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Research article

Impacts of traditional and industrial approaches to oil palm cultivation on bird biodiversity and conservation in a West African rainforest landscape

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ABSTRACT

Agricultural expansion threatens tropical ecosystems worldwide. Oil palm is cultivated primarily in Southeast Asia, but production in West Africa (its native range) is increasing rapidly. Here, oil palm is cultivated under traditional and industrial management, and the impacts on native West African ecosystems are poorly understood. Working within the framework of the Sustainable Oil Palm in West Africa (SOPWA) Project in Sinoe County, Liberia, we derived bird occurrence data using point count surveys across 54 plots in January–February 2023, spanning rainforest ('forest'), traditionally managed oil palm ('country palm'), and industrial oil palm systems, to investigate differences in bird species richness, community composition and community-level trait associations. Forest and country palm had comparable species richness, which was significantly higher than industrial oil palm. Taxonomic community composition differed across systems, with assemblages in country palm representing a mix of those in forest and industrial oil palm. Further, communities in forest and country palm were more associated with foraging in high strata, ant-associated behaviour, and an invertebrate diet. We detected four species of conservation concern in all systems, showing no consistent collective response to any specific system. Our findings show that country palm offers a promising option to preserve relatively high biodiversity as well as traditional cultivation practices in Liberia's managed landscape, although country palm is likely less productive than industrial oil palm. Oil palm systems are no replacement for rainforest ecosystems, and protection and designation of reserves and remnant forest patches are critical for wider bird conservation across West Africa.

1. Introduction

Agriculture is a dominant habitat globally, and expansion is increasing in the tropics (Ramankutty et al., 2018). Tropical agricultural production is needed to support human health and livelihoods and to achieve global food security goals in the long term, but unsustainable agricultural development threatens ecosystems worldwide (Oakley and Bicknell, 2022; Ramankutty et al., 2018). For instance, a recent meta-analysis

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focused on tropical agriculture globally found that, in comparison to native habitat, agriculture supports significantly fewer individuals and species of birds, herpetofauna and invertebrates (Oakley and Bicknell, 2022).

Oil palm (*Elaeis guineensis*), which produces palm oil, is grown pantropically as a cash crop (Descals et al., 2021; Meijaard et al., 2020). Oil palm is highly productive, yielding 2.5-6 times more vegetable oil per unit land than soybean or oilseed rape (Meijaard et al., 2020). Owing to its high productivity and profitability, palm oil is the most traded vegetable oil worldwide (USDA FAS, 2018), and production is integral to the economies of many tropical countries (e.g., the gross value of Malaysia's palm oil production in 2021 alone was >21 billion USD (Malaysian Palm Oil Council, 2021)). Further, production supports farmer livelihoods (Santika et al., 2020) and is a key component of current efforts to meet global food security goals (Meijaard et al., 2020). However, conversion of native habitat to oil palm systems (which often involves clear-cutting forest) has resulted in severe ecological consequences, including changes in habitat structure and microclimate, with associated declines in biodiversity and levels of ecosystem functioning (Drescher et al., 2016). Once plantations are established, ecological conditions are often further transformed owing to management associated with monoculture cultivation, including regular disturbance and applying high levels of chemical fertilisers and herbicides (Fitzherbert et al., 2008; Luskin and Potts, 2011). Depending on historical socioeconomic dynamics, oil palm cultivation can also adversely influence communities, for instance, by increasing the number of intra-community conflicts (Santika et al., 2019) or reducing the biodiversity of culturally important species (Strona et al., 2018). We urgently need to manage oil palm more sustainably in ways that maintain or increase yields while mitigating the environmental impacts of production (Luke et al., 2020; Zemp et al., 2023).

Most scientific understanding of oil palm as a crop derives from studies in Southeast Asia, where about 80% of traded palm oil is produced (Meijaard et al., 2020; Reiss-Woolever et al., 2021). Owing to rising labour costs, reduced land availability, and more stringent environmental regulations in Southeast Asia, oil palm cultivation is increasing rapidly in other tropical regions including West Africa (Pashkevich et al., 2024). Oil palm is native to West Africa and today is found commonly across West and Central Africa in low-lying rainforest areas (Corley and Tinker, 2016). As oil palm is native to this region, it is cultivated by local people using traditional practices that are regionally unique, which often involve managing and harvesting wild groves of oil palm (Pashkevich et al., 2024). In West Africa, traditional cultivation practices are carried out in addition to the practices developed in Southeast Asia. Such Southeast Asian management practices include industrial cultivation (involving growing oil palm as a monoculture across vast areas and using high chemical input and industrial machinery) and smallholder cultivation (involving a single farmer or group of farmers growing oil palm as a monoculture or polyculture and—in comparison to industrial oil palm—across a smaller area and with more variable chemical applications and less machinery) (Reiss-Woolever et al., 2021). While the impacts of oil palm cultivation in Southeast Asia are relatively well studied (for instance, at least three large-scale research programmes in Malaysia and Indonesia are investigating the social-ecological impacts of oil palm cultivation (Drescher et al., 2016; Ewers et al., 2011; Luke et al., 2020)), relatively little is known about the impacts of oil palm cultivation in West Africa, regardless of management practices (Pashkevich et al., 2024; Reiss-Woolever et al., 2021). Understanding the impacts of such land management practices on biodiversity is valuable from both conservation and crop production perspectives, owing to the important ecosystem services (e.g., pollination, pest control) that many species provide within oil palm systems (Dislich et al., 2017). In addition, it is likely that the impacts of oil palm cultivation in West Africa will differ from those in Southeast Asia, owing to differences in climate, geophysical, and ecological conditions between the regions, their distinct cultivation practices (as described above), and the co-evolution of oil palm in West Africa with other African species (potentially influencing species-to-species interactions including pest, predator, and disease dynamics within oil palm cultivation systems) (Pashkevich et al., 2024). More studies in this region are needed to assess whether the impacts of oil palm cultivation, mostly studied in Southeast Asia and South America, are consistent globally. Further, West Africa-based studies are needed to inform understanding of perennial crop expansion in this region, and pave the way for strategies to enable more-sustainable management (Pashkevich et al., 2024).

Birds are abundant and functionally important in many tropical habitats, including oil palm landscapes, where managing for bird biodiversity is relevant to both conservation and crop yields, owing to the pest-control services that many species provide. Studies indicate that birds exhibit a complex response to oil palm cultivation. In West Africa, studies comparing rainforest and oil palm plantations found that industrial management strongly reduced the number of bird individuals and species, while farms in close proximity to forest maintained bird biodiversity comparable to natural rainforest (Hamer et al., 2021; Ocampo-Ariza et al., 2019). These findings are similar to those from Southeast Asia, although certain species were highly abundant in oil palm depending on management practices (Azhar et al., 2011; Senior et al., 2013; Teuscher et al., 2015). Variability in bird responses to oil palm cultivation is partly trait-based. For example, in Malaysia, oil palm cultivation was associated with declines in the biodiversity of insectivores and frugivores but with increases in the biodiversity of granivores (Azman et al., 2011; Edwards et al., 2013). Trait-based responses indicate that some species capitalise on the environmental changes that are caused by oil palm cultivation. The homogenisation of vegetation structural complexity, for instance, provides open understory preferred by ground-foraging species (Almeida et al., 2016), while some species can capitalise on oil palm fruits as a food source (Barlow, 2021; Dueker et al., 2020; Eitniear and Bech, 2023). Such effects have the potential to assist conservation of threatened species, such as the grey parrot (*Psittacus erithacus*) in Southwest Cameroon, which was abundant in oil palm owing to its propensity to feed on the fruit (Dueker et al., 2020; Tamungang et al., 2016). Conversely, species that are highly specialised to forest (e.g., ant-following specialists) are likely to be particularly negatively affected by oil palm expansion (Ocampo-Ariza et al., 2019; Srinivas and Koh, 2016; Tchoumbou et al., 2020). Despite the enormous importance of oil palm cultivation to bird conservation, food supply, and livelihoods in West Africa, the extent to which traditional and industrial approaches to cultivation influence regional bird communities (including species of conservation concern) remains relatively unknown. It is risky to assume that findings from other oil palm cultivation regions (e.g., Southeast Asia and Latin America) will be replicated in West Africa, owing to West Africa's unique bird biodiversity and oil palm industry and cultivation styles.

In this work, we focus on the multi-use landscape of Southeast Liberia to investigate how traditional and industrial approaches to oil palm cultivation affect avian biodiversity, compared to native rainforest. Making use of joint species distribution models based on point count data collected within the framework of the Sustainable Oil Palm in West Africa (SOPWA) Project in Sinoe County, we assessed the influence of oil palm cultivation on all bird species including those of conservation concern. Comparing to rainforest, we ask whether traditional and industrial approaches to oil palm cultivation influence: (1) bird species richness and species-level community composition; (2) trait diversity, in terms of traits related to foraging and vertical strata preference; and (3) occurrence of bird species of conservation concern. We hypothesised that, in comparison to rainforest and oil palm under traditional management, industrially managed oil palm would (1) support the fewest number of bird species and exhibit the greatest change in taxonomic and trait community composition compared to native rainforest; (2) harbour fewer species specialised on an invertebrate diet and that forage in the canopy, but more species specialised on a plant diet; (3) still harbour species of conservation concern that can utilise oil palm. We respectively justify these hypotheses as follows: (1) industrial oil palm is the most intensely managed and least structurally complex of the studied systems (Pashkevich et al., 2024). Intensive management generally has a negative influence on biodiversity, and greater structural complexity typically begets higher levels of

biodiversity across animal groups (Drescher et al., 2016); (2) previous studies have shown that oil palm expansion negatively influences insectivorous birds (Ocampo-Ariza et al., 2019) and reduces canopy complexity (Luskin and Potts, 2011); (3) bird species of conservation concern (e.g., *Psittacus timneh*, 'Timneh Parrot') have been detected previously within oil palm landscapes (Lopes et al., 2018).

