PROJECT REPORT

Ecoacoustic Biodiversity Monitoring in Forest Gardens Around Homa Bay, Kenya

In Partnership With: Catona Climate, Trees for the Future

ARBIMON | RAINFOREST CONNECTION

March 2024

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EXECUTIVE SUMMARY

Rainforest Connection (RFCx), Arbimon, Catona Climate, and Trees for the Future (TREES) are partnering on an impactful passive acoustic monitoring project in Homa Bay, Kenya, to better understand how the Forest Garden Program (FGP) supports local biodiversity.

The goal of the present study was to use acoustic detection algorithms, AI models, and soundscape analyses to assess the presence and distribution of wildlife as well as factors (like FGP) that influence them. FGP is a "Reduced-Impact Agriculture" initiative under the Climate, Community & Biodiversity (CCB) Standard. This project's results can then, in part, inform compliance with the CCB Standard.

From May to June 2023, our on-ground partners deployed acoustic recorders at 67 sampling sites within FGP agroforestry plots. We then used an AI-powered automated species detection pipeline in combination with ecological analyses to derive biodiversity insights in FGP sites.

We detected 128 species across 67 sites within Forest Garden agroforestry plots around Homa Bay, Kenya. The most commonly detected species were the village weaver, common bulbul and white-browed robin-chat. One of the detected species, the grey crowned crane, is classified as Endangered (IUCN RedList). Several additional species, like the woodland kingfisher, are also prioritized for conservation in inter-continental action plans.

Our comprehensive analyses consistently show that **sites that have been in FGP the longest have a positive influence on bird diversity**. Specifically, we found higher acoustic space use in FGP sites of 2 - 3 years compared to year 0 sites; this difference was attributed primarily to higher bird call activity. Moreover, we found a significantly greater likelihood of bird species occurrence in FGP sites of 1 - 3 compared to year 0 sites. **Sites in FGP for 1 to 3 years had a higher number of species compared to year 0 sites.** Our models also identified canopy height and proximity to Lake Victoria as significant influences on bird occurrence.

This study has unveiled important insights into bird species' presence and distribution in agroforestry sites of western Kenya. Our results underscore the positive impact of Forest Gardens on avian biodiversity, providing compelling evidence for its effectiveness in enhancing habitat quality and species richness. Our results offer valuable guidance for conservation efforts and restoration planning, contributing to the preservation of the region's unique biodiversity.

METHODS

Data Collection

We implemented passive acoustic monitoring (PAM) within agroforestry plots in western Kenya from May 29 to June 21, 2023 (rainy season). Agricultural land predominates the region's land cover (58%), followed by water bodies (34%), with natural grassland & vegetation, and forest, comprising a smaller proportion of land (Onyango et al. 2021).

Our on-site partners deployed Song Meter Micro recorders (Wildlife Acoustics) across 70 Forest Garden Program (FGP) sites around Homa Bay. These sites encompassed various stages of FGP development, from newly established (0 years) to 3 years old at the time of the survey (Figure 1).

Song Meter Micros recorded a one-minute audio clip every five minutes (48kHz sample rate), resulting in 288 recordings per site per day. Recorders lasted an average of 17.1 days (range: 8-21 days; Figure 2). This resulted in a total of 294,000 one-minute recordings, which were subsequently uploaded to the Arbimon platform for analysis.

Three sites (FG-026529, FG-050564, and FG-059538) were excluded from the analyses due to a scarcity of recordings. The shortage of recordings at these sites may have resulted from deployment issues or recorder malfunctions.

Figure 1. Map of the area of interest (AOI). Sampling sites are represented by blue symbols.

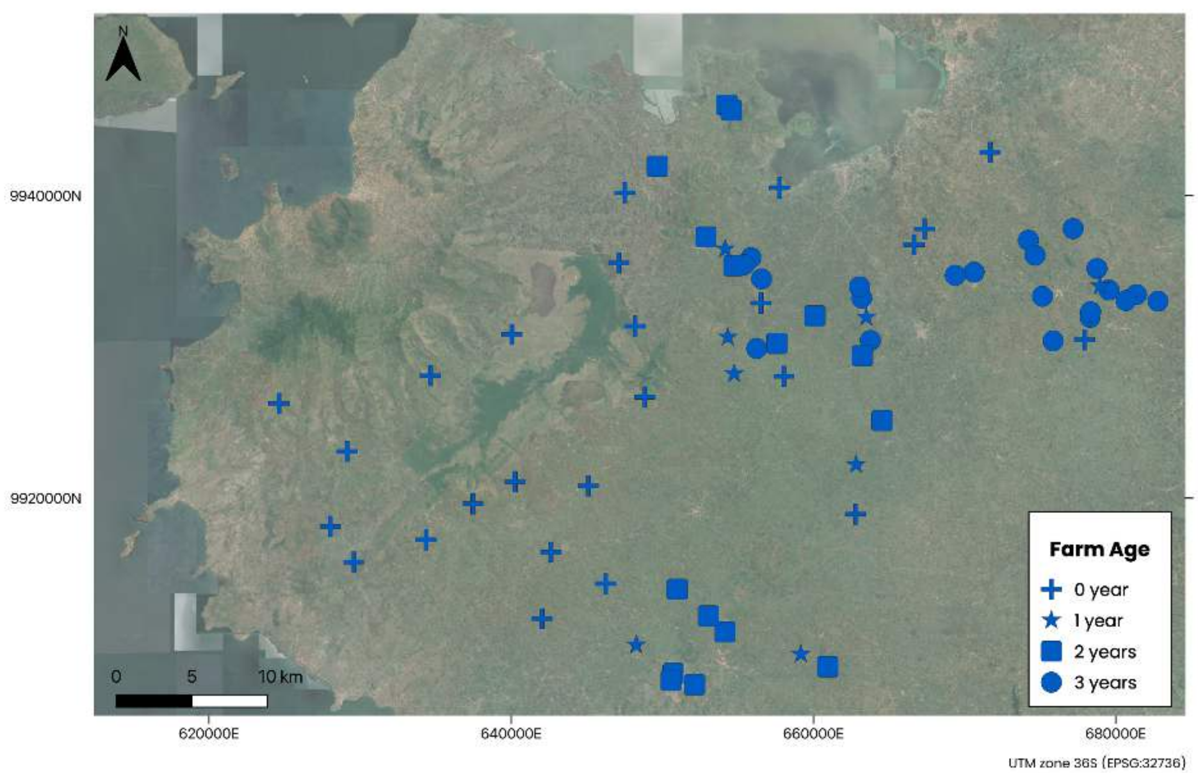
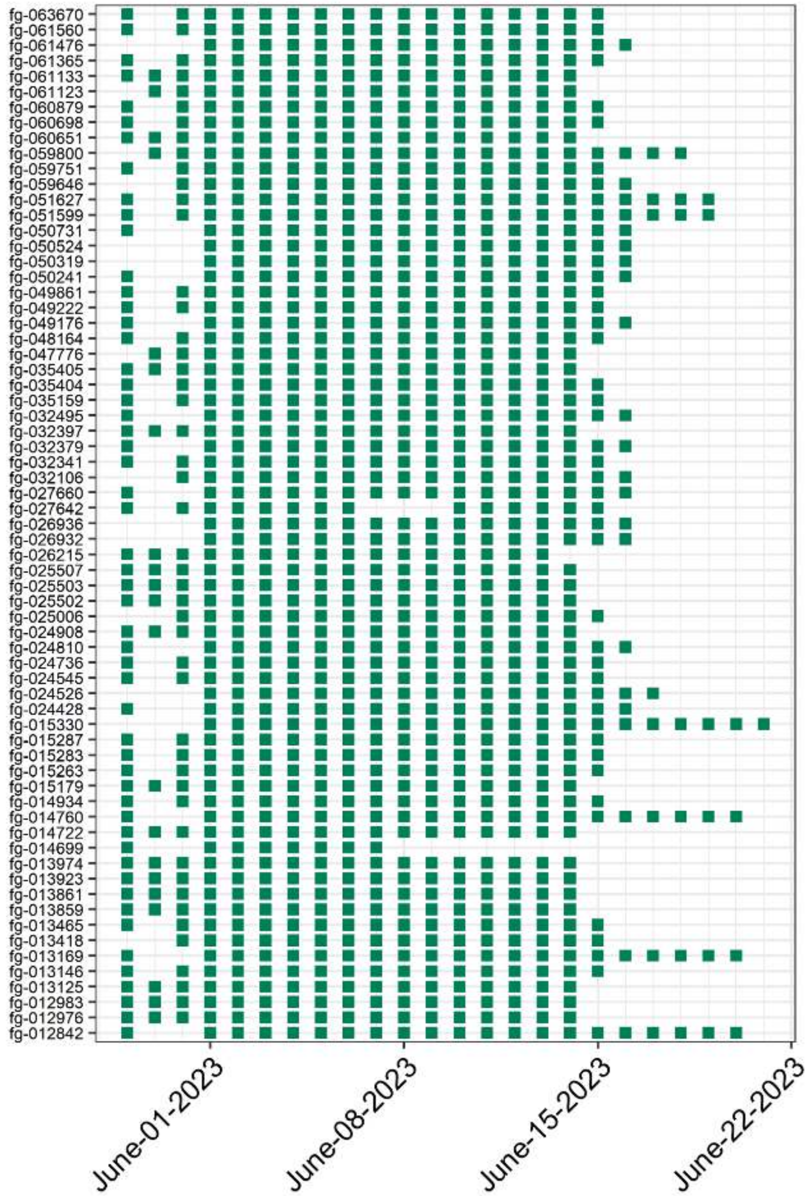


