Enhancing the ecological value of tropical agriculture through set-asides

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Enhancing the ecological value of tropical agriculture through set-asides

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Abstract

Agricultural expansion across the tropics is the primary driver of biodiversity declines and ecosystem service degradation. However, efforts to mitigate these negative impacts may reduce commodity production. We quantify trade-offs between oil palm cultivation and ecological outcomes (biodiversity, above-ground carbon storage and dung nutrient cycling) across different potential set-aside (uncultivated areas in agricultural landscapes) strategies. We show that all set-aside configurations yield substantial gains in ecological outcomes. The best strategy involves spatially targeted riparian reserves, such as those used in oil palm certification schemes, where species occurrence can be doubled without reducing overall cultivation area. Adopting this strategy throughout the 8 million hectares of plantations in Borneo would lead to extensive improvements in ecological outcomes without losses to production area, and consequently, enhancing agricultural sustainability.

Main text

Agricultural expansion is considered critical to meeting the growing food demands of an increasing human population, yet it is also the primary driver of habitat loss across the planet (*1*, *2*). With food demand predicted to double by 2050 (*3*), it is estimated that up to 1 billion hectares of previously uncultivated land will need to be bought under production to ensure food security (*4*, *5*). Much of this land is expected to replace tropical forest (*6–8*). Over the past three decades alone, more than 150 million hectares of tropical forest have been cleared for agriculture (*4*, *9*, *10*). This leads to disproportionate biodiversity losses (*11–13*), is a major driver of climate change (contributing 7–14% of global CO_2 emissions (*14–17*)), and has negative impacts on multiple ecosystem functions and services, including soil fertility, soil stability and the provision of freshwater (*18*). Consequently, the challenge of reconciling rising food demand while safeguarding critical ecosystems is dependent on the manner in which tropical agricultural landscapes are established and managed.

Just four agricultural commodities (beef, palm oil, soy and wood products) drive 40% of tropical deforestation (*19*). Oil palm (*Elaeis guineensis*) occupies ~19.5 million hectares in the tropics, mostly (82%) in Southeast Asia (Supplementary Fig. 1). Since 1980, there has been a 15-fold increase in its production, and about half the people in the world currently rely on palm oil as part of their diet, as well as it being a key ingredient in animal feed, cosmetics and biofuels (*20*, *21*). As such, it is predicted that oil palm agriculture will cover 29-33 million hectares by 2050 (*20*, *22*). The associated deforestation is anticipated to negatively affect 54% and 64% of threatened mammals and birds globally (*20*), and release ~330 Mt CO_2 each year (*19*, *23*), equivalent to almost half the average annual CO_2 emissions from global aviation (*24*).

Pressure is mounting on food supply chains to improve sustainability standards, or risk continued strident calls for palm oil to be boycotted (*25–27*). However, switching to alternatives will only exacerbate the problem (*20*, *25*), given that producing palm oil requires four to ten times less land per unit of oil than other vegetable oils (*20*, *28*). To try to alleviate environmental concerns, over 4000 companies have now adopted voluntary commitments to source, produce and sell certified sustainable palm oil, which is cultivated conforming to social, environmental and agricultural best-practice guidelines (*23*, *29*, *30*). Nonetheless, we have little understanding of how these guidelines may reduce the environmental impacts of agricultural expansion in tropical landscapes without compromising food security. Here, we quantify the trade-offs between oil palm cultivation and ecological outcomes (biodiversity, ecosystem function and service) across different potential set-aside strategies, which we identified through oil palm producer consultations (Fig. 1). We do this in the carbon- and biodiversity-rich forested landscapes of Borneo, which are considered the global epicenter of palm oil production (*31*, *32*). Our results show that set-asides yield substantial ecological gains, and that locally optimized set-aside enhancements can augment carbon storage, soil nutrient cycling and biodiversity with little or no reduction in cultivated area.

Set-aside in tropical agriculture

The creation of set-asides, which are uncultivated areas within agricultural landscapes, have long been used as a voluntary and regulatory practice to alleviate the adverse environmental effects of agriculture (*33*). Set-asides can offer important biodiversity refugia (*34–36*), help maintain ecosystem functions and services (*37–39*), and can support livelihoods (*40*). In relation to oil palm agriculture specifically, set-aside is often incorporated into national legislation (Methods), as well as being required by voluntary sustainability certification systems (e.g. Roundtable on Sustainable Palm Oil (RSPO), which certifies 19% of all palm oil). Nevertheless, set-aside policies vary greatly, and are not necessarily informed by scientific evidence (*34*).