2. Methods

2.1. Study site

We conducted fieldwork in Southeast Liberia (Sinoe County), in the framework of the Sustainable Oil Palm in West Africa (SOPWA) Project (5.135195° N, 9.078423° W; Fig. 1). The SOPWA Project is a large-scale, replicated, field-based study that is investigating how traditional and industrial approaches to oil palm cultivation affect rainforest ecosystems (Pashkevich et al., 2024). It is a collaboration between international academic researchers, the Government of Liberia's Forestry Development Authority, local Liberian communities, and palm oil industry partner Golden Veroleum Liberia (GVL), the largest oil palm developer in the country and a member of the Golden Agri-Resources (GAR) group. Sinoe County is one of the most densely forested areas of West Africa, forming part of the Upper Guinean lowland rainforest bioregion/West Africa Forests ecoregion (Davis et al., 2020). It is a globally recognised biodiversity hotspot (Myers et al., 2000), and supports an array of rare and threatened species. For instance, thirteen of Liberia's twenty-two threatened bird species, according to the IUCN Red List, are found in Sinoe County (Suppl. Table 1) (IUCN, 2025), with eight of these species recorded during just one expedition in Sapo National Park (Liberia's largest protected area, and located in Sinoe County) alone (Freeman et al., 2019). Mean annual temperature in Sinoe County is 25.4 °C, and mean annual rainfall is 3633.0 mm (calculated over 1970-2000 from WorldClim data (Hijmans et al., 2005)). Since 2003, land development in Sinoe County has increased rapidly (including oil palm agriculture), after Liberia's domestic conflict ended. Oil palm is cultivated primarily in two ways in the country. First, local people, who traditionally practise shifting cultivation, burn small areas of rainforest annually (typically 2 ha or less) to grow crops for consumption. When preparing lands for farming, local people often choose areas with wild-growing oil palms (called 'country palms' locally), which survive the burning process or grow-up after the area is left to regenerate (typically after one or two years). Fruits from country palms are harvested to produce palm oil or to eat fresh, while the sap is used to produce palm wine. This 'country palm' cultivation system is unique to Africa and not found in Southeast Asia, where the majority of oil palm-focused studies have occurred (Pashkevich et al., 2024). Second, oil palm is cultivated by industrial companies. GVL currently manages six large-scale farms in Sinoe County, with ~19,000 ha cultivated (Pashkevich et al., 2024).

To evaluate the impact of traditional and industrial approaches to oil palm cultivation on bird communities, we surveyed birds in the SOPWA Project's ecological monitoring plots (Pashkevich et al., 2024). We surveyed 54 plots (each 50 × 50 m), with 18 plots in each of three systems (hereafter, 'System'; Fig. 1).

1) *Forest* – Areas of old-growth Upper Guinean lowland rainforest with no historical record of large-scale degradation/timber extraction. These areas are part of GVL's concession area but used by local people for hunting, harvesting of non-timber forest products (NTFPs), and spiritual and cultural purposes.
2) *Country palm* – These plots are in fallowed traditionally-managed smallholder farms with wild-growing oil palms ('country palms'), which are still harvested by local community members. Areas were farmed between two and thirty years ago, and therefore these are

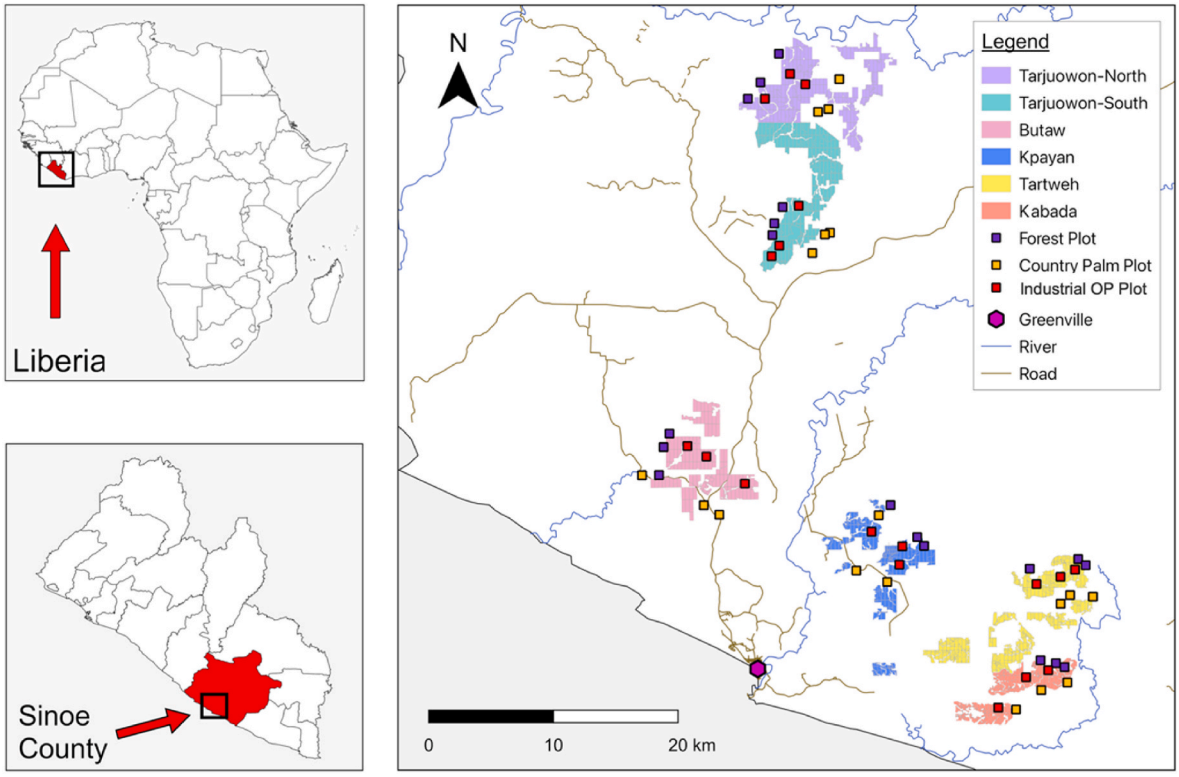

Fig. 1. Study area of the Sustainable Oil Palm in West Africa (SOPWA) Project in Sinoe County, Liberia. SOPWA Project study plots (50 × 50 m) are in forest (N = 18; purple squares), country palm (N = 18; orange squares), and industrial oil palm ('Industrial OP' in legend, N = 18; red squares) systems. Plots are spatially clustered in and around each of six industrial oil palm farms: Tarjuowon-North (purple), Tarjuowon-South (turquoise), Butaw (pink), Kpayan (blue), Tartweh (yellow), and Kabada (peach). The city of Greenville (pink hexagon), the capital of Sinoe County, is shown as a reference. Blue and brown lines indicate major rivers and roads, respectively. Figure originally published in (Pashkevich et al., 2024) under the CC BY 4.0 license (http://creativecommons.org/licenses/by/4.0/).

areas of dense, young regrowth (called 'low bush' by local communities). During farming, a variety of crops were grown. Chemical fertilisers, herbicides, or pesticides have never been applied within these plots. See Pashkevich et al. (2024) for information on crops previously grown in plots and years since farming occurred.

3) *Industrial oil palm* – These plots are in GVL's oil palm farms, which are monocultures and organised into 300 × 1000 m blocks, separated by dirt roads. Palms are planted approximately 8 m apart in a staggered design. Farms are managed according to business-as-usual practices, developed on estates in Southeast Asia, which include frequent application of herbicides and fertilisers. For full management details, see (Pashkevich et al., 2024). Palms are harvested manually (using a chisel or telescopic pole, depending on palm age) at 10-15-day intervals. All palms were fruiting (i.e., sexually mature), with ages ranging between five and 11 years at the time of sampling (Pashkevich et al., 2024). The farms are intersected by riparian reserves and small forest fragments, which were retained at the time of farm establishment (Pashkevich et al., 2024).

Plots are in six clusters (nine plots per cluster, and each cluster having three plots per system), arranged around the six GVL oil palm farms in Sinoe County (Fig. 1).

Before any fieldwork, we met with local communities and obtained prior informed consent for our work. At meetings, we recruited two local people to work with us as local guides, paying a standard accepted daily rate.

2.2. Bird surveying

Data collection occurred from January – February 2023, during the dry season. We surveyed birds by conducting 20-min point counts (led by A.N. G.) in each SOPWA Project plot (total plots = 54). We visited each plot once and surveyed between 6.30 and 11.30. Each morning of the survey period, we aimed to sample one plot in each system, semi-randomly alternating the order in which plots were surveyed to mitigate potential confounding impacts of survey time on our findings. During surveys, we recorded every bird seen and heard, pooling these data for analysis, and converting species-level data in each plot to binary data (i.e., whether the species was detected or not). We did not attempt to quantify bird abundance, due to potential bias stemming from differences in detectability in the different systems and the difficulty of distance sampling in tropical forests (Buckland et al., 2008).