Figure 2. Recording periods at 67 sampling sites during the survey. Each square represents a recording day. The first recording day was May 29 and the last was June 21, 2023.



Environmental Variables

To better understand how environmental variables influence species distribution and occurrence, we extracted landscape-scale remote sensing (GIS) layers to use in our ecological models. We selected these environmental variables based on their public accessibility and potential to explain biodiversity patterns based on previous literature (Appendix A). Some environmental variables tend to be correlated with each other, which can cause problems in ecological models. Therefore, to avoid such multicollinearity issues, we excluded highly-correlated variables within the same models.

We utilized data from various geospatial data repositories:

- **canopyMax** - maximum canopy height for each polygon (Global Forest Canopy Height 2020 [GLAD] dataset)
- **elev** - elevation (STRM dem)
- **dist_vict** - shortest distance to Lake Victoria (Impact Obs. 9-class LCLU)
- **dist_pa** - distance from closest protected area
- **NDVI23** - mean normalized difference vegetation index from June 2023 (Planet Surface Reflectance Basemaps)
- **Year** - years a farm has been in FGP (Year-0 = sites that registered <12 months before start of this survey).

To incorporate these variables in our model, we used ArcGIS Pro to create a 200-meter radius buffer around each site (12.57 hectare total area; this corresponds to the estimated detection distance across species' calls). This buffer allows us to capture the site-specific micro-environment to better understand how environmental variables influence species detection and occurrence. This approach allows us to systematically and uniformly incorporate relevant environmental data into ecological analyses at a landscape-scale, and effectively assess these variable's influence on species distribution and occurrence.

Because we wanted to use the results of our ecological models to predict species occurrence across the entire area of interest (even areas where we did not put recorders), we generated a grid of hexagons with the same internal area as the site buffer zones (12.57 hectares) across the entire study area. This allowed us to extract value for each of the environmental variables per 12.57ha hexagon, across the region (using ArcGIS Pro's Zonal Statistics and Tabulate Area tools).

Soundscape Analyses

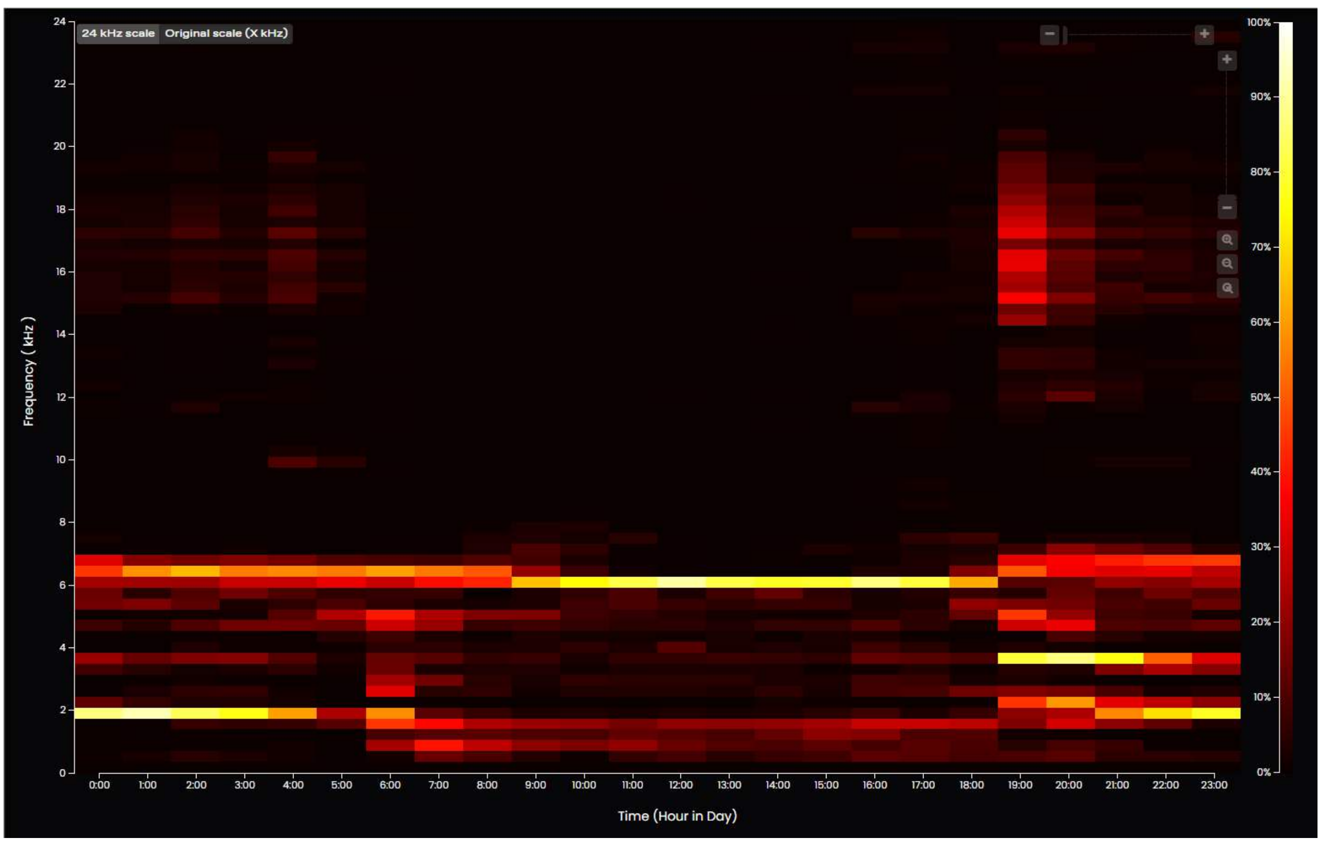
A soundscape encompasses all sounds from a specific location and time, including biophony (sounds from living organisms), geophony (natural sounds like rain), and anthrophony (human-made sounds; Pijanowski et al. 2011). Soundscape analyses serve as a valuable tool to assess spatial and temporal variations of acoustic patterns, unveiling patterns in the community of acoustically-active species. Soundscape analyses can also provide insights into how environmental factors, such as land cover and restoration, influence local biodiversity.