Set-asides generally come in two forms in industrial-scale tropical agriculture: the maintenance of natural forest habitat on steep slopes (25° and above; hereafter 'maximum slope for cultivation') to protect soils and watersheds, and, retention of forest near rivers ('riparian reserve width') to maintain hydrological systems (Supplementary Note 1). Each of these components can contribute to broader environmental outcomes beyond their intended objectives. For example, remnant forest on steep slopes or in riparian zones may provide habitat for biodiversity and maintain carbon stores (Supplementary Note 1) (*35*, *41–43*). In industrial oil palm estates, most riparian reserve legislation stipulates fixed widths (e.g. 20 m or 50 m) of forest are retained either side of the river, depending on the country/state. Conversely, some policies, including those of RSPO, vary based on river width and local context (e.g. 5 m of forest to be retained either side of small rivers, but up to 100 m of forest for larger rivers or areas considered to be particularly important for wildlife or habitat connectivity; Supplementary Note 1, Supplementary Table 1). Maximum slope for cultivation is often 25°, but this is climate and soil dependent (Supplementary Note 1).

Impacts of set-aside policies on cultivation area

Given the variability of set-aside policies, we examine the trade-offs between the amount of land available for cultivation and the ecological outcomes that can be realized for a suite of different set-aside configurations. We do so in a 119,000-hectare production landscape in Sabah, Malaysian Borneo, comprising four industrial-scale plantations and an array of remnant forest in set-asides (Methods; Supplementary Figs. 2-6, Supplementary Table 2). Before evaluating the impacts of set-aside policies, we consulted major producers across the palm oil industry to ensure our analyses focused on maximum slopes for cultivation and riparian reserve widths that could be implemented feasibly in a real-world context (Methods). We then examined different set-aside configurations, encompassing combinations of 20 riparian reserve widths (in 5 m increments, ranging from 5 to 100 m, on both sides of rivers) and 11 maximum slope angles (ranging from 15 to 25°) per plantation, equating to 880 combinations across the four plantations (220 in each). Larger riparian reserve widths and lower maximum slopes for cultivation both mean that there is a greater area of set-aside in the landscape and, correspondingly, less area available for cultivating crops.

Across all the set-aside configurations examined, 61–92% of the landscape remained available for cultivation. We find that riparian reserve set-aside comprised 0.5 to 10% of the landscape, while set-aside based on maximum slope for cultivation accounted for 4 to 30%. By comparison, 20 and 50 m riparian reserve widths (corresponding, respectively, to current policies for Sabah in Malaysia and Indonesia), combined with 25° maximum slope, would leave 89-91% of the landscape available for oil palm cultivation (Fig. 2A & B).

Optimizing trade-offs

To assess the trade-off between the land available for cultivation, and ecological outcomes (biodiversity, ecosystem function and ecosystem service), we combined our set-aside configurations with field-derived distributions for 235 species (150 birds, 19 non-volant mammals, 21 bats and 45 dung beetles), dung nutrient cycling and LiDAR-derived above-ground forest carbon storage (Methods). We express ecological outcomes of different landscape scenarios in terms of net and relative percentage changes in species occurrence, and total above-ground forest carbon storage and dung nutrient cycling under different set-aside configurations. Net changes in species occurrence are calculated as the percentage change in landscape area, whereas relative changes are calculated as a percentage change in species area. For example, if a species occurred in 20% of the landscape in one set-aside configuration and then 30% in another, this would equate to a 10% net increase and a 33% relative increase.

We evaluated two categories of set-aside policies. First, we considered 'uniform' policy scenarios, meaning a one-size-fits-all approach, as implemented in most national/state-scale legislation. Even with these very simple policies, the potential importance of set-asides in delivering ecological gains in tropical agricultural landscapes becomes clear. In our landscape, each 10% of the area in set-aside results in a net increase in species occurrence, ranging from 3% to 23% across all 235 species (mean = 10% net increase, but up to 223% relative increase), a 6% net increase in above-ground carbon storage, and 9% net increase in dung nutrient cycling (Fig. 3 and Fig. 4A blue curve). We also evaluated 'variable' policies, under which we optimized set-aside configurations, allowing these to vary between plantations in a way that maximized ecological outcomes at least cost to cultivation. To calculate the variable policy outcomes, we used multi-objective optimization models to maximize ecological outcomes (species occurrence, above-ground carbon storage and dung nutrient cycling across set-aside in the landscape) (objective one) and maximize area of the landscape available for oil palm cultivation (objective two).