We assigned traits to each detected species, using a selection of traits that we hypothesised to be important in explaining how communities are structured with respect to system (see Table 1). Broadly, these traits related to foraging strata (association to low strata: sum of association to ground and understory; or high strata: sum of association to midhigh strata and canopy), foraging lifestyle (ant-associated), or diet specialism (invertebrates; plants: sum of association with seed or other plant material diet, including cultivated crops). Ant-associated species included actively ant-following birds, as well as birds that frequently join mixed-species flocks around ant-following species, i.e. exhibit ant-associated foraging (Craig, 2022). We derived traits from the Elton database, for which traits are assessed semi-quantitatively based on the estimated percent relevance in text sections, derived in part by word order (Wilman et al., 2014). Higher values signify a stronger association with the given trait (e.g. a value of 100 for 'Diet: Invertebrates' suggests no other food source is mentioned). Because our low- and high-strata association scores always summed to 100 (e.g. a low-strata association of 70 implies a high-strata association of 30), using only the high-strata category captured the entire variation. See Supplementary Table 2 for an overview of all species-specific trait values included in the analysis.

To consider the influence of oil palm cultivation on conservation-relevant species, we additionally classified species by their global IUCN Red List category using the package *rredlist* (Gearty and Chamberlain, 2025) in *CRAN R* (R Core Team, 2025), and considered species 'Threatened' if they fell into the 'Vulnerable', 'Endangered' or 'Critically Endangered' category.

2.3. Statistical analyses

We conducted all statistical analyses in *R* (version 4.4.3 (R Core Team, 2025)). We used *tidyverse* (Wickham et al., 2019) for data exploration, wrangling, and visualisation.

We analysed differences in bird communities across systems (rainforest, country palm, industrial oil palm) in a unified framework, using joint species distribution models (jSDMs) in the *Hmsc* package version 3.3-4 (Tikhonov et al., 2025). jSDMs estimate each species' environmental niche while jointly modelling the residual covariation in occurrences among species (Ovaskainen et al., 2017), i.e. covariation not explained by the measured environment. This improves uncertainty propagation across the community but does not alter the estimation of species' environmental responses. Within jSDMs, the Hierarchical Modelling of Species Communities (HMSC) framework has gained increasing popularity due to its flexibility and broad applicability, and better predictive ability compared to other jSDMs (Norberg et al., 2019). In the HMSC framework, community-level variation is partitioned in a hierarchical structure that is estimated jointly. Species' environmental niches are modelled as a function of species traits (here association with high foraging strata, ant-associated behaviour, association with invertebrate or plant and seed diet). Because the complete set of traits is rarely known or quantified across all species in the survey, the influence of unknown traits is inferred by the presence and strength of a phylogenetic signal, or taxonomic relatedness used as a proxy of phylogeny (i.e. closely related species are assumed to share similar traits) (Ovaskainen and Abrego, 2020). Covariation in occurrences that remains after accounting for the environmental predictors, traits, and relatedness is captured as residual species associations through the random-effects structure, describing pairs of species that co-occur

Table 1
Overview of species traits included in the community analysis. SOPWA: Sustainable Oil Palm in West Africa Project.

Trait	Description	Rationale	Source
Foraging strata: High	Degree of association (0-100), sum of mid-high and canopy association	Previous work in SOPWA shows oil palm cultivation reduces canopy height and complexity (Marshall et al., 2024), likely negatively impacting birds in this microhabitat and potentially favouring birds that forage in lower strata	Elton Traits 1.0 (Wilman et al., 2014)
Foraging lifestyle: Ant-associated	Binary classification (0 or 1)	Ant-associated birds shown to be less common in oil palm compared to rainforest in West Africa (Ocampo-Ariza et al., 2019)	Craig (2022)
Diet: Invertebrates	Degree of association (0-100)	Insectivorous birds are often sensitive to habitat loss/conversion to oil palm (Senior et al., 2013; Tchoumbou et al., 2020); previous work in SOPWA shows oil palm cultivation changes invertebrate communities, with different impacts in industrial oil palm versus country palm (Timperley et al., 2025)	Elton Traits 1.0 (Wilman et al., 2014)
Diet: Plants	Degree of association (0-100)	Previous work in SOPWA shows oil palm cultivation changes plant communities, with country palm and industrial oil palm having different impacts (Marshall et al., 2024), potentially affecting the food sources available to birds and space availability for ground foraging (Tchoumbou et al., 2020)	Elton Traits 1.0 (Wilman et al., 2014)

more or less often than expected from their environmental niches alone. Further residual structure can be accommodated through non-spatial or spatially explicit random effects, the latter quantifying greater similarity between plots that are closer together (i.e. spatial autocorrelation). We interpret these residual associations as patterns of covariation rather than direct biotic interactions, since co-occurrence alone cannot separate interaction from shared responses to unmeasured environmental factors (Blanchet et al., 2020; Poggiato et al., 2021).

We defined a taxonomic tree at species level, based on the GBIF taxonomic backbone ('classification' function in the package *taxize* (Chamberlain and Szöcs, 2013)). We included traits using an additive trait formula in the format: '~ ant-associated + diet: plants + diet: invertebrates + foraging strata: high'. To ensure parsimony, we tested collinearity of these traits based on variance inflation factors (VIF) and linear correlation coefficients in the package *usdm* (Naimi et al., 2014). VIFs were below 1.5 for all traits, and linear correlation coefficients were at most −0.48, indicating no serious collinearity.

In terms of random effects structure, we included a full spatial random effect based on exponential distance decay to account for spatial autocorrelation in residuals. To account for additional latent cluster-specific factors, we included a random effect of farm identity.

Since infrequently occurring taxa contribute little to jSDMs, complicate model convergence (Ovaskainen and Abrego, 2020), and their removal typically does not affect broad community patterns (Edwards et al., 2013, 2021), we included only species observed at least four times. This filtering step retained 77 bird species, or 55.8% of the original species pool. We tested the potential effects of species omissions on community turnover results by comparing non-metric multidimensional scaling (NMDS) plots using the full as well as filtered species pool. We created NMDS plots based on Jaccard dissimilarity and 1000 tries in the 'metaMDS' function in the package *vegan* (Oksanen et al., 2025). Community dissimilarity between systems was not affected by this filtering step (Suppl. Fig. 1).

Due to the binary nature of the data, we fitted our model using a probit distribution. We conducted posterior sampling using four Markov Chain Monte Carlo (MCMC) chains, each sampled for 1,125,000 iterations. Of these, we discarded the initial 375,000 iterations as a transient (burn-in) phase and applied a thinning factor of 750 to the remaining iterations, yielding 1000 posterior draws per chain (4000 draws in total). To speed up computations, we implemented GPU-porting through '*Hmsc-HPC*' (Rahman et al., 2024).

We evaluated MCMC convergence using potential scale reduction factors over parameters related to the fixed effects in the model (beta) as well as traits (gamma), taxonomic relatedness signal (rho), and spatial random effect (alpha), where median values not exceeding 1.1 suggested satisfactory convergence (Ovaskainen and Abrego, 2020).

We evaluated individual model performance in estimating species based on both the explanatory and predictive ability of the model. For the explanatory ability, we compared all model predictions derived using the full dataset with observed values, using the Tjur R^2, root mean squared error (RMSE), and area under curve (AUC) statistic. Based on explanatory performance in comparable published examples (Barrero et al., 2023; Bonfim et al., 2024; García-Navas et al., 2023), we expected average explanatory Tjur R^2 across the community to lie in the range of 0.06 - 0.3 for a well-fitting model. We assessed predictive ability with cluster-based cross-validation. Since plots on different clusters were always spaced by at least ~5 km, and each cluster featured the same number of plots per system, this setup prevented performance inflation from spatial proximity between testing and training points and avoided uneven covariate distributions across folds. For each fold, we used one of the six clusters as the testing partition and predicted the bird community using the remaining data. We then compared predictions for each testing partition with observed values using the Tjur R^2, RMSE, and AUC, and derived a summary performance value using the average across all folds. For a well-fitting model, we expected the predictive performance to be lower yet close to the explanatory performance, with a large discrepancy suggesting overfitting (Ovaskainen and Abrego, 2020).

We presented contrasts in posterior species- or trait-level estimates between systems using median values with 95% credible intervals visualising uncertainty, based on the 'plotGradient' function in HMSC. We derived statistical support for each contrast of system pairs by computing the proportion of posterior draws in which the estimate of one system exceeded that of the other.

2.3.1. *Do traditional and industrial approaches to oil palm cultivation influence bird species richness and species-level community composition in Liberian rainforest landscapes?*

To assess changes in species richness, we first visualised how species distributed and overlapped between systems with Venn diagrams derived using the package *ggVennDiagram* (Gao and Dusa, 2024). We then visualised observed and extrapolated species numbers in each system, alongside estimates of sampling completeness, using sample-based species accumulation curves in the package *iNEXT* (Hsieh et al., 2024), based on the full species pool. Finally, we statistically compared species richness using a generalised linear mixed effects model (GLMM) in the package *lme4* (Bates et al., 2015) with Poisson family distribution, containing system as a fixed effect, and a random intercept term of cluster. We evaluated our GLMM based on plots of simulated residuals in the package *DHARMa* (Hartig, 2024) and compared system estimates using pairwise post-hoc tests in the package *emmeans* (Lenth, 2025) with Tukey multiplicity adjustment.