We used two soundscape analyses: composition and Acoustic Space Use (ASU). Soundscape composition focuses on the recurrence of acoustic energy in particular time-frequency bins across recording days within a site, as a means to understand the acoustic community of a site. On the other hand, ASU aims to provide a proxy for species richness by averaging the proportion of time-frequency bins occupied across recording days per site. ASU quantifies how much the soundscape from each location is used over time. Species-rich sites, particularly those with many insects, tend to generate more saturated soundscapes with a higher ASU (Aide et al. 2017; Campos-Cerqueira et al. 2019; Ramesh et al. 2023). Both approaches can be valuable for understanding biodiversity patterns and ecological dynamics.

Soundscape Composition

We compared soundscape composition among the sites and tested whether any environmental variables influenced composition. We used Arbimon's soundscape tool to summarize acoustic activity per site; this tool aggregates the amount of acoustic activity at each frequency and hour-of-day period across all sampling days at that site (Figure 3). To summarize the variability and composition of acoustic activity in these soundscape maps, we employed an ordination technique called non-metric multidimensional scaling (NMDS). NMDS is a dimensionality reduction method that creates a visual representation of objects (in this case, study sites) based on their similarities to a certain variable (here, soundscapes; Figure 3). The resulting NMDS components were then used in further analyses to assess their relationship to environmental variables using linear models. We used a suite of follow-up tests (PERMANOVA, beta-dispersion) to confirm the robustness of our linear model results.

Figure 3. Soundscape view from the Arbimon platform showing acoustic activity throughout the day in one site, FG-015330. Color gradient represents the soundscape saturation in each time/frequency bin.



Acoustic Space Use

To calculate each site's ASU, we divided each site's recordings into 1,656 time/frequency bins (24 hours X 69 frequency bins) and calculated the percentage of bins 'used' out of the 1,656 total. We considered a time/frequency bin 'used' if a sound with an amplitude >0.05 was detected.

We categorized soundscapes into three distinct frequency ranges:

- **<2 kHz:** low-frequency sounds typical of human noise/machinery, geophony (wind) and some animals
- **2-8 kHz:** mid-frequency sounds typical of terrestrial vertebrates (e.g., birds, amphibians, primates)
- **>8 kHz:** high-frequency sounds typical of insects (e.g., crickets, cicadas)

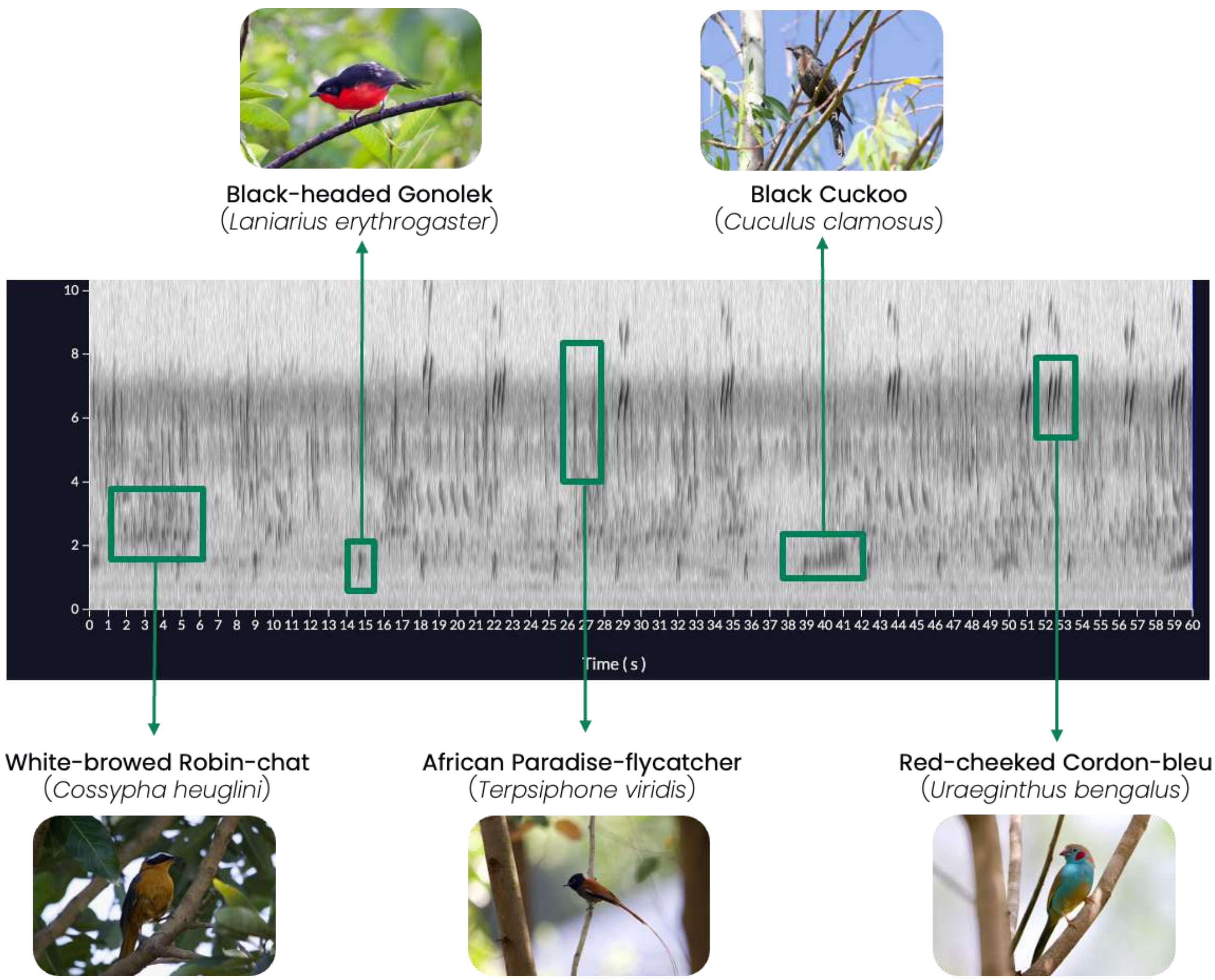
We conducted our analyses separately across these frequency bands because this enables us to gain a more nuanced understanding as to which taxonomic groups/sound classes are influenced by which factors. Species can respond differently to various environmental factors, so analyzing ASU across distinct frequency bands gives us insights into these patterns.

We then used general linear models (using automated model selection/averaging) to identify which environmental variables most influenced ASU across all frequencies as a whole, as well as within each of the three frequency subsets. Additionally, we explored the relationship between ASU and species richness per site to assess whether ASU can be used as a proxy for the number of bird species present in a given area.
For all soundscape analyses, results were considered statistically significant for p-values <0.05.

Preliminary Species List

Experienced biodiversity scientists from the RFCx science team reviewed recordings in Arbimon. They manually detected and tagged species from one day of recordings per sampling site to create a preliminary species list and identify any issues with the recordings (Figure 4). This species list serves as a baseline for understanding the overall species assemblage found in the study area and facilitates our development of species identification models in Arbimon.