Compared to a uniform approach, the variable policy yields even higher levels of species occurrence and above-ground carbon storage for any given percentage of the landscape cultivated. Alternatively, the variable policy achieves specified levels of species occurrence and above-ground carbon storage at lower overall set-aside area than in the equivalent uniform policy (Fig. 4). The greatest gains from the variable policy are obtained when set-aside configurations result in 77–87% of the landscape cultivated (upper quartile of the difference between uniform and variable policies; Fig. 4A,B). The most efficient of these is achieved when 83% of the landscape is cultivated ('maximum efficient'). In this scenario, net species occurrence within set-asides rises by 8.1% (range: 0.3–18% net increase in occurrence across all species), from an average across species of 55% for the uniform policy to an average of 63% for the variable policy, and 3.8% more above-ground carbon stored (Supplementary Table 3; Fig. 4A,E). By comparison, achieving the same gain in ecological outcomes with the uniform policy would require a reduction in cultivation area of 7.7% (Supplementary Table 3; Fig. 4A,C). At maximum efficient cultivation levels, all species had increased occurrence under the variable policy, compared to the uniform policy (Fig. 5 & Supplementary Figs. 7-11; Supplementary Note 2), with the greatest average gains among the birds, including endemic and threatened species. We also find that at 90% ('business-as-usual'; broadly equivalent to current policies in Indonesia and Malaysia) and 70% ('high level set-aside') of the landscape cultivated (Fig. 4C-F), the variable policy enhances ecological outcomes, albeit to a lesser degree than when 83% of the landscape is planted (Fig. 4D,F; Supplementary Table 3; Supplementary Note 2).

With 83% of the landscape cultivated, the corresponding set-aside (17% of the landscape) can be achieved through a range of uniform set-aside configurations of riparian reserve widths (mean = 61 m) and maximum slope for cultivation (mean = 22°; Supplementary Table 4). However, the flexibility of the variable policy, allows for more spatially targeted set-asides to be distributed heterogeneously across the landscape to maximize ecological outcomes. As a result, the variable policy could have lower overall set-aside with a mean riparian reserve width of 44 m and mean maximum slope for cultivation of 22° to achieve the same ecological outcome (Supplementary Table 4). This is particularly pertinent for the variable set-aside configurations used in most certification schemes (Supplementary Note 1), because they should translate into improved ecological outcomes without the need to reduce cultivation area.

We also conducted our optimizations with a uniform maximum slope of 25° but letting riparian reserve width vary. We did this because the palm oil industry told us that varying maximum slopes for cultivation would be less favorable from an operational perspective. Again, the variable policy resulted in ecological gains, albeit with reduced benefit compared to when the maximum slope for cultivation could also vary (Fig. 4A). Nonetheless, at current business-as-usual cultivation (90% of the landscape), the reduction in gains compared to the fully variable policy were only marginal. Our findings additionally demonstrate that riparian reserves are the more important set-aside policy component for optimizing ecological outcomes. Indeed, when more than ~85% of the landscape is cultivated, the impact of changes to maximum slope diminish, and riparian reserve width primarily drives changes in the amount of set-aside and, consequently, ecological outcomes (Fig. 2, Supplementary Fig. 12; Supplementary Note 3).

The importance of plantation topography

Across the tropics, agricultural plantations are less likely to occur on steep slopes, because they are more expensive to deforest and harder to cultivate successfully (*6*, *44*). Landscape topography is, therefore, a key attribute affecting the impacts of set-aside policies. In our study landscape, each plantation had a distinct topographic profile (Supplementary Table 2), varying with the percentage of the plantation consisting of slopes above 15°, ranging from 18% of the plantation (Plantation D) to 56% (Plantation A; Supplementary Figs. 1 and 4). In general, rugged tropical landscapes with high proportions of steep areas, have more rivers and riparian areas. Accordingly, the set-aside policy changes we explore have the most pronounced consequences. This is highly relevant because much of the undeveloped land remaining in the tropics comprises forest on steep slopes, as opposed to lowlands that have already been converted to agriculture (*6*).