To identify evidence for general community turnover between systems in terms of species composition, we estimated the relative variance in occurrence explained by fixed and random effects in the fitted model, at the species level, using the 'computeVariancePartitioning' function in HMSC. We scaled variance values by the overall explanatory ability of the model for each species to reflect model uncertainties. Next, we visualised how species' responses to specific systems were distributed across the community as well as taxonomically structured, using beta plots based on the 'plotBeta' function in HMSC, with a 0.95 support threshold, essentially highlighting species with ≥ 95% posterior support for presence or absence in each focal system relative to the reference level.

2.3.2. *Do traditional and industrial approaches to oil palm cultivation influence bird trait diversity, in terms of traits related to foraging?*

To assess the degree to which species' traits related to foraging explained community shifts between systems, we visualised differences in community-weighted mean trait values between the systems using the 'plotGradient' function and derived posterior support for trait effects on species responses using the 'plotGamma' function in HMSC with a 0.9 support threshold. We identified species' potential to shift community trait values in each oil palm system, relative to forest plots, by ranking them according to a 'Potential Trait Contribution Index' (PTCI), calculated as

$$\mathbf{PTCI_{s,t}} = \mathbf{VP_s} * \mathbf{beta_s} * \mathbf{assoc_{s,t}}$$

where VP_s is the variance of occurrence of species s explained by system, $beta_s$ is the directional posterior support estimate (presence or absence) for a given oil palm system relative to the intercept (forest plots) for species s, and $assoc_{s,\ t}$ is the magnitude of association of species s with trait t (divided by 100 for association traits). Species with a high positive PTCI score were therefore those most associated with the trait (e.g., association with invertebrate diet approaching 100) while also responding strongly positively to system differences (i.e., system explained large amounts of variance in occurrence, and the species was substantially more likely to be observed in the given system compared to forest plots). While advantageous due to its easier interpretability, this index is not community-weighted, and values might hence differ from realised predictions especially in rare species.

We tested the residual contribution of taxonomic relatedness on results using quantiles of posterior estimates for the taxonomic relatedness factor rho, where 95% credible intervals not overlapping zero constitute a well-supported signal.

2.3.3. Do traditional and industrial approaches to oil palm influence occurrence of bird species of conservation concern?

We visualised differences in bird communities according to their IUCN threat status across systems, using categories 'Critically Endangered', 'Endangered', 'Vulnerable', 'Near Threatened' and 'Least Concern'. We then highlighted system associations of threatened species ('Critically Endangered', 'Endangered' or 'Vulnerable') using posterior occurrence estimates from HMSC model results.

3. Results

3.1. Do traditional and industrial approaches to oil palm cultivation influence bird species richness and species-level community composition in Liberian rainforest landscapes?

We detected 138 bird species across surveys, with 88 species in forest, 94 species in country palm, and 71 species in industrial oil palm systems (Fig. 2A). The five most-detected species were *Tauraco macrorhynchus* ('Yellow-billed Turaco', 46 plots), *Eurillas virens* ('Little Greenbul', 36 plots), *Cyanomitra olivacea* ('Olive Sunbird', 32 plots), *Nicator chloris* ('Western Nicator', 29 plots), and *Turtur afer* ('Blue-spotted Wood Dove', 27 plots). There was some, but not complete, overlap in species across systems (Fig. 2A). Forest and country palm shared a unique set of 29 species (21% of total species), while only 3 species (*Bycanistes fistulator*, 'Piping Hornbill'; *Cyanograucalus azureus*, 'Blue Cuckooshrike'; *Dryotriorchis spectabilis*, 'Congo Serpent Eagle') were uniquely shared between forest and industrial oil palm (2%) (Fig. 2A). Forest and country palm shared the largest number of species overall (64 species, 46%), followed by country palm and industrial oil palm (48 species, 34%) and finally forest and industrial oil palm (38 species, 27%). Species accumulation curves were levelling off (Fig. 2B), with sampling completeness in all systems estimated at >91%. Bird species richness differed significantly across rainforest, country palm, and industrial oil palm systems ($\chi^2 = 22.6$, $P_{System} < 0.001$). Industrial oil palm (Mean ($\overline{X}$) ± standard error (SE) = 15.3 ± 0.92 species) had significantly fewer bird species on average than forest (20.5 ± 1.07 species, $P_{Comparison} = 0.001$) and country palm (22 ± 1.11 species, $P_{Comparison} < 0.001$) (Fig. 2C).

The HMSC evaluation steps showed good explanatory performance across the community (average R^2: 0.2, average RMSE: 0.32, average AUC: 0.88) that did not differ strongly from the cross-validated predictive performance (average R^2: 0.14, average RMSE: 0.34, average AUC: 0.62), suggesting that the model did not overfit to the data (Suppl. Fig. 2). The top 50% of models by explanatory performance reached an average explanatory R^2 of 0.3 (RMSE of 0.34).

The beta plot of species responses revealed that species found in forests were more frequently absent from industrial oil palm plots. Thirty-five species (45.5% of the total) were substantially less likely to be present in industrial oil palm (Fig. 3A). In comparison, only half as many species were more likely to be observed in industrial oil palm over forest plots (n = 19, 24.7% of the total) (Fig. 3A). For country palm, probability of presence or absence relative to forest were more evenly balanced: fourteen species (18.1%) were more likely to be observed in

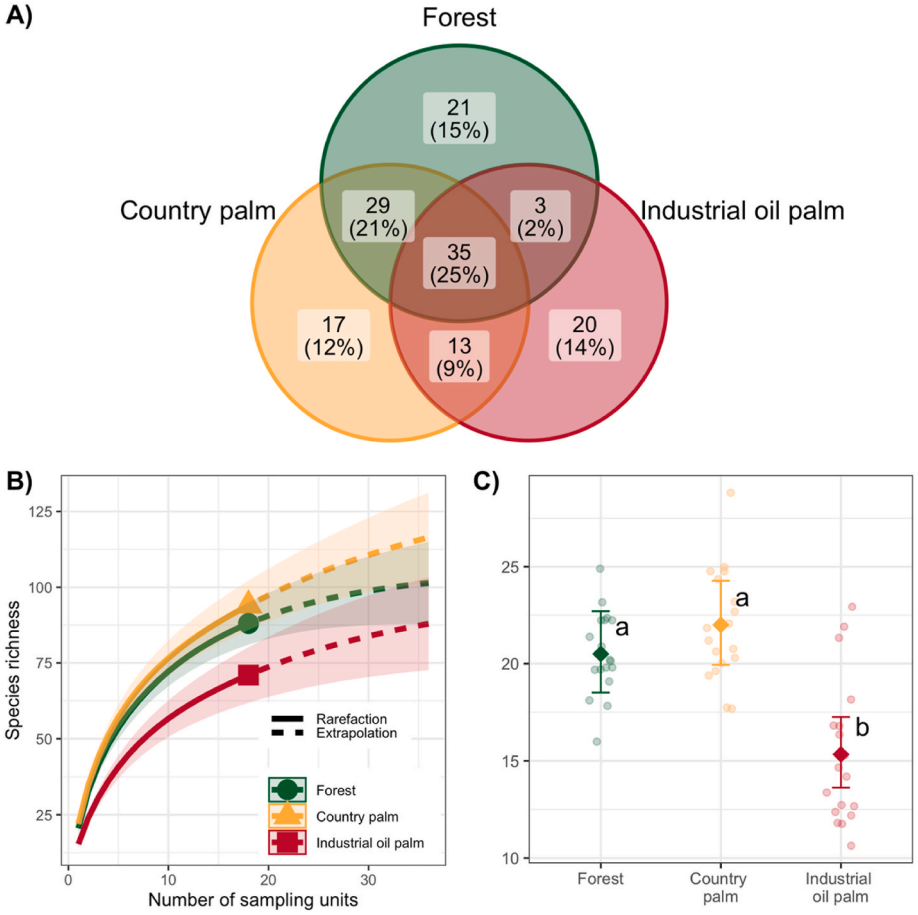

Fig. 2. Comparison of total species richness observed in the study. A) Venn diagram showing distribution and overlap of species between systems (with counts and percentages of total species counts). B) Sample-based species accumulation curves, with extrapolated occurrence data to double the number of samples. Points represent the highest number of observed species in each system. C) Mean estimated species richness (diamonds) with upper and lower confidence levels (error bars) for each system. Background points are observed richness values at each plot, by system. Letter annotations give significance of pairwise comparisons, where differing letters highlight a significant difference in mean estimates ($P < 0.05$).

forest compared to country palm, and twenty species (26% of the total) showed the opposite trend (Fig. 3A). Responses to industrial oil palm were frequently mirrored for country palm, with 44 species (57% of the total) showing the same direction of association (positive or negative) with country palm relative to forest as they did for industrial oil palm, although magnitudes of positive association differed (Fig. 3A).