Figure 4. Annotated spectrogram with species calls from a 1-min recording collected in an FGP site..



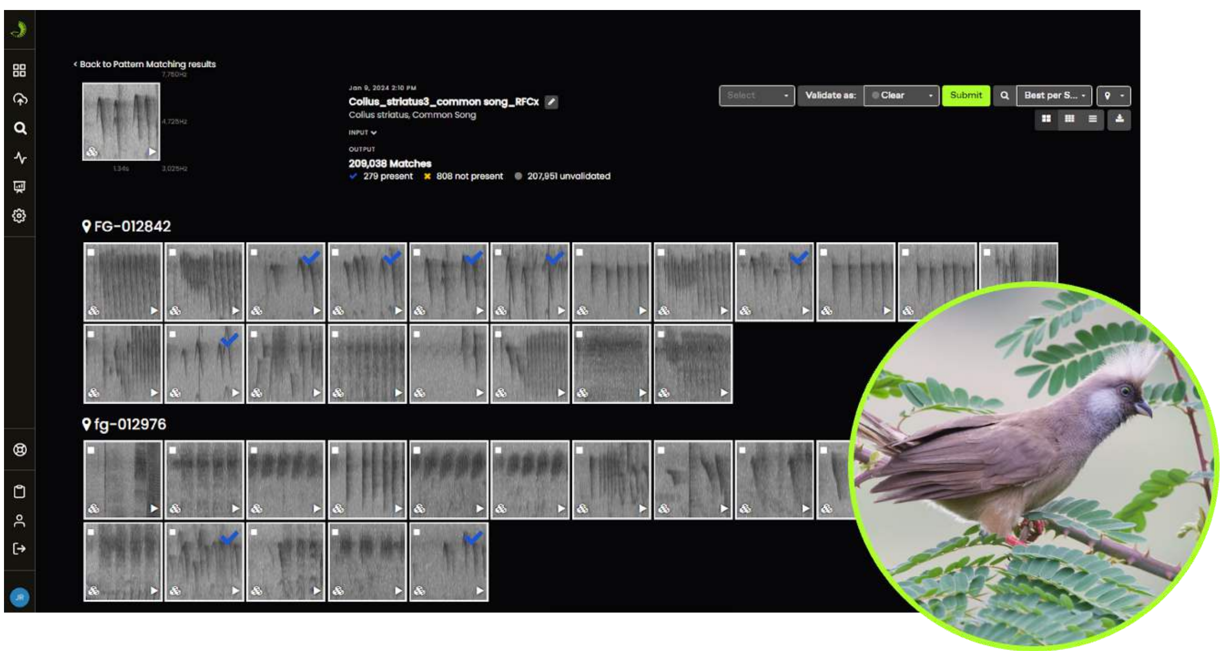
Species Identification - Pattern Matching

Arbimon's Pattern Matching (PM) tool allows users to choose an acoustic signal template (i.e., an example of a species' vocalization) and then search through a user-defined playlist of audio recordings to identify signals that match the selected template. RFCx's Biodiversity Scientists then validate PM results (Figure 5), which are to be used in later models and analyses. This semi-automated approach significantly speeds up the species detection process and also facilitates the creation of training datasets for AI models. This process is documented in more detail in LeBien et al. (2020), Ribeiro et al. (2022), and the Arbimon glossary.

We used PM to automatically identify 100 species (95 birds, 4 amphibians, 1 insect; Appendix B). These species were selected based on two primary criteria:

- species' ecological traits, which help to understand overall biodiversity patterns
- availability of good species call templates

Figure 5. Arbimon Pattern Matching validation page for the speckled mousebird (*Colius striatus*).



Species Identification - AI Model

We used the validated PM detections as presence and absence data to train a Convolutional Neural Network (CNN) model capable of classifying species using spectrogram images (LeBien et al. 2020). We combined species detections from this project with those from a nearby RFCx project (in Tanzania) to increase CNN's training dataset. Appendix C provides more details about this AI model training, evaluation, and deployment workflow.

The final trained CNN model had 104 species (106 classes; class = species + song type) and showed strong performance on evaluation and test subsets. The model achieved a weighted average precision (wAP) of 0.96 across classes (full evaluation metrics in Appendix D). Our biodiversity scientists then validated the model predictions to ensure they were correct (true positives).

We did find that 4 classes had a wAP that was lower than expected (<0.70), indicating that the model tended to incorrectly classify audio clips as having that species 'present' when the species was actually absent. These four species-classes were:

- Eastern plantain-eater (wAP = 0.58)
- African common toad (wAP = 0.61)
- Scarlet-chested sunbird (wAP = 0.62)
- Cinnamon-chested bee-eater (wAP = 0.65)

The low performance of these species could stem from various factors, including the inherent complexity of their call types, the presence of similar sounds in the environment, or the limited amount of training and evaluation data available.

Ecological Analyses - Occupancy Models

Occupancy modeling is a powerful method that can be used to predict the probability that a species "occupies" sites while accounting for imperfect detection. Further, occupancy modeling enables us to integrate environmental variables to assess how these influence species presence and distribution (Doser et al. 2022).

We developed multi-species occupancy models (MSOM) for 95 bird species using the validated detections from PM analyses together with the aforementioned environmental variables. We focused on birds since they are the most diverse group in the dataset and can often be proxies for broader ecosystem health. We were unable to fit MSOM for the four frog species because most of the species were detected in >10% of the sampling sites. Modeling species with detections in only a few sites can present challenges for developing a robust model.

The supplementary files provide further information on all analyses (PM, soundscape, occupancy models, etc.), including support tables, models, and figures.

RESULTS

Soundscape Composition

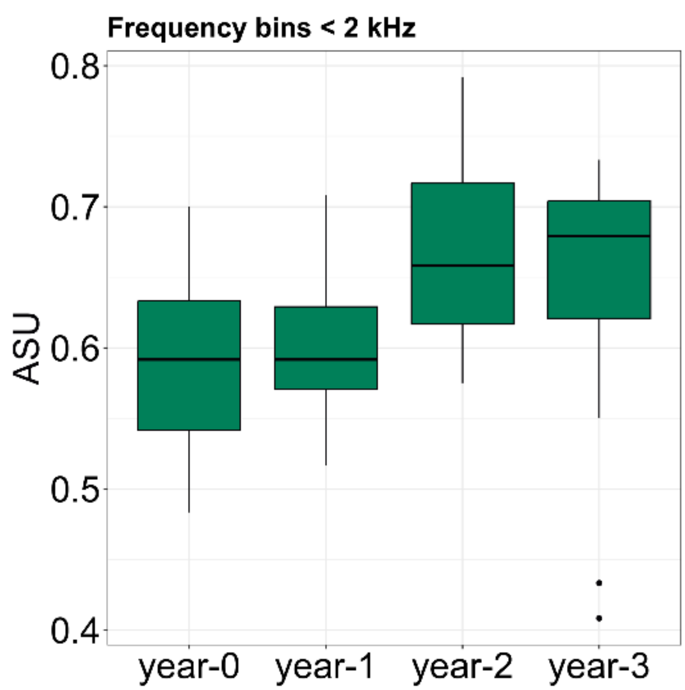
Our ordination analyses showed that elevation and distance to the protected area (Ruma National Park) significantly influenced soundscape composition. However, each variable explained a relatively low amount of variation in the model.

Acoustic Space Use (ASU)

Our results reveal a wide range of ASU across sites (mean 44.7%, range: 30.5% - 86.5%). Similar to our soundscape composition results, our ASU analysis identified elevation and distance to the protected area as significant drivers of ASU variation. However, these models exhibited weak explanatory power and should, therefore, be interpreted with caution.

