than conventional surveys. However, we observed a lack of significant differences between eDNA and visual methods for reptiles, suggesting that dilution or increased turbidity from heavy rainfall may have affected reptile detection across sites. Furthermore, the high number of unidentified OTUs, particularly within amphibians (20.5 ± 2.5 OTUs) and birds (13 OTUs), suggests that rain-induced sediment resuspension may have contributed to degraded or fragmented DNA, making taxonomic identification more challenging. This effect has been documented in previous studies, where rainfall-driven shifts in sediment loads and water chemistry altered the availability and persistence of eDNA [69]. While eDNA was significantly more effective than conventional surveys at detecting birds, mammals, amphibians, reptiles and ray-finned fish, the variability in Shannon Diversity Index values across sites underscores how environmental conditions, including precipitation, played a role in detection efficiency. Future eDNA sampling efforts in tropical ecosystems should incorporate hydrological monitoring to assess the impact of precipitation on eDNA transport and degradation, and sampling strategies should be adjusted to account for periods of extreme rainfall [70].

Because this was a rapid, multi-taxa biodiversity inventory covering fish, birds, mammals, amphibians, and reptiles, no single eDNA sampling method could be entirely effective across all taxa. Aquatic eDNA sampling, while well-suited for detecting freshwater species, has inherent limitations when applied to terrestrial and fossorial organisms. Our results demonstrated the effectiveness of water-based sampling for certain groups, as eDNA significantly outperformed conventional surveys in detecting amphibians, and ray-finned fish. However, whilst the results in Figure 6 present scaled detections, gross detections by eDNA per site for the terrestrial vertebrate groups (mammals, birds and reptiles), were more infrequent than the aquatic groups. This aligns with existing research indicating that terrestrial reptiles shed minimal DNA and have limited interaction with water sources, making aquatic eDNA an unreliable detection method for this group [56].

To address these limitations, future multi-taxa biodiversity surveys in diverse tropical ecosystems should incorporate complementary eDNA sampling strategies tailored to taxon-specific needs. Novel eDNA technologies are rapidly evolving, offering new opportunities to overcome the limitations observed in the MFPA and improve biodiversity detection across multiple taxa. Automated and multi-sampler eDNA technologies could further enhance future surveys by increasing sampling efficiency, reducing human error, and allowing for long-term, continuous sample collection. Autonomous samplers, such as the DOT-NM Autosampler, can collect multiple eDNA samples at pre-programmed intervals, ensuring a more representative snapshot of biodiversity across different times of day and environmental conditions (NatureMetrics; 1 Occam Court, Surrey Research Park, Guildford, GU2 7HJ United Kingdom, https://www.naturemetrics.com/dot-nm-autosampler). For terrestrial reptiles, soil eDNA sampling and substrate swabbing at basking sites, burrows, or movement corridors would likely yield better results, as reptiles shed DNA primarily through skin and faecal deposits rather than into water [71]. This approach would be particularly beneficial for fossorial species, whose limited

surface activity makes them difficult to detect through conventional methods. Rainwater eDNA collection could offer an effective, minimally invasive method for detecting arboreal and ground-dwelling species by capturing DNA washed from the canopy and forest floor during precipitation events. Airborne eDNA sampling, using HEPA filters or drone-mounted vacuum collection, has the potential to significantly enhance the detection of birds and mammals, particularly those that roost or nest in dense forest canopies, where direct observation and physical sampling are challenging [72]. Additionally, leaf swabbing could be a valuable tool for detecting species that interact with vegetation, especially in areas where terrestrial mammals and reptiles frequently climb or feed. As eDNA methodologies continue to advance, these emerging approaches represent some of the most promising solutions for improving biodiversity assessments, expanding detection capabilities across a wider range of taxa while minimizing disturbance to the ecosystem.

Future Research Directions

While eDNA is an efficient and cost-effective tool for detecting rare and cryptic species, it rarely provides insights into behaviour, population dynamics, or habitat use. For more comprehensive biodiversity assessments, future efforts should consider integrating eDNA with conventional surveys, as the two methods offer complementary strengths and can compensate for each other's limitations [73]. Further, combining eDNA with other non-invasive technologies, such as camera trapping, bioacoustics, 3D scanning, and drone surveys-can enhance conservation monitoring, particularly in dense forest environments where species detection is inherently challenging.

Community-based conservation initiatives are critical for ensuring biodiversity data remains accessible and beneficial to local stakeholders. Incorporating eDNA sampling into local monitoring programs fosters consistent, participatory biodiversity assessments, strengthening conservation efforts through direct community engagement. Training local conservation teams to collect, process, and analyse eDNA data enhances long-term ecological monitoring and empowers communities to take an active role in protecting their environment [74]. In the MFPA, integrating eDNA into local conservation efforts could improve species detection, track environmental changes more effectively, and provide communities with the tools to respond to emerging threats.

Tropical rainforest ecosystems like Makira-despite their size and ecological significance-are increasingly threatened by a convergence of pressures common across much of the global tropics. During this expedition, we documented widespread anthropogenic impacts, including deforestation near Sahametreha, gold and gemstone mining, rice paddy expansion, and watercourse diversion. Free-ranging livestock (pigs and cattle) were found deep within forested areas, and eDNA analysis confirmed the presence of multiple invasive species (e.g., *Channa maculata*, *Rattus rattus*, *Gambusia holbrooki*). Signs of poaching, including bird and lemur traps and reports of armed individuals, further underscored the vulnerability of even the most remote and protected, forested regions. These challenges are by no means unique to Madagascan forests, and are seen in tropical forests across Southeast Asia, the Amazon, and Central Africa. These compound threats highlight the urgent need for scalable, non-invasive biodiversity monitoring tools. Integrating eDNA with conventional survey methods offers one such approach, enabling broader, more effective, tracking of biodiversity at the community-level across threatened tropical systems.

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DATA AVAILABILITY STATEMENT

All raw datasets (eDNA, amphibians, reptiles, birds, mammals and ray-finned fish) have been deposited and are publicly available in Harvard Dataverse: Cosmo Le Breton; Biggs, Christina, 2025, "A rapid, multi-taxon biodiversity survey of the Makira Forest Protected Area, Madagascar", https://doi.org/10.7910/DVN/QK3E1D, Harvard Dataverse, V1. Further associated metadata is publicly available on the RIDGES Foundation website: https://www.ridgesfoundation.org.

ETHICS STATEMENT

All research was conducted in accordance with national and institutional guidelines governing biodiversity studies in Madagascar. Approval for all proposed activities was granted by the Wildlife Conservation Society, which manages the MFPA, as documented in their official letter dated 07/07/2023. All research protocols, including sampling and specimen handling, complied with the ethical standards outlined in WCS's Standards of Conduct and the Makira Natural Park Guidelines, including Articles 11, 15, and 16 of the cooperation agreement signed by all parties on the 26/08/2023.

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