System explained the largest amount of variance in species occurrence, with an average of 16.8% across all species, providing strong

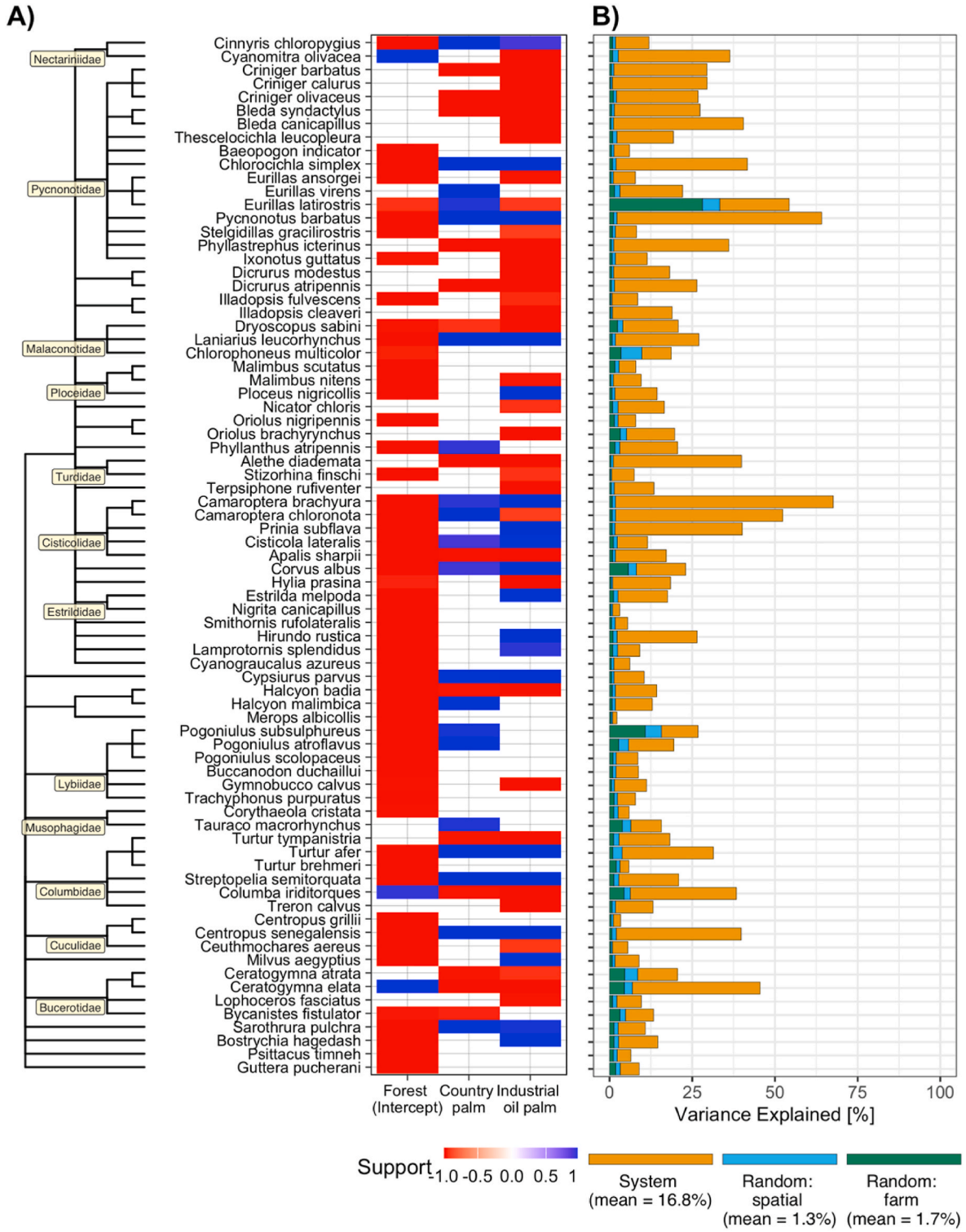

Fig. 3. Overview of HMSC model results detailing species' associations with different systems. A) Posterior support estimates for species-specific associations with each of the three systems in the model. Forest plots represent the intercept, i.e. the reference level in the model. The colour scale differentiates positive (blues) from negative (reds) estimates, while the transparency reflects the degree of the trend. Estimates below the posterior support threshold of 0.95 are set to be fully transparent. The taxonomic tree along the y-axis reflects the taxonomic relatedness used during model fitting. Labels overlaying the taxonomic tree represent family nodes. B) Variance partitioning plot visualising the species-level proportional variance in occurrence explained by the fixed (i.e. system) and random effects in the model (i.e. spatial and farm). Variance proportions are scaled by the overall explanatory power of the HMSC model for each species, measured by Tjur R^2.

evidence for community turnover at the system level (Fig. 3B). The random effect of farm identity explained an additional 1.7% of variance, on average, across the community. For two species, *Eurillas latirostris* ('Yellow-whiskered Greenbul') and *Pogoniulus subsulphureus* ('Yellow-throated Tinkerbird'), large proportions of variance were explained by farm alone (51.7% and 40.2% of total variance explained, respectively), suggesting that unexplained farm-level effects, beyond system, were driving occurrence patterns (Fig. 3B). An additional 1.3% of variance, on average, was explained by the spatial random effect (Fig. 3B), suggesting mild spatial structuring in responses. Certain species exhibited strong habitat associations paired with large amounts of variation explained by system, highlighting them as key species driving community change (Fig. 3A–B). *Pycnonotus barbatus* ('Common Bulbul') and *Camaroptera brachyura* ('Grey-backed Camaroptera') were most likely to be observed in industrial oil palm compared to forest, paired with the overall largest amounts of occurrence explained by system (62% and 65.8%, respectively), and *Phyllastrephus icterinus* ('Icterine Greenbul') and *Alethe diademata* ('White-tailed Alethe') were most likely to be observed in forest compared to industrial oil palm, although with lower variance explained (34.8% and 38.8%, respectively) (Fig. 3A–B). Supplementary Fig. 3 shows detailed species-level occurrence patterns by system, with posterior model estimates.

3.2. Do traditional and industrial approaches to oil palm cultivation influence bird trait diversity, in terms of traits related to foraging?

Of the species retained for the joint species distribution model in HMSC, 14 were ant-associated. Association with the trait 'Diet: Invertebrates' ranged from 0 to 100 with a mean of 55.8 ± 3.8, association with the trait 'Diet: Plants' ranged from 0 to 90 with a mean of 11.8 ± 2.1, and association with the trait 'Foraging strata: High' ranged from 0 to 100 with a mean of 50 ± 4.3 in the species community. Supplementary Table 2 provides an overview of all species-specific trait values included in the model. In the beta plots, more closely related species tended to exhibit similar responses, such as species in the genera *Criniger* and *Bleda* (Fig. 3A). However, we did not find support for taxonomic structuring of species' habitat associations, suggesting that these similarities in responses were sufficiently explained by species traits in the model.

The traits included in our model explained 31.4% of variance in overall species occurrences. Traits explained the largest proportion of variance among species (i.e. the degree to which system associations were shared between species with similar traits) in industrial oil palm (28.6%), followed by forest (16.2%) and country palm (14%). This corresponded to community turnover in trait composition, with forest communities being positively associated with high foraging strata and ant-associated behaviour, compared to negative associations for these same traits in industrial oil palm. Both land uses shared a negative association to invertebrates overall (Fig. 4A). Country palm also had a negative association to high foraging strata species (Fig. 4A). Compared to forest, country palm exhibited a reduction in association to high foraging strata from 58 (Credible interval (CI): 54.5-62) to 47.4 (CI: 43.9-51.1) (median difference = 10.7, Probability of decrease (P(decrease)) = 1), with a larger decrease observed in industrial oil palm, where the median association was 33.6 (CI: 29.4-38.4) (median difference = 24.5, P(decrease) = 1) (Fig. 4A and B). The drop in high-strata association in industrial oil palm compared to forest was most strongly driven by *Columba iriditorques* ('Western Bronze-naped Pigeon'), *Criniger calurus* ('Red-tailed Greenbul') and *Phyllastrephus icterinus* ('Icterine Greenbul') (Suppl. Fig. 4).

Industrial oil palm contained a lower proportion of ant-associated species in the community than forest (median difference: 0.11, P (decrease) = 0.99) or country palm (median difference: 0.15, P (decrease) = 1), alongside lower associations with invertebrate diet (difference: 7.8, P(decrease) = 0.94) compared to forest, while forest and country palm did not differ significantly in these traits (Fig. 4A–C, D). Ant-associated species that drove the decline of this trait in industrial oil palm were *Camaroptera chloronota* ('Olive-green Camaroptera'), *Bleda canicapillus* ('Grey-headed Bristlebill'), and *Alethe diademata* ('White-tailed Alethe') (Suppl. Fig. 4). The reduction in association with an invertebrate diet was largely caused by this same group of species not being found in industrial oil palm (Suppl. Fig. 4). Communities at industrial oil palm plots were characterised by a slightly higher association with a plant and seed diet (median difference: 7.2), though this was below the support threshold of 0.9 (Fig. 4A–E). This trend was driven most strongly by *Turtur afer* ('Blue-spotted Wood Dove') and *Streptopelia semitorquata* ('Red-eyed Dove') (Suppl. Fig. 4).

3.3. Do traditional and industrial approaches to oil palm influence occurrence of bird species of conservation concern?

Of the 138 species detected, 127 species were listed as Least Concern, seven species as Near Threatened, three species (*Ceratogymna elata*, 'Yellow-casqued Hornbill'; *Criniger olivaceous*, 'Yellow-bearded Greenbul', *Phyllanthus atripennis*, 'Grey-hooded Capuchin Babbler') as Vulnerable, and one species (*Psittacus timneh*, 'Timneh Parrot') as Endangered (Fig. 5A). Threatened species (i.e., species with an IUCN Red List status of Vulnerable or Endangered) represented only a small portion (2.2%) of all species observed and were found in all systems (Fig. 5).

System explained 38.7% of variation in the occurrence of *C. elata* (Fig. 3B). The species was most likely to be found in forest (median P (presence) = 0.80, CI: 0.41-0.97; Fig. 5B), with strong posterior support for higher presence there than in country palm (median P(presence) = 0.19, CI: 0.02-0.54) or industrial oil palm (median P(presence) = 0.10, CI: 0.01-0.39) (Figs. 3A and 5B).