When analyzing ASU across frequency bands, the models for high (>8 kHz) and medium (2-8 kHz) frequencies yielded results comparable to the overall ASU (weak explanatory power). Interestingly though, the best models for low frequencies (<2 kHz) included the number of years in FGP and NDVI. Sites that entered the FGP 2 and 3 years ago showed significantly greater ASU than year 0 sites (Figure 6).

Figure 6. Assessment of low-frequency Acoustic Space Use (<2 kHz) in relation to years since FGP entry.



To investigate this further, we conducted a qualitative evaluation of the dominant sound sources below 2 kHz at a random subset of sites (~3 sites per FGP year). This revealed that the most common low-frequency sounds were human activities (e.g., music, mechanical noise), wind, domestic animals (eg., roosters, dogs), and wild birds. A significant portion of the birds detected in this project exhibit vocalizations <2 kHz (at least partially; Appendix E).

Human sounds, wind, and domestic animals appeared relatively consistent across sites with different FGP years; however, sites in years 2 and 3 showed a higher prevalence of low-frequency bird vocalizations compared to years 0 and 1. This indicates that sites that have been in FGP longer may have increased bird vocal activity.

We did not observe any significant relationship between ASU and species richness. This indicates that ASU cannot be directly employed as a proxy for the species richness of the analyzed bird community at this time.

Species Identification

We identified a total of 128 species, including 123 birds, 4 amphibians, and 1 insect (Appendix B). One of these species, the grey crowned crane (*Balearica regulorum*) is classified as Endangered on the IUCN RedList. None of the recorded species are considered endemic or invasive alien species to Kenya. While no endemic species were detected, it's important to note that Kenya harbors a very low number of endemic bird species (only 9 out of 1000 species; BIODEV2030 2020). Thus, the absence of endemic species in this project aligns with our expectations.

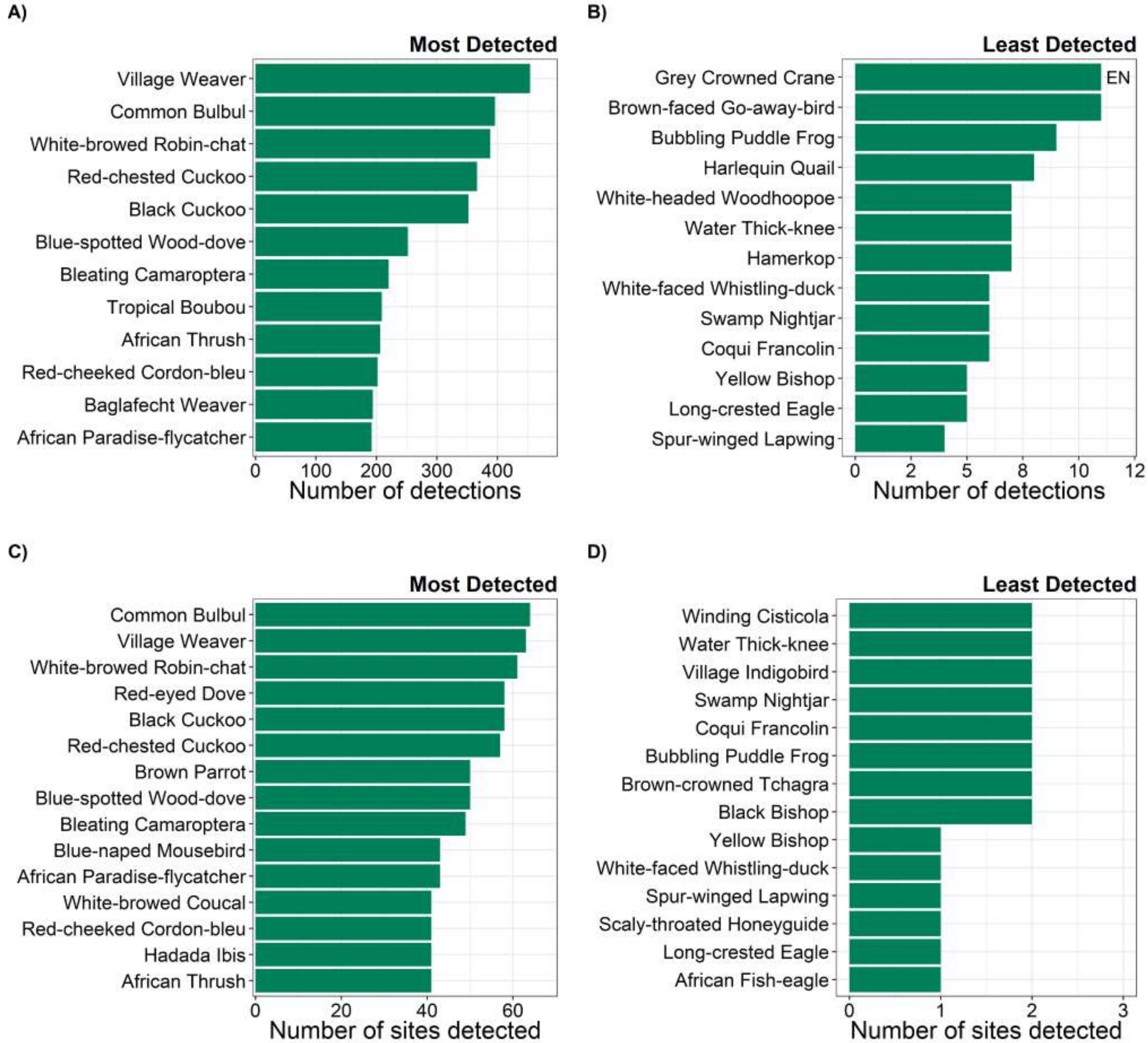
Further, the African-Eurasian Migratory Landbirds Action Plan (AEMLAP) has classified several of the species detected in this project as High Conservation Value. Among these, the woodland kingfisher (*Halcyon senegalensis*) has been prioritized for conservation due to its status as a migratory land bird species facing global population declines (Category B, Annex 3 of AEMLAP).

There are additional detected species listed in AEMLAP (Category C, Annex 3) which require regulation of human activities such as harvesting and trade due to their varying population trends; these include the African paradise-flycatcher (*Terpsiphone viridis*), red-chested cuckoo (*Cuculus solitarius*), black cuckoo (*Cuculus clamosus*), blue-spotted wood-dove (*Turtur afer*), and red-eyed dove (*Streptopelia semitorquata*) These classifications underscore the importance of prioritizing conservation efforts for these bird species as well.

The majority of recorded bird species belong to the Passeriformes family (54% of species), followed by Piciformes (woodpeckers, 8%), and Columbiformes (pigeons, 6%; Appendix B). These findings generally align with the known diversity of bird species in Kenya, although Charadriidae (plovers and lapwings) species were underrepresented in this project. The relatively low number of Charadriidae detections may be attributed to specific habitat requirements of some species, particularly those associated with shorelines such as plovers.

Of the species we used for PM analyses, the species with the most detections were the village weaver (*Ploceus cucullatus*), common bulbul (*Pycnonotus barbatus*), white-browed robin-chat (*Cossypha heuglini*), red-chested cuckoo, and black cuckoo (Figure 7). In general, the most detected species were also those found in the greatest number of sampling sites (Figure 7).

Figure 7. Bar plot displaying the most and least detected species in total (A, B) and across sites (C, D). EN = endangered species (IUCN RedList).



