A multi-zone conservation planning and trade-off explorer for a community-forest landscape in West Kalimantan

Jan Hildebrand · methods note, November 2026 · code, data provenance and live app: github.com/yanhildebrand/zoning-explorer

Purpose

This is an open, fully scripted demonstrator of the workflow in the ARIES studentship *Integrating biodiversity, climate mitigation and livelihoods in Borneo's largest community-led nature-based solution.* It integrates biodiversity, carbon, condition, pressure and livelihood layers. It solves a multi-zone spatial optimisation and lets users explore the trade-offs in a static web app. It is meant to be re-run on the project's own landscape and data. It is a method, not a zoning proposal.

Study area and planning units

The project's 12-village landscape is not publicly delineated. I therefore used the closest public analogue among Planet Indonesia's sites, the forest–agroforestry mosaic around **Cagar Alam Gunung Nyiut** on the Sarawak border (Bengkayang, Landak, Sanggau regencies). The planning region is the reserve (92 kha, OpenStreetMap boundary) plus a 10 km belt of village land on the Indonesian side, 294 kha in total. Layers were harmonised to a 100 m grid (UTM 49N) and aggregated to 11,730 500 m (25 ha) planning units (PUs); the 3,662 PUs inside the reserve are locked into protection. The whole study area is defined in one configuration file.

Data (open, no accounts; clipped by HTTP range requests)

Tree cover and loss 2001–2024 (Hansen GFC v1.12, 30 m); land cover (ESA WorldCover 2021, 10 m); above-ground biomass 2024 and its SD (ESA CCI Biomass v7.0, 100 m; C = 0.47 × AGB); elevation (Copernicus GLO-30); Biodiversity Intactness Index 2020 (Impact Observatory, via the Planetary Computer STAC); roads, settlements and rivers (OpenStreetMap); boundaries (geoBoundaries); GBIF occurrences. Hansen "loss" covers 30% of the year-2000 forest. That figure includes swidden and plantation rotations, so it overstates permanent deforestation (Figure 1).

Derived layers. *Structural connectivity* is the forest share within 2 km (Hughes et al. 2026 found it the strongest driver of mammal occurrence in Indonesian community forests). *Condition* is forest share × √connectivity × BII. *Travel time* from settlements is least-cost over Tobler walking speeds and OSM road speeds (Indonesian side only). *Streams* are D8 flow accumulation (≥10 km²) after priority-flood filling of the DEM. *Livelihood opportunity* (0–1 ha^{-1}) is slope suitability × elevation suitability × $e^{-t/1\,h}$ (t = travel time) × a current-use factor (open/fallow land 1, low-biomass tree cover 0.85, mature forest 0.5).

Biodiversity features

Four coarse-filter forest types, each condition-weighted: lowland (<300 m), hill (300–900 m), upper/montane (>900 m) and riparian (≤100 m from streams). **Seven indicator species**: helmeted and rhinoceros hornbills, Abbott's grey gibbon, Sunda pangolin, Sunda clouded leopard, sun bear and bearded pig. Each has an area-of-habitat-style rule model (Brooks et al. 2019):

$$H = [f(1 - w + ws) + m\mu] \cdot E(\text{elev}) \cdot k^{\gamma} \cdot \left(1 - he^{-t/\tau}\right)$$

where f, m are the forest and open-mosaic shares, s is forest structure (AGB/250), k is connectivity and the last term is hunting pressure. The parameters (w, μ, γ, h, elevation limit) are expert-judgement placeholders informed by IUCN accounts. GBIF shows why primary data are needed: there is no helmeted hornbill record within 500 km and no clouded leopard or sun bear record within 250 km, while bearded pig and rhinoceros hornbill are recorded close by (Table 1).

Species	Borneo	≤100 km	Nearest (km)
Helmeted hornbill	68	0	572
Rhinoceros hornbill	12,285	44	9
Abbott's grey gibbon	28	5	52
Sunda pangolin	128	4	38
Sunda clouded leopard	51	0	357
Sun bear	91	0	259
Bornean bearded pig	704	161	62

Table 1: GBIF occurrence records (open API) for the indicator species: on Borneo, within 100 km of the planning region, and distance to the nearest record.

Formulation

Each PU i takes one zone: **P** protection, **A** sustainable use/agroforestry (no forest clearing) or **C** community use (unrestricted, the remainder). With binaries x_{iP}, x_{iA} and $s_i = x_{iP} + x_{iA} \le 1$:

$$\min \sum_i (c_{iP} x_{iP} + c_{iA} x_{iA}) + \beta \sum_{(i,j)} l_{ij} \left(w_P \, |x_{iP} - x_{jP}| + w_S \, |s_i - s_j|\right)$$

$$\text{s.t.} \sum_i a_{if} \left(x_{iP} + \kappa_f x_{iA}\right) \ge T_f \quad \forall f$$

Here c_{iz} is the livelihood opportunity forgone in zone z (P keeps 5 %, A keeps 50 %) plus a small management cost. κ_f is the share of feature f that zone A still secures. The boundary term penalises P|C edges twice as much as P|A or A|C edges, which favours protection cores buffered by agroforestry. β is scaled to the median PU cost. This is the prioritizr / Marxan-with-Zones minimum-set problem with zone contributions, mandatory allocation, locked-in PUs and zone boundary penalties (Watts et al. 2009; Hanson et al. 2025). It is solved exactly as a MILP with HiGHS 1.15.1 (1 % gap; median 2.6 s per scenario, all within 0.8%). Re-solving 6 scenarios without the boundary term in R with prioritizr 9.0.1 (via the `highs` package) gives identical objectives and zonings (relative differences below 10^{-11}). Unit tests also check the solver against brute-force enumeration on small instances.