For *C. olivaceous*, system accounted for 24.7% of occurrence (Fig. 3B). It was also most likely to be found in forest (median P(presence) = 0.31, CI: 0.09-0.63; Fig. 5C), with strong posterior support for higher presence there than in country palm (median P(presence) = 0.02, CI: 0-0.17) or industrial oil palm (median P(presence) = 0, CI: 0-0.05) (Figs. 3A and 5C).

Contrastingly, for *P. atripennis*, system accounted for 17.5% of occurrence (Fig. 3B). It was most likely to be found in country palm (median P(presence) = 0.37, CI: 0.14-0.67; Fig. 5D) and less likely to be found in forest (median P(presence) = 0.13, CI: 0.02-0.39) or industrial oil palm (median P(presence) = 0.02, CI: 0-0.18), with strong posterior support for these contrasts (Figs. 3A and 5D).

System explained little of the occurrence of *P. timneh* (4.2%, Fig. 3B), and no clear system association was detected in the beta plot (Fig. 3A). There was slight statistical support for an increased probability of presence in industrial oil palm (median P(presence) = 0.19, CI: 0.04-0.46) compared to forest (median P(presence) = 0.06, CI: 0.01-0.26; Fig. 5E).

4. Discussion

In this study, we compared the biodiversity of birds across rainforest and two oil palm cultivation systems ('country palm', i.e., fallowed farmland with wild-growing oil palms, managed traditionally by local Liberian communities, and industrial oil palm plantations). We found that country palm supports a comparable number of species to rainforest, and both country palm and rainforest support more species than industrial oil palm. We also found that while there were shared species across the landscape, bird community composition differed across all systems related to changes in species and traits, highlighting the impact of land-use change in the region. We additionally found that threatened bird species (i.e., with an IUCN Red List status of Vulnerable or Endangered) were present in all systems but tended to be found more commonly in forest and country palm over industrial oil palm.

4.1. Impacts of converting rainforest to oil palm

In this study, we demonstrated that conversion of rainforest to oil palm profoundly affects bird communities in West Africa, reducing species

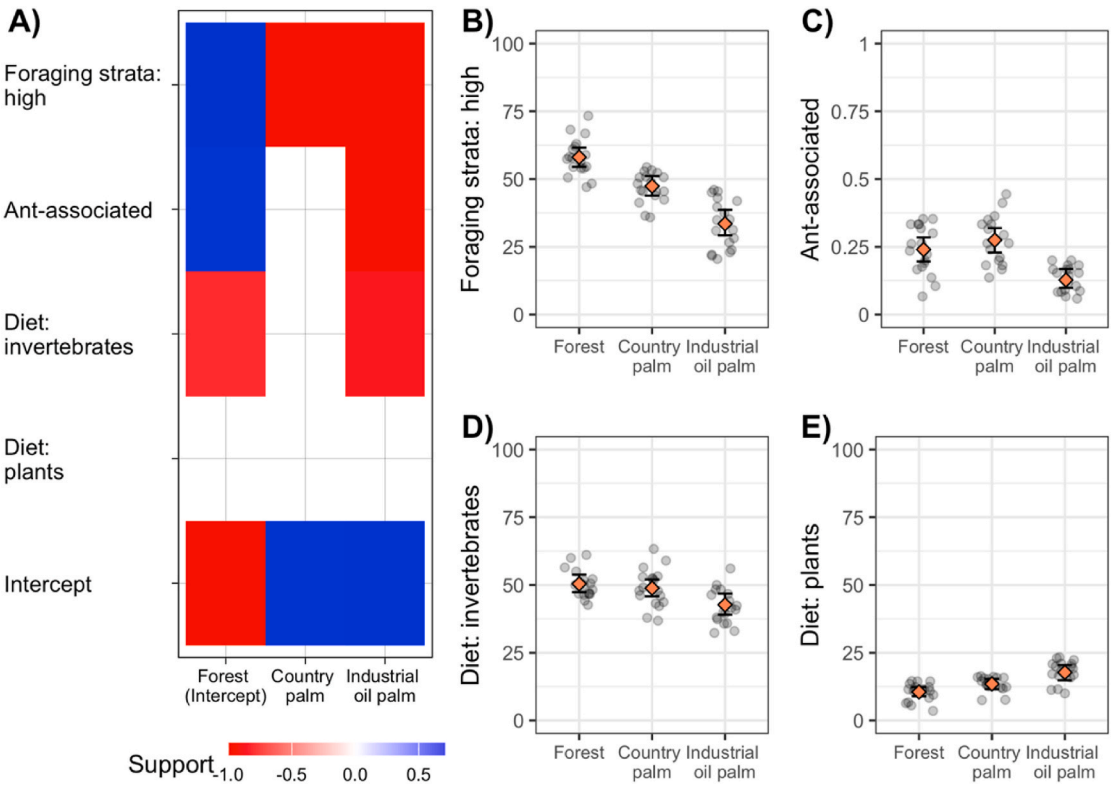

Fig. 4. Overview of HMSC model results related to species trait relationships. A) Posterior support for trait effects on system associations across the species community. Colour scale differentiates positive (blues) from negative (reds) support estimates, while the transparency reflects the degree of the trend. Estimates below the posterior support threshold of 0.9 are set to be fully transparent. Forest plots on the x-axis represent the intercept, i.e. the reference level in the model. B) - E) Posterior community-weighted mean estimates of trait values (orange diamonds) alongside credible intervals (vertical error bars) for each system, with observed community-weighted mean trait values for each plot (black points).

richness and reshaping species and trait composition. The strongest impact occurred in industrial oil palm plantations, where species numbers declined, and communities shifted towards low foraging heights with weaker ties to invertebrate diets and ant-associated behaviour.

Previous SOPWA Project research found that oil palm cultivation markedly reduces vegetation complexity, including stand structural complexity index (SSCI), canopy height (Marshall et al., 2024) and ground vegetation cover (Pashkevich et al., 2024), and changes the abundance of some taxonomic groups of ground-dwelling arthropods, leading to arthropod community turnover between systems (Timperley et al., 2025). Although we did not directly test the effects of these variables on birds (all these variables were directly collinear with system), existing research points to potential causal links. Vegetation complexity has previously explained losses in understory bird biodiversity in oil palm plantations (Aratrakorn et al., 2006; Nájera and Simonetti, 2010). Insectivorous birds, often adapted to inhabiting lower forest strata, are especially sensitive to habitat alteration (Canaday, 1996; Gray et al., 2007; Miller et al., 2021; Sekercioglu et al., 2002), so the marked changes in vegetation complexity seen in SOPWA plots might explain the lower incidence of insectivorous birds we observed in industrial oil palm. Lower complexity reduces available ecological niches for this group in terms of foraging strategies and microclimates (Castaño-Villa et al., 2014; Mammides et al., 2015), while also reducing insect prey abundance (Allen, 2016; Rebaudo et al., 2016), supporting fewer insectivore species. Since structural complexity is inversely correlated with microclimate metrics (Ehbrecht et al., 2017), our country palm and industrial oil palm plots differed from forest plots in both of these factors (Pashkevich et al., 2024), a difference that plausibly contributed to the observed reduction in association with insectivore diet. Aside from vegetation complexity, tropical rainforest insectivores are generally sensitive to changes in the community composition of insect prey due to high diet specialism (Mansor et al., 2018; Sherry et al., 2020), potentially excluding species specialised on arthropods that are mainly found in forest plots in the SOPWA study area. This combination of factors may therefore have contributed to the patterns we documented in insectivore birds.

In terms of ant-associated species, research has identified changes in ant communities and ant-swarm behaviour in response to conversion of habitat to tropical crops, including oil palm (Luke et al., 2014; Ocampo-Ariza et al., 2019; Peters and Okalo, 2009), and potential loss of ant species richness where adjacent forest cover decreases (Lucey et al., 2014). Consequently, ant-associated birds can decline in oil palm compared to forest (Ocampo-Ariza et al., 2019), as we observed in our study.

The reduction in canopy height in our study likely explains the observed reduction in association with high-strata foraging in oil palm. Of the species identified as contributing most strongly to this trend, some frequently perch in the midstory and actively forage in the foliage (*P. icterinus*, 'Icterine Greenbul'; *C. calurus*, 'Red-tailed Greenbul'), or almost exclusively live in the forest canopy (*C. iriditorques*, 'Western Bronze-naped Pigeon'). Where this habitat is replaced with the lower and structurally different canopy of oil palm, many of the requirements of these species disappear. In line with this, previous research in Southeast Asia showed a near-complete loss of arboreal foraging species in oil palm compared to rainforest (Edwards et al., 2013).