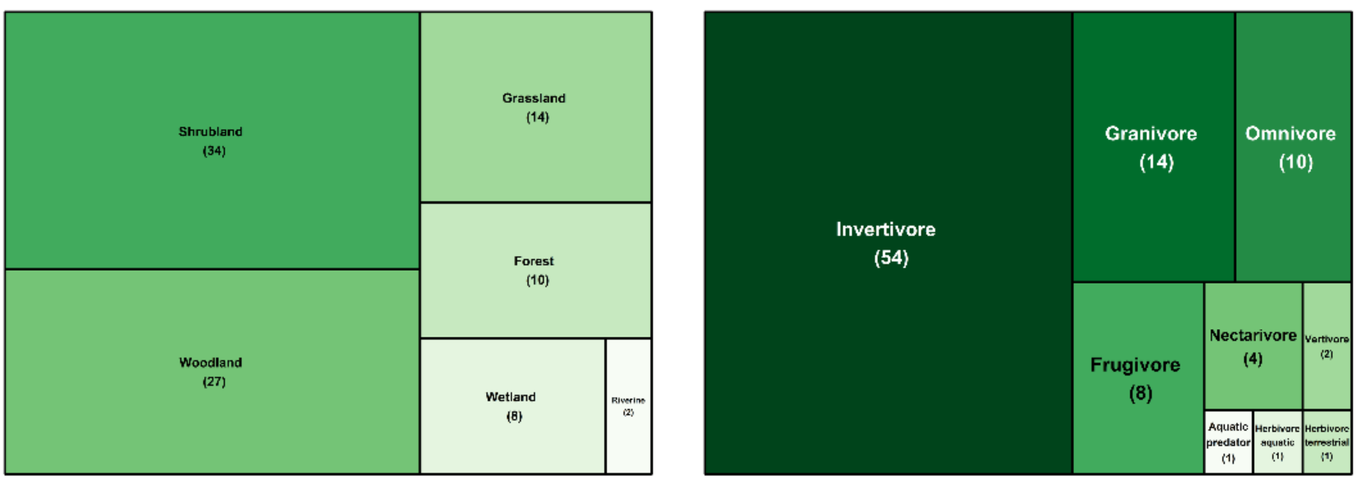
The majority of species detected were those that prefer shrub/brush habitats, Acacia woodlands, and savannas. Only 10 species are considered forest-specialists (Figure 8). These results strongly reflect the landscape coverage in the region, which has a very small amount of forest cover (<1%). The FGP is expected to benefit the region's forest-specialist birds by increasing the quantity and diversity of trees.

Analysis of dietary guilds reveals that the majority of identified species are invertivores (invertebrate- and insect-eaters), while frugivores (fruit-eaters) represent only 8% of the birds detected. Frugivorous birds play a critical role in ecosystem function by acting as seed dispersers and contributing to the success of restoration efforts. Reforestation can increase frugivorous bird populations; we expect that as FGP sites develop over time, they will facilitate the movement of these frugivorous species into Forest Gardens.

The increased presence of frugivorous birds in Forest Gardens could potentially create a positive feedback loop by catalyzing the recovery of ecological services through enhanced seed dispersal. Continuing to monitor these dynamics as the project develops will provide more evidence to support the efficacy of Forest Gardens.

Figure 8. Number of bird species detected in this project, grouped by habitat preference (left-panel) and dietary guild (right-panel), based on Avonet.

Invertivore = eats insects/invertebrates. Granivore = seeds/grasses. Omnivore = plant matter & animals. Frugivore = fruits. Nectarivore = nectar.

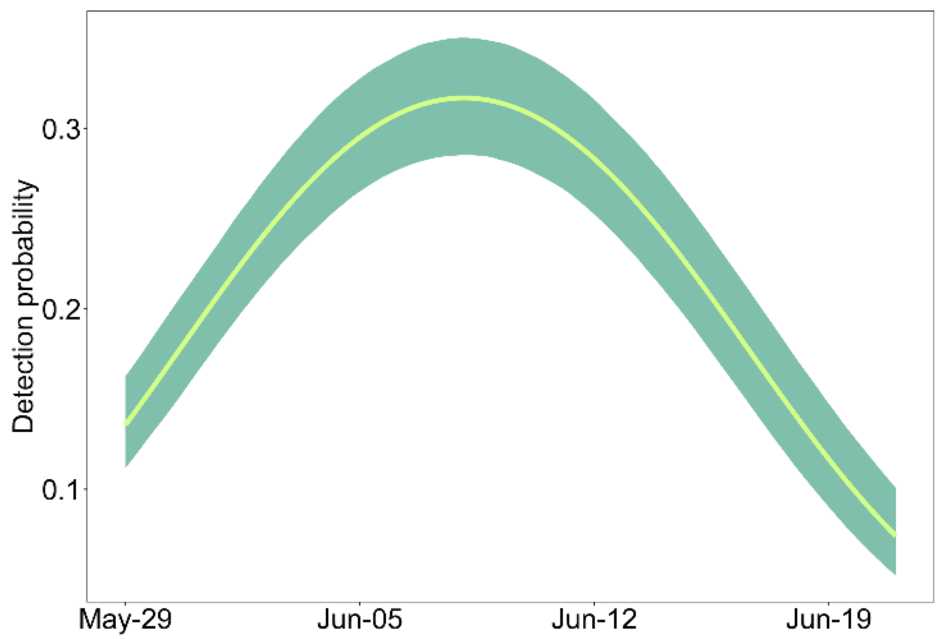


Occupancy Models - Detection Probability

The detection probabilities across bird species showed considerable variation, ranging from a low of 0.105 for the red-billed Oxpecker (*Buphagus erythrorynchus*) to a high of 0.766 for the black bishop (*Euplectes gierowii*; mean = 0.327; supplementary files).

The best detection model had sampling day as an explanatory variable. There was a peak in detection probability during the midpoint of the sampling period (Figure 9). This pattern of detection was consistently observed across all species (Appendix F). The fluctuations in detectability observed across sampling days may be due to weather conditions. Variables such as wind speed, temperature, and rainfall can all influence bird detection rates (Bas et al. 2008; Morelli et al. 2022). Collecting climate data in combination with acoustic monitoring could offer valuable insights into the relationship between bird detectability and environmental conditions.

Figure 9. Community-level detection probability relationships with Julian day, showing 95% credible intervals (shaded areas).