Scenarios

150 scenarios form a full factorial: biodiversity target (30–70 % of each feature) × carbon target (30–90 % of AGC, 31.6 Mt C in total) × agroforestry compatibility κ (low/central/high) × connectivity penalty (off/on). Metrics per scenario are attainment per feature, carbon secured, livelihood opportunity kept, zone areas and network connectivity (patches, largest-patch share, edge length).

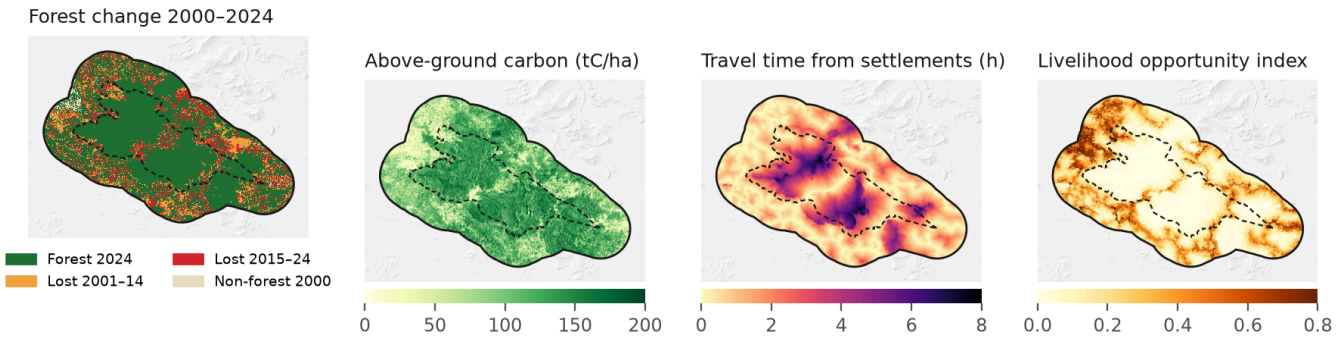


Figure 1: Planning region (solid) and nature reserve (dashed) with four of the input layers.

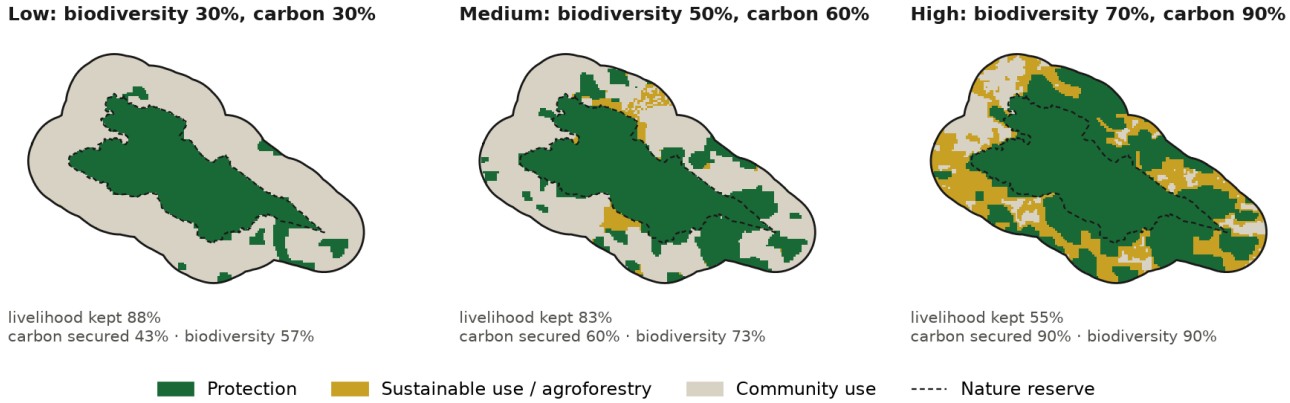


Figure 2: Optimal zonings at three ambition levels (central agroforestry compatibility, connectivity on). Dashed: nature reserve, locked to protection.