Implementing set-aside in tropical agricultural landscapes

On Borneo, an additional 30 million hectares (40% of the island) is suitable for oil palm cultivation and falls outside of protected areas (*44*). Of this, we estimated that 8 million hectares (11% of the island) could be potential set-aside in future plantations, as this is the area of forested slopes of 15–25° and within 100 m of a river. Therefore, compared with existing plantations, for no net decrease in ecological outcomes, future plantations with optimized set-asides (i.e. variable policies) could represent a potential increase in cultivated area of up to 7.7%, yielding 189 million tonnes of crude palm oil over 20 years (Table 1).

Our findings are important for both conservation and food security debates as we show that set-asides can greatly enhance ecological outcomes without compromising the area of the landscape available for cultivation. This is critical because perceived losses to production may disincentivize growers from adopting best practice set-aside measures. To this end, our study shows that locally tailored riparian set-asides may be the best way to boost the biodiversity and ecosystem service value of tropical agricultural landscapes.

Methods

Study landscape

Our study site is made up of four oil palm plantations and a logged forest reserve in Sabah, Malaysian Borneo (Supplementary Fig. 2). One of the plantations lies within the Stability of Altered Forest Ecosystems (SAFE) project (https://www.safeproject.net/; *46*). The other three are commercial plantations owned by two Malaysian palm oil producers. Together, the study area covers 119,000 ha of forest and plantation. Most of the remnant forest has been logged two to four times over 30 years and contains few mature trees (*47*), although some areas are less disturbed and are now formally protected. The surrounding agricultural matrix comprises oil palm trees, which were planted 12–15 years prior to our data collection. Remnant logged forest areas are present within the agricultural matrix, occurring on steep slopes and alongside some rivers, with widths between 5 and 470 m either side of the river. Each plantation has a distinct topographic profile varying in ruggedness from 18 to 56% of the landscape above 15 degrees slope. The area of a plantation within 100 m of a river varies from 12 to 23% (Supplementary Table 2).

Across the study area, we sampled multiple taxonomic groups, above-ground carbon storage and dung nutrient cycling. Methods, locations, and sample sizes varied, but all encompassed logged forest and riparian forest fragments and oil palm (details for each group or function are provided below). Species occurrence data from the logged forest reserve was used to improve our estimates of species distributions, but were not used in the trade-off analyses.

We obtained plantation boundaries for the experimental landscape directly from plantation owners. We mapped rivers across the landscape using a combination of geographic information system (GIS) data from the Sabah DID and the Shuttle Radar Topography Mission (STRM) (http://srtm.usgs.gov) digital elevation model (DEM) at a resolution of 30 × 30 m. The DID data included the location of rivers, but did not include hydrological information such as flow, which is used to estimate channel width. To estimate flow, we first used the r.watershed module in GRASS GIS to create raster files for flow accumulation and drainage direction, which were then inputted into the r.stream.extract module to create a raster and vector of channels using the flow accumulation and direction layers. We subsequently added network information to the raw vector channels using an R script to find links between channels (https://www.safeproject.net/dokuwiki/safe_gis/stream_networks). The STRM generated data matched very closely with the governmental DID data, so we used the STRM generated river network in our analysis, which allowed us to exclude small streams estimated to be under 5 m in channel width, because in all guidelines and legislation these size rivers receive no or very small riparian reserves. We ground-truthed 20 rivers to ensure that predictions of channel width were broadly accurate. To estimate and map slope across the landscape, the SRTM data was further processed using the gdaldem_slope function (https://gdal.org/programs/gdaldem.html) for Python to generate a raster of slope angles measured in degrees.

Palm oil producer consultations

Before undertaking our landscape analyses, we consulted palm oil producers to inform the range of set-asides policies to be tested, to ensure that the policies tested were feasible to implement from an industry perspective. We conducted semi-structured interviews with nine representatives from seven of the largest palm oil producers, with plantations located in nine different countries across Southeast Asia and West Africa. Collectively, these companies manage about 9% of the world's industrial palm oil plantations, an area of land covering 1.7 million ha. From these consultations, two key set-aside components emerged, riparian reserve widths and maximum slope for cultivation. Eight of the nine respondents felt that increasing riparian reserve width was both feasible and important for enhancing ecological outcomes (biodiversity, ecosystem functions and ecosystem services). Additionally, all respondents indicated that they would support the establishment of wildlife corridors within plantations, with riparian reserves being the main way to achieve this. Four out of the nine respondents were supportive of policy changes to maximum slope for cultivation, but explained that they rarely cultivate slopes steeper than 20°.