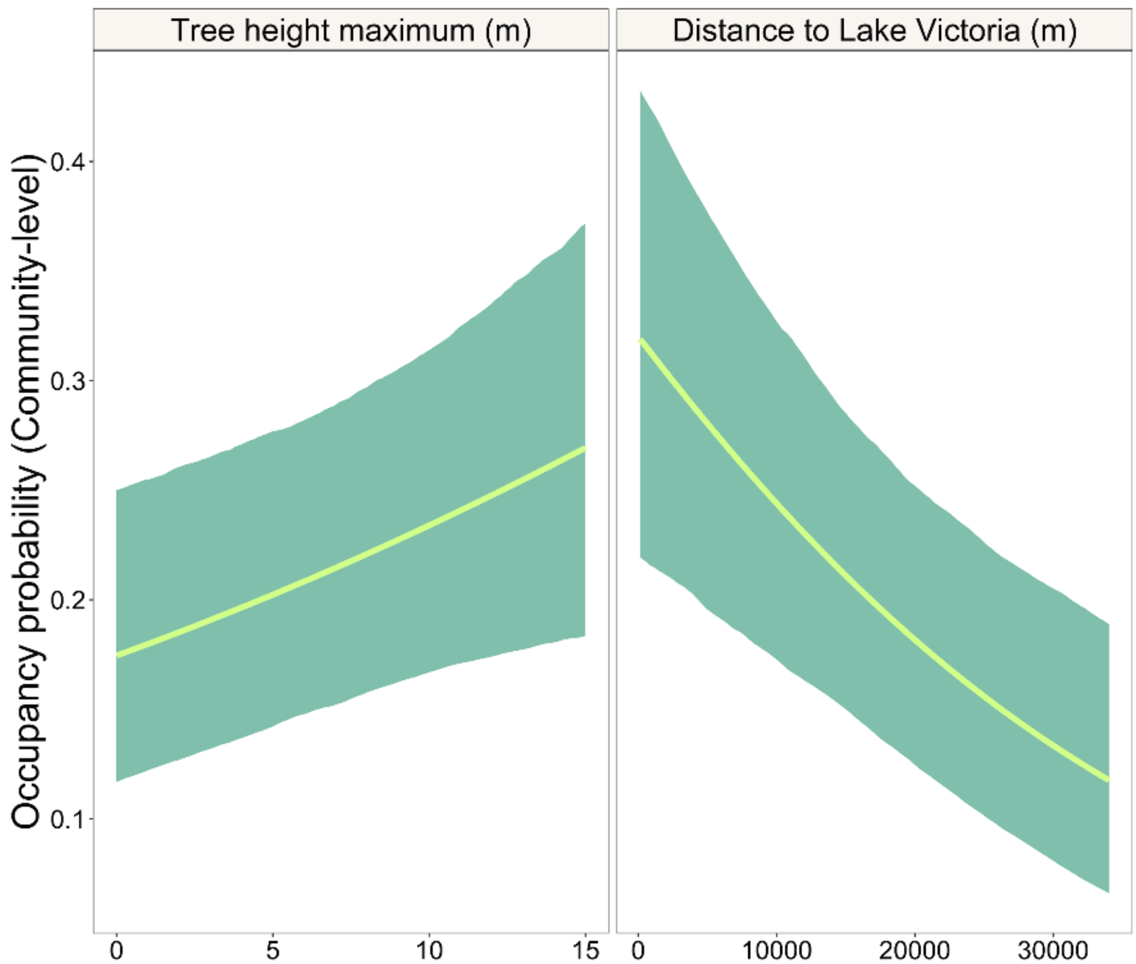


Occupancy Models - Occupancy Probability

The top-ranked MSOM included years since entry to FGP, maximum canopy height, and distance to Lake Victoria as significant influencers of occupancy. Sites enrolled in the FGP for 1 - 3 years showed significantly higher bird occupancy compared to year 0 sites (in FGP < 12 months). All species had a higher probability of occurrence in year 1 - 3 FGP sites than in year 0 sites (Appendix F). Additionally, the presence of high-canopy trees emerged as a key driver of species occurrence. Sites that had higher maximum tree heights had higher probabilities of bird presence (Figure 10). This finding underscores the pivotal role of tree-planting initiatives and long-term management to ensure tree growth. Our results provide evidence that ongoing restoration efforts can enhance available habitat for birds and increase species' occurrence.

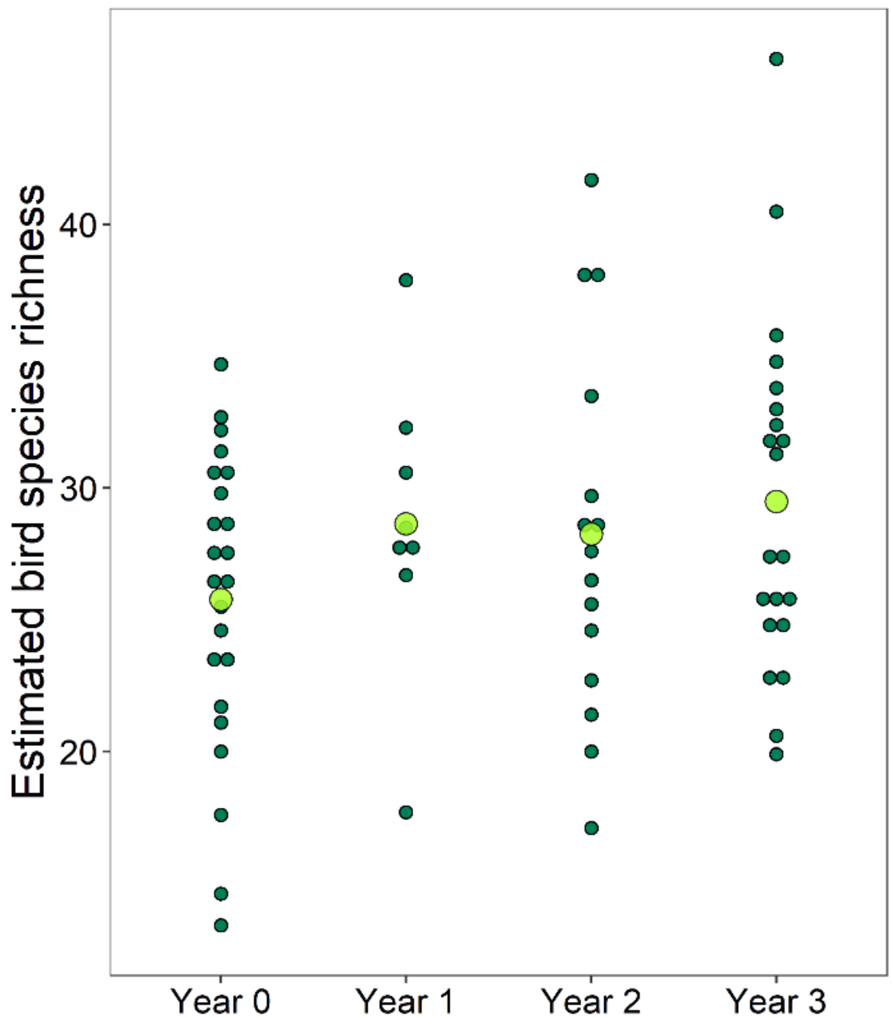
Finally, our analysis identified distance from Lake Victoria as a significant predictor of bird occupancy. Sites closer to the lake were more likely to be occupied by bird species (Figure 10). It may be that the lake influences microclimates and vegetation composition, which provide favorable conditions for bird species.

Figure 10. Community-level occupancy probability relationships with significant predictor variables, showing 95% credible intervals (shaded areas).



We used the model results to compare bird species richness across sites enrolled in the FGP for a varying number of years. There was a notable increase in the estimated species richness of sites involved in FGP for 1-3 years compared to year 0 sites (<12 months in FGP; Figure 11). The average richness for year 0 sites was estimated at 25.7 species, while year 3 sites had an estimated 29.5 species. This is a remarkable 14% more species compared to baseline (year 0). Years 1 and 2 also had 10% increases in species richness compared to year 0 (Figure 11). These findings provide compelling quantitative evidence of the positive impact that FGP has on bird diversity within the study area.