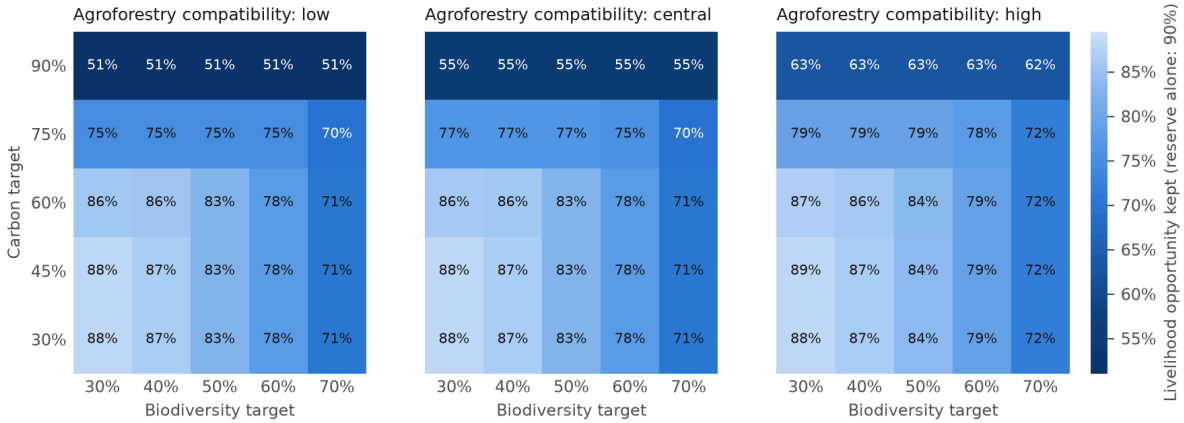


Figure 3: Livelihood opportunity kept for every combination of biodiversity and carbon targets (connectivity on). Each cell is one optimised plan.

Results (connectivity on)

The reserve alone secures 50%–56% of each species' habitat and 84% of montane forest. It secures only 17% of lowland and 32% of riparian forest, and these two features drive most of the zoning outside it, as is typical of upland-biased reserves. Livelihood opportunity kept falls from 90% (reserve only) to 83% at 50 %/60 % targets and 55% at 70 %/90 % (Figure 2, Figure 3).

A 90 % carbon target is the most costly constraint. At that level agroforestry compatibility is decisive: livelihood kept is 51% with low κ and 63% with high κ, where 123 kha is zoned for agroforestry. How much biodiversity agroforests retain is therefore the key empirical question for camera-trap and acoustic surveys. The connectivity penalty cuts zone edge length by 43% on average.

Limitations

The species layers are rule-based habitat models, not fitted occupancy models. The livelihood index is a biophysical proxy; it does not measure income, tenure or customary use, and village boundaries and permits are not represented. CCI biomass carries large per-pixel uncertainty and over-estimates low biomass. Hansen loss conflates rotation with clearing. Results are conditional on targets and κ values that communities and data should set.

Supporting, not replacing, co-production

The tool is designed for workshops. Communities and partners set targets and zone rules, see the consequences immediately on a map and on trade-off charts, and can discuss the "protection frequency" map of robust versus contested areas. Any real zoning would need free, prior and informed consent and participatory mapping of customary land and resource use, with community-defined targets. The pipeline is modular: the PhD's validated camera-trap and acoustic occupancy layers, SMART patrol threat maps and village boundaries can replace the placeholder layers without changes to the solver or the app.

Reproducibility

One command (`make all`, or `uv run zx all`) downloads the clipped inputs (about 55 MB, with URLs and byte counts logged in `data/manifest.json`). It then derives the layers, solves all scenarios (about 2 min on 5 cores) and rebuilds the app data, the figures and this note. The environment is locked (`uv.lock`). GitHub Actions runs lint, a prioritizr cross-check job and tests: the solver against brute force, travel-time geometry, flow routing, habitat-rule bounds, a re-solve of committed scenarios, and app-data consistency. The explorer is a static MapLibre page (3.4 MB of data) served by GitHub Pages.

Next steps within the PhD

1. Replace the rule-based layers with occupancy layers built from AI-classified, human-validated camera-trap and acoustic detections, and carry their uncertainty into the targets.
2. Estimate κ empirically by sampling agroforests (tembawang, rubber) against forest.
3. Add SMART patrol encounter rates as a threat layer and as a management cost.
4. Use village boundaries for equity constraints, e.g. each village keeps at least a set share of its livelihood opportunity. This is straightforward in the MILP.
5. Add a participatory "serious-game" mode in which groups lock zones and the optimiser completes the plan, and couple the zonings to an agent-based model of village forest use.

References. Barnes et al. 2014 *Comput. Geosci.* 62:117 · Brooks et al. 2019 *TREE* 34:977 · Hanson et al. 2025 *Conserv. Biol.* 39:e14376 · Hansen et al. 2013 *Science* 342:850 · Huangfu & Hall 2018 *Math. Prog. Comp.* 10:119 · Hughes et al. 2026 *J. Appl. Ecol.* 63:e70518 · Newbold et al. 2016 *Science* 353:288 · Santoro & Cartus, ESA Biomass CCI v7.0 (CEDA) · Struebig et al. 2026 *Research Square* doi:10.21203/rs.3.rs-10818958/v1 · Tobler 1993 NCGIA TR 93-1 · Watts et al. 2009 *Environ. Model. Softw.* 24:1513 · Zanaga et al. 2022 ESA WorldCover v200.