Set-aside configurations used in the analyses

Set-aside configurations of maximum slopes for cultivation and riparian reserve widths were assessed in a GIS. We created 20 different riparian reserve width layers by adding buffers of 5–100 m (in 5 m increments) around the river network. We created polygons for 11 different thresholds for maximum planting slope ranging from 15 to 25° (in 1° increments). These two sets of layers were subsequently merged to produce 220 combined riparian reserve width and maximum slope for cultivation layers and then clipped to each plantations (but not the forest reserve) to produce 880 plantation-specific set-aside layers. Across the four plantations, this resulted in 220^4 or 2,342,560,000 unique ways to configure the landscape. The landscape configurations were overlaid with species distributions, above-ground carbon storage and dung nutrient cycling layers. These allowed us to examine and optimize trade-offs between between the amount of land available for cultivation and the ecological outcomes.

Each five-meter increase in riparian reserve width results in an increase in set-aside of just 0.44 – 0.52% of total production area, staying more-or-less constant across the 20 riparian reserve widths we tested (Fig. 2A). On the other hand, decreasing the maximum slope for cultivation reduces planted area to a much greater extent, with a one-degree change leading to a 0.9–4.1% reduction in cultivated area (Fig. 2B).

Bird biodiversity field methods

We sampled bird communities via point counts at 376 sample locations across the landscape spaced a minimum of 200 m apart. Our point count locations covered all habitats types across the landscape. During each point count, a single experienced observer (SLM) recorded all bird species heard or seen within a 50 m radius of the point for 15 min, including fly-overs. We conducted point counts between 05:50 and 11:00 in clear weather and these were repeated on three separate occasions at each site between 2014 and 2016. For further details see *(48).*

Non-Volant mammal biodiversity field methods

Camera-traps (HC500 Hyperfire, Reconyx, WI, USA) were deployed at 121 locations across the landscape between May and September 2015. Locations were separated by a mean distance of 1.4 km and were stratified to capture the heterogeneity of the landscape. The camera-traps were positioned at a standardised height of 30 cm and were deployed for 42 consecutive nights per location, yielding a total survey effort of 4,669 camera nights. For further details see *(49).*

Bat biodiversity field methods

We sampled bat communities via harp trapping at 294 sample points across the landscape from 2015 to 2016. Locations were stratified to capture the heterogeneity of the landscape and tactically to maximize captures. At each site and each year, we performed ten nights of trapping using six four-bank harp traps (60 harp trap nights per site total) from 20:30 to 08:30. For further details see *(50).*

Dung beetle biodiversity field methods

We sampled dung beetle (*Scarabidae* sp.) communities via baited pitfall traps at 197 sample points across the landscape from 2015 to 2016. Traps were plastic containers 14 cm deep and 13 cm in diameter, part-filled with a mixture of water, salt, detergent, and chloral hydrate. These were placed flush with the soil surface. A muslin bag of human dung (c.25 g) was suspended 5 cm above the trap. Each trap was protected from rain by a plastic plate held 20 cm above it. Traps were set in the morning and left for 48 h before collection. For further details see *(51)*.

Biodiversity species distribution predictions

We generated presence-pseudo absence species distribution models (SDMs) for 235 species (150 birds, 21 bats, 19 non-volant mammals, and 45 dung beetles). For each species, we constructed an ensemble model of six algorithms: generalized linear models (GLMs), generalized boosted models (GBMs), random forests (RFs), support vector machines (SVMs), multivariate adaptive regression splines (MARSs), and artificial neural networks (ANNs), with five repetitions of each algorithm. Accuracy of each model was assessed using cross-validation with a 70-30 split of the occurrence data into training and evaluation sets, repeating the procedure to combine the ensemble using the highest AUC (area under curve). A presence-absence prediction was then made using the sensitivity-specificity (SES) equality metric. We did not use bioclimatic variables as predictors because we were working at a fine-resolution landscape-scale and there was not enough variability. Instead, we used location and landcover predictors (elevation, slope, distance to river and soil type), which are static and do not change with the configuration of the experimental landscape. As such, our estimated species distributions represent the largest possible predicted distribution for each species across the landscape. Relative variable importance was computed using Pearson's correlations between predictions of the full model and with each variable iteratively removed. All SDMs were constructed using the SSDM package for R (https://www.r-project.org/).