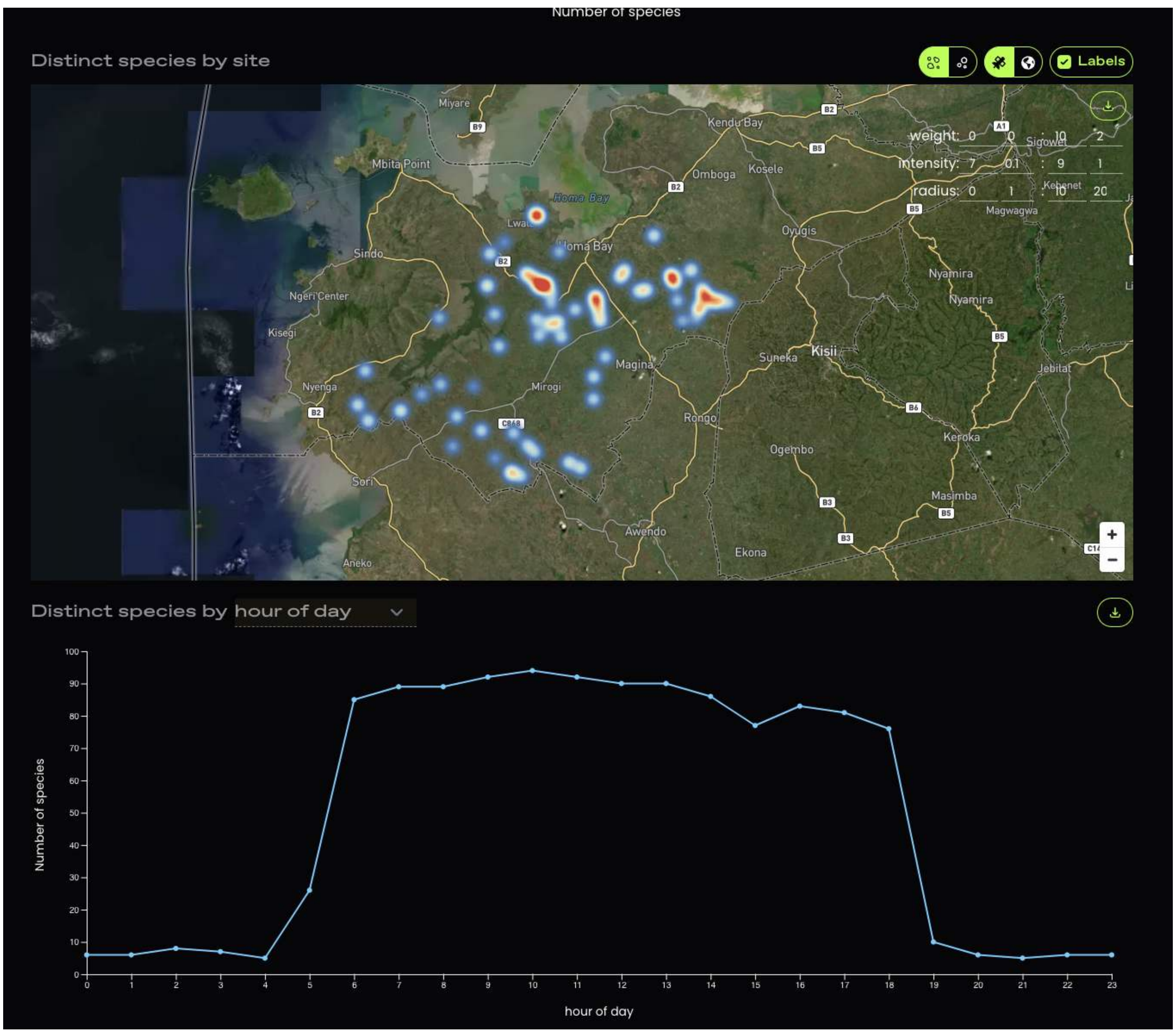
Figure 11. Estimated species richness for each year, derived from the MSOM. Dark green circles = estimated average richness per site. Light green circles = estimated average richness per treatment (FGP year).



Arbimon Insights Dashboard

We developed an [Arbimon Insights dashboard] to report, display, highlight and summarize the main results from this project (Figure 12). This webpage allows partners to interact with the data in a non-coding, user-friendly interface. The Insights dashboard provides community-wide biodiversity metrics and figures, as well as species-specific information for the species detected in the project (see [Appendix G] for descriptions of each page within the Insights platform).

Figure 12. Arbimon Insights page richness tab for the TREES Forest Garden project in Homa Bay, Kenya.



CONCLUSIONS

Limitations & Future Recommendations

While this project has generated valuable insights, there is ample opportunity for expansion to better understand FGP's biodiversity impacts over time and space. There are currently no 'control' sites (e.g., traditional agriculture) in the project, meaning we cannot compare biodiversity in sites with and without FGP intervention.

In the future, monitoring traditional agricultural plots alongside FGP farms would allow for such direct comparisons, as outlined in the "Scenario Without Project" section of the CCB Standard. Moreover, long-term monitoring is essential to evaluate the sustained positive impacts on biodiversity over the project's lifespan, enabling assessment of "Expected Biodiversity Changes" in the CCB Standard. This underscores the critical need for long-term monitoring to track the arrival and establishment of threatened and rare species in project areas.

Moreover, the study is limited by the absence of reference sites representing "natural habitat," which could serve as an optimal baseline to work towards in FGP plots. Additionally, incorporating natural habitat sites would increase the likelihood of discovering new threatened species, facilitating the expansion of the CNN model. This, in turn, would support long-term monitoring efforts to track when new species move into FGP areas as they develop.

The CCB standard recognizes the importance of evaluating threatened, endemic, and rare species at national and regional levels. However, our efforts were impeded by the absence of a national Red List for Kenyan birds (BIODEV2030 2020) or a regional Red List for Homa Bay County. This limited our assessment of threatened species to global Red Lists. However, other initiatives, such as the African-Eurasian Migratory Landbirds Action Plan (AEMLAP), have identified additional species of concern. Identifying other similar types of action plans will help us conduct more detailed species threat assessments in the future.

Key Takeaways

Using an integrated passive acoustic monitoring and AI model pipeline, we detected 128 species across 67 sites within Forest Garden agroforestry plots (FGP) around Homa Bay, Kenya. The most commonly detected species were the village weaver, common bulbul, white-browed robin-chat, red-chested cuckoo, and black cuckoo. One species, the grey crowned crane, is classified as Endangered (IUCN RedList). We did not detect any invasive species, nor did we detect species endemic to the region.

While the lack of detections from endemic species may initially seem discouraging, this is actually expected given Kenya's overall low rate of bird endemism (only 9 of 1000 species are endemic). We did detect several species prioritized for conservation in the African-Eurasian Migratory Landbirds Action Plan (AEMLAP), such as the woodland kingfisher, African paradise-flycatcher, red-chested cuckoo, black cuckoo, blue-spotted wood-dove, and red-eyed dove.

We found that Acoustic Space Use (how saturated a soundscape is) at low frequencies was significantly higher in locations where FGP had been implemented for 2 and 3 years compared to year 0 sites. This disparity appears to be primarily influenced by increased bird vocal activity, indicating that sites participating in the FGP for longer may better support birds.

Notably, we found that sites in the FGP for 1-3 years exhibited higher bird occurrences at both the community and species levels compared to year 0 sites (<1 year in FGP). Furthermore, year 3 sites had higher species richness than year 0 sites, demonstrating that **sites in the FGP program have a positive impact on avian biodiversity**. We also found that maximum canopy height and proximity to Lake Victoria influenced bird occupancy. Bird species were more likely to occur in sites with high canopies (taller trees) and sites closer to the lake.
Our analyses provide compelling quantitative evidence that FGP sites are enhancing habitat quality and increasing species richness. Sites that have been in FGP longer have a higher number of bird species, demonstrating the success of restoration efforts even in the short term. The agroforestry practices implemented in FGP positively impact local wildlife, and these results can then inform compliance with the CCB Standard.

Our results provide important insights into species presence and distribution within FGP sites across the Homa Bay region of western Kenya. Additionally, the **AI model developed in this project can be re-used** to efficiently detect species in new datasets. **This will facilitate long-term monitoring** to assess patterns and trends as the FGP sites continue to develop over time.

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