We acknowledge that we did not formally test the effects of these drivers on bird biodiversity, and future research is needed to establish causal links between establishment and management of African oil palm systems on avian diversity. Such future research could also consider a wider breadth of traits, such as those related to nesting and reproduction (detailed reproductive traits for all species were unavailable at the time of this study). However, fulfilling foraging requirements is a prerequisite of reproductive success (Lescroël et al., 2010; Vollrath, 1987), suggesting

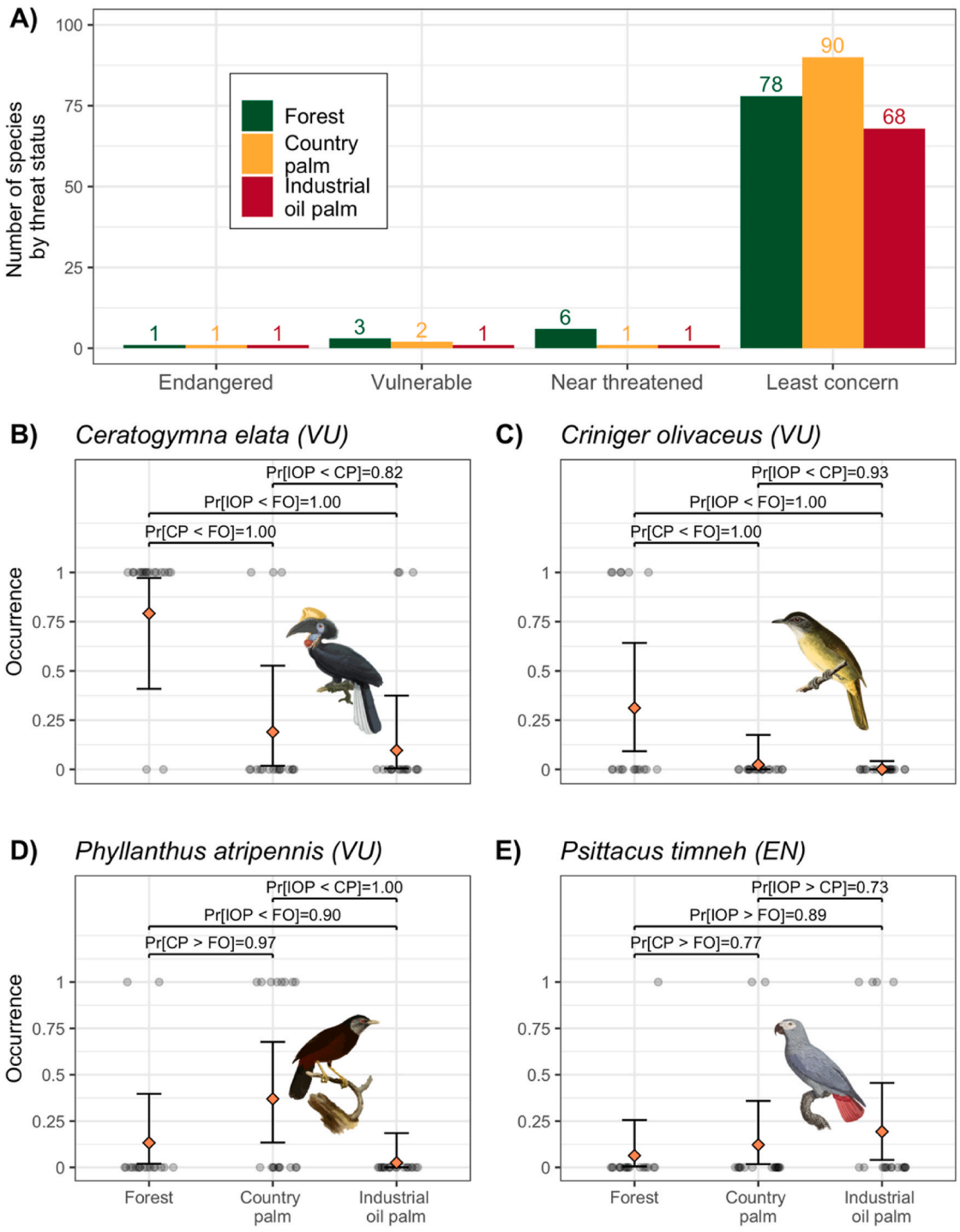

Fig. 5. A) Overview of the number of species by IUCN threat level in each system studied (forest, country palm, industrial oil palm). B)-E) Posterior HMSC model estimates of probability of presence in each system (orange diamonds) of the four species classified as threatened (IUCN Red List status of Vulnerable (VU) or Endangered (EN)) in the study, alongside 95% credible intervals (vertical error bars). Also shown are observed species occurrences at each plot (black points). B) *Ceratogymna elata* ('Yellow-casqued Hornbill'), C) *Criniger olivaceus* ('Yellow-bearded Greenbul'), D) *Phyllanthus atripennis* ('Grey-hooded Capuchin Babbler'), E) *Psittacus timneh* ('Timneh Parrot'). Annotations provide posterior support for contrasts between the systems. FO: forest; CP: country palm; IOP: industrial oil palm. Inset images in B)-E) are traced versions of public-domain illustrations obtained from Wikimedia Commons.

overlap in responses of these traits. Including abundance as a biodiversity metric might provide further information, with previous research suggesting that bird diversity responses to oil palm differ when considering abundance compared to species richness (e.g. individual species becoming more abundant while richness decreases, leading to lower species evenness (Azhar et al., 2011; Srinivas and Koh, 2016)). However, reliably assessing abundance of birds is difficult and bias is easily introduced through differences in detectability (Buckland et al., 2008; de Oliveira e Silva et al., 2017; Meadows et al., 2012). Occurrence data can adequately be used to model bird populations when abundance data are not available (Estrada and Arroyo, 2012; Joseph et al., 2006).

A further limitation is that we surveyed each plot only once. Repeated sampling would have led to more precise estimates of plot-level species richness, and would have helped to distinguish genuine absence from

failure to detect a species during the 20-min survey. In temperate forests, a single visit has been shown to capture 70–75% of the species recorded across three visits, and a single 20-min count recorded a similar number of species to two 6-min counts at the same point (Petit et al., 1995). In species-rich tropical forest, however, species accumulate more slowly, with new species still being detected after eight repeated 20-min counts (Esquivel and Peris, 2008). Our richness estimates should therefore be considered conservative. This underestimation is likely to be greatest in our forest sites, where many species are rare and dense foliage and understory vegetation reduce detection (Darras et al., 2016; Pacifici et al., 2008), so repeated sampling would likely widen the differences in richness we found between rainforest and oil palm systems.

We found that traditional and industrial oil palm cultivation lead to changes in species richness and taxonomic and trait composition compared to rainforest, identifying both winners and losers of oil palm cultivation. This reflects the importance of studying whole bird community responses to cultivation rather than the biodiversity of only a few flagship species, and indicates that oil palm systems can provide some important resources (e.g. food, shelter, refugia habitat in passing) that support birds in the landscape. Importantly, of the four threatened bird species we detected across our surveys, three were found in country palm and two in industrial oil palm, in addition to being found in rainforest. *P. timneh*, a close relative of *P. erithacus* and only recently declared a separate species (Smith et al., 2024), was detected most often in industrial oil palm. The species, and other frugivorous species we detected, was likely seeking out palm nuts and fruits as a food source, as demonstrated in previous studies (Dueker et al., 2020;Benedictus Freeman et al., 2018; Tamungang et al., 2016), particularly since our surveys occurred in the dry season which is the peak fruiting season. However, this species' specialised nesting and roosting requirements (secondary nest cavities in patches of mature trees (Lopes et al., 2018)) mean that oil palm plantations represent only a transitional habitat for *P. timneh*.

Climate is highly variable in Southeast Liberia (Pashkevich et al., 2024), including pronounced dry and wet seasons that highly influence seasonal biodiversity patterns. We only surveyed in the dry season, as access to the study sites cannot be guaranteed during the wet season owing to flooding. It is possible that patterns in bird biodiversity across the studied systems would be different in the wet season, due to seasonal phenological events such as migration in response to changes in food availability (Sekercioglu, 2010; Rime et al., 2025), and we recommend such future work. Further, bird presence and detectability are influenced by weather and temperature patterns when sampling. While we alternated the order in which we sampled forest, country palm and industrial oil palm each day, and sampled each habitat each survey day, to minimise the effect of weather and temperature on our sampling design as much as possible, it is still possible that these factors could have influenced our findings. We note that long-term datasets in West Africa generally and Liberia specifically are needed to fully understand the impacts of land use and climate on bird biodiversity in this region. This study provides a useful baseline for such future long-term survey work.

4.2. Differences between country palm and industrial oil palm

We found different bird diversity impacts of traditional compared to industrial oil palm management. Relative to forest, country palm had comparable species numbers, and while the taxonomic community composition differed, the trait composition remained largely the same. In industrial oil palm, species numbers were lower in comparison to rainforest, and both taxonomic and trait composition were markedly different. In addition to the contrasts in structural complexity discussed above, the similarities between country palm and rainforest, rather than to industrial oil palm, are likely also due to differences in establishment and subsequent management between the oil palm systems, with country palm being managed less intensely. In industrial oil palm, establishment involves clear-felling of rainforest trees and planting an oil palm monoculture, which is then managed using, at times, heavy machinery and chemically-intensive applications of herbicides and fertilisers (Luke et al., 2020; Pashkevich et al., 2024). Studies from Africa and Southeast Asia have previously shown that these establishment and management practices change environmental conditions including increasing canopy openness, reducing ground vegetation cover, and creating a hotter and drier microclimate, and consequently impacting biodiversity (Hardwick et al., 2015; Luke et al., 2020; Luskin and Potts, 2011; Pashkevich et al., 2024; Rembold et al., 2017). In country palm, which is unique to Africa and fundamentally different to smallholder management in Southeast Asia, local communities burn down a small area of rainforest and farm numerous understory crops for one or two years before allowing the area to fallow (Pashkevich et al., 2024). This management can allow the development of relatively high levels of floral biodiversity and vegetation structural complexity, microclimates more similar to rainforest, and intact food-web networks (e.g. availability of fruits, flowers or insects) (Mammides et al., 2015; Pashkevich et al., 2024), providing conditions for a diverse avian community. Critically, areas of country palm cultivation are also often smaller and have more rainforest in surrounding areas, compared to industrial oil palm, facilitating spillover of rainforest bird communities (Pashkevich et al., 2024). Finally, termite mounds and ant nests from multiple species are typically left intact in country palm, and no chemical pesticides and herbicides are applied (Pashkevich et al., 2024), which in turn is likely to benefit insectivorous and ant-associated birds. To these ends, country palm may be an intermediate habitat between rainforest and industrial oil palm, supporting similar taxonomic richness and trait composition as found in rainforest.

4.3. Management implications

Our findings show that country palm and industrial oil palm cannot replace the ecological value of rainforest, which must be protected. They also indicate that incorporating aspects of traditional management (e.g., enabling more-diverse understory vegetation) within industrial plantations may bolster bird richness and trait composition. However, we note that higher bird biodiversity generally comes at the cost of yield (Teuscher et al., 2015), and therefore the economic consequences of any biodiversity-oriented intervention must be considered (although the trade-off is not universal; evidence from industrial estates shows that retaining forest or increasing understory complexity need not reduce yields (Edwards et al., 2014; Prescott et al., 2015)). Applying traditional practices to selected subsections of industrial estates might offer a way to preserve local agro-ecological knowledge and enhance biodiversity while keeping overall estate-level productivity intact. Management that aims to enhance the biodiversity of insectivorous birds specifically may not only benefit bird conservation but also crop production, since insectivorous birds prey on insect pests in tropical agro-ecosystems. This includes slug caterpillars (*Parasa pallida* and *Parasa viridissima*, also called *Latoia pallida* and *Latoia viridissima*, respectively) which defoliate oil palm fronds and are significant pests in West African oil palm systems (Corley and Tinker, 2016). Managing oil palm farmlands to support higher levels of insectivorous bird biodiversity may be a more-sustainable alternative to current pest management practices, which can involve application of chemical pesticides during pest outbreaks, resulting in harmful knock-on impacts on animal biodiversity more broadly and potentially influencing human health by contaminating water supplies (Chellaiah and Yule, 2018a, 2018b; Luke et al., 2017).

While we are aware of no research that has tested strategies (from traditional management or otherwise) for enhancing bird biodiversity in West African oil palm systems, studies from elsewhere in the tropics point to several promising approaches. For instance, work from Peninsular Malaysia demonstrated that growing oil palm alongside other crops (i.e., as a polyculture system) enhances bird species richness within farmlands more generally (Yahya et al., 2017); and an Indonesia-based project showed that planting diverse tree islands within oil palm monocultures increases bird species richness, diversity (measured as Simpson's Diversity

Index), and levels of predation (Zemp et al., 2023). However, recent research in Brazil showed little evidence of spillover of bird functional and phylogenetic diversity from forest patches to oil plantation, questioning the notion that preserving adjacent forest alone can mitigate biodiversity loss caused by oil palm conversion (Cardoso et al., 2025). It is possible that understory vegetation management, such as enhancing the diversity and structural complexity of understory vegetation by reducing herbicide use, could benefit bird communities both directly and indirectly by supporting insect communities on which insectivorous bird species feed (Stone et al., 2023). Species-specific management is also possible and has been successfully applied in Southeast Asia, e.g. creating nests for barn owls for natural pest control (Zainal Abidin et al., 2022). Future work should investigate whether the effects of these strategies - studied to date in Latin America and Southeast Asia oil palm systems - hold true in West African oil palm contexts. When grown industrially, oil palm typically has a 20 - 30-year cultivation cycle and, therefore, managing oil palm plantations with bird biodiversity and the ecosystem services they provide in mind could pave the way for more sustainable oil palm management over the long term.

The transferability of our findings to other oil palm-producing regions such as South and Southeast Asia, where most research on the impacts of oil palm cultivation has been conducted (Reiss-Woolever et al., 2021; Pashkevich et al., 2024), is uncertain, owing to several reasons. First, oil palm is native to West Africa and grows naturally in lowland rainforest across West and Central Africa (Pashkevich et al., 2024). Co-occurring species therefore share a long evolutionary history with the palm, which could make the impacts of cultivation either more muted or stronger than in regions where oil palm was introduced, such as South and Southeast Asia (Pashkevich et al., 2024). Second, oil palm-producing regions–and therefore oil palm agroecosystems–have a fundamentally different ecology. For instance, in West Africa, oil palm inflorescences are visited and pollinated by a diverse insect community (Syed, 1979), whereas pollination in Southeast Asia relies largely on a single weevil species, *Elaeidobius kamerunicus*, introduced from Cameroon in 1981 (Syed et al., 1982). Similarly, rats are a major pest in many Southeast Asian plantations (Hood et al., 2019) but they are not problematic in the estates in which our study took place. The bird communities are also largely distinct between producing regions, as the regions belong to different zoogeographic realms (Holt et al., 2013), so the species, and the interactions among them that determine which birds persist in cultivated landscapes, differ. Third, country palm is unique to Africa (oil palm's native home) and does not compare to Southeast Asian smallholder systems. It arises from rotational slash-and-burn agriculture, in which farmers select areas with fire-tolerant wild-growing palms and continue to harvest them after farms are fallowed (Pashkevich et al., 2024). The sites we sampled were fallowed farmland ('low bush') rather than actively farmed monocultures or polycultures. Because these palms grow natively rather than being planted, the system has no direct counterpart outside the native range of oil palm. Fourth, although management within the industrial plantations we sampled follows practices developed in Sumatra (Pashkevich et al., 2024), the plantations were developed under the RSPO New Planting Procedure and national environmental impact assessment requirements. These regulations required riparian buffers, wetlands, former village sites and forest contiguous with nearby protected areas to be set aside from planting (Green Consultancy Inc. and Daemeter Proforest, 2013). As a result, the farms are intersected by non-oil palm habitat (e.g., riparian reserves, conserved forest fragments) and embedded in a landscape that remains largely forested (Pashkevich et al., 2024), unlike many plantations in Southeast Asia. For these reasons, we advocate caution to readers attempting to extrapolate our findings to other oil palm-producing regions, especially ones outside West and Central Africa where oil palm is not native and there is no traditional cultivation of wild-growing palms (Pashkevich et al., 2024).

5. Conclusion

In summary, our findings indicate that converting rainforest to industrial oil palm alters and constrains available niche space, resulting in compositional changes in terms of species and traits. We show that the ecological value of country palm is between that of rainforest and industrial oil palm, harbouring high species richness and trait composition comparable to rainforest, and supporting some species of conservation concern. As industrial oil palms are very likely to be more productive than country palms, since they are high-yielding varieties and benefit from high applications of fertilisers, our findings suggest trade-offs between bird conservation and crop production (Hamer et al., 2021). Future work that quantifies the ecological value of rainforest, country palm, and industrial oil palm, adjusting for the economic value of these systems while accounting for the spatial scale at which they occur and the temporal scale of the productive systems' life cycles, is ultimately needed to determine oil palm cultivation practices that maximise food production and economic benefit while minimising ecological impacts.

CRediT authorship contribution statement

Joris H. Wiethase: Writing – review & editing, Writing – original draft, Visualization, Validation, Methodology, Investigation, Formal analysis, Data curation. **Andrew N. Gweh:** Methodology, Investigation, Data curation, Conceptualization. **Cicely A.M. Marshall:** Project administration, Methodology, Data curation, Conceptualization, Writing – review & editing. **Ari Saputra:** Data curation, Conceptualization, Project administration. **Jean-Pierre Caliman:** Project administration, Conceptualization. **Felicity Edwards:** Writing – review & editing, Methodology. **Bility Geninyan:** Data curation, Conceptualization. **Marshall Guahn:** Conceptualization. **Peter Hadfield:** Conceptualization. **Morris T. Jah:** Conceptualization. **Tiecanna Jones:** Conceptualization. **Edgar C. Turner:** Writing – review & editing, Supervision, Resources, Project administration, Methodology, Investigation, Funding acquisition, Data curation, Conceptualization. **Romeo Weah:** Data curation, Conceptualization. **Rudy Widodo:** Project administration, Conceptualization. **Benedictus Freeman:** Writing – review & editing, Supervision, Resources, Project administration, Methodology, Investigation, Funding acquisition, Conceptualization. **Michael D. Pashkevich:** Writing – review & editing, Writing – original draft, Visualization, Supervision, Resources, Project administration, Methodology, Investigation, Funding acquisition, Data curation, Conceptualization.

Declaration of competing interest

Co-authors with an affiliation to Forestry Development Authority (FDA), Golden Veroleum Liberia (GVL), and Sinar Mas Agro Resources and Technology Research Institute (SMARTRI) were employed by their respective institutes while research was conducted. University of Cambridge retains all intellectual property rights and data use for all researchers involved in this study. This research is therefore a collaboration between all affiliated parties.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jenvman.2026.131333.

Data availability

Data are available openly on Zenodo: Wiethase, J., Gweh, A., Marshall, C., Saputra, A., Caliman, J.-P., Edwards, F., Geninyan, B., Guahn, M., Hadfield, P., Jah, M. T., Jones, T., Turner, E., Weah, R., Widodo, R., Freeman, B., & Pashkevich, M. (2026). Datasets accompanying Wiethase et al. (2026) "Impacts of traditional and industrial approaches to oil palm cultivation on bird biodiversity and conservation in a West African rainforest landscape" [Dataset]. In Journal of Environmental Management. Zenodo. https://doi.org/10.5281/zenodo.24099029.

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