Dung nutrient cycling predictions

Dung removal is an important part of the soil nutrient cycling process and reduces greenhouse gas emissions *(52)*. We measured nutrient cycling via dung removal at 309 sample points across the landscape. At each location, 700 g of dung were placed under a rain cover and, 24 hours later, any remaining dung was collected and weighed. We also used three evaporation/precipitation controls, comprising 700 g piles which were not accessible to fauna. For further details see *(51)*. To estimate dung removal across the entire landscape, we used residual corrected ordinary regression kriging between our point estimates, and landscape level predictors implemented in SAGA GIS. We predicted dung removal using the same predictors as for the species distribution models, plus dung beetle diversity and non-volant mammal diversity (summed from our species distribution models), due to the relationship between mammals and dung beetles *(53,54)*.

Above-ground carbon storage predictions

To estimate above-ground carbon stored across the landscape we used data from the Carnegie Airborne Observatory-3. The dataset combines airborne Light Detection and Ranging (LiDAR) with satellite imaging and other geospatial data to map forest above-ground carbon density at 30 m resolution throughout the Malaysian state of Sabah, Borneo. For further details see *(55,56)*. In our trade-off analyses that included above-ground carbon storage, we only considered pixels above a threshold of 35 tonnes of carbon per hectare, to ensure we were only considering High Carbon Stock forests.

Estimating the trade-off between cultivation and ecological outcomes

To describe species occurrence, and total above-ground forest carbon storage and dung nutrient cycling responses to changes in the proportion of the landscape cultivated, we fit a linear regression model with quadratic and cubic terms (due to non-linear response of most species) in the general form:

$$y = b_0 + b_1 x + b_2 x^2 + b_3 x^3$$

where y is the proportion of the landscape occupied by a given species or total above-ground forest carbon storage and dung nutrient cycling, x is the proportion of landscape cultivated, and $b_0, \ldots, b_3$ are regression model coefficients.

For each species, above-ground carbon storage and dung nutrient cycling we then calculated the slope (1st derivative) of the model, which characterizes the strength of the relationship between the ecological outcome and the proportion of the landscape cultivated. As a proxy for the linearity of each trade-off curve, we also calculated acceleration (2nd derivative), which measures how the rate of change for the trade-off curve is itself changes.

Optimization of trade-offs

We formulated a mixed integer linear programing (MILP) model to optimize set-aside policies for riparian reserve width and maximum slope for cultivation across the oil palm plantations. The objective of the model is to maximize ecological outcomes in set-aside, subject to a limit on the area of land taken out of cultivation and put into set-aside. The model was run for a range of different set-asides to produce Pareto-optimal curves of ecological outcomes, where:

I	Set of biodiversity and ecological service/functions, indexed by i
J	Set of palm oil plantations, indexed by j
K	Set of riparian reserve widths, indexed by k
L	Set of maximum slopes for cultivation, indexed by ℓ
$c_{jk\ell}$	Set-aside area in plantation j given selection of riparian reserve width k and maximum slope for cultivation ℓ
b	Maximum feasible set-aside area across the landscape ($b = \sum_{j \in J} \max_{k \in K, \ell \in L} c_{jk\ell}$)
θ	Parameter for controlling total set-aside area limit (range 0-1)
A_i	Areal range size of biodiversity or ecological service/function i across the landscape
$a_{ijk\ell}$	Area of biodiversity or ecological service/function i in set-aside in plantation j by riparian reserve width k and maximum slope for cultivation ℓ
w_i	Weight assigned to biodiversity or ecological service/function i
ϕ_i	Fraction of biodiversity or ecological service/function i's range that must be in set-aside areas

and the following decision variables:

$$x_{jk\ell} = \begin{cases} 1 & \text{if riparian reserve width } k \text{ and maximum slope for cultivation } \ell \text{ are selected} \\ & \text{for plantation } j \\ 0 & \text{otherwise} \end{cases}$$

y_i = fraction of biodiversity or ecological service/function i's range protected across the landscape

The MILP formulation of our variable policy is then:

$$\max \sum_{i \in I} w_i y_i \tag{S1}$$

$$s.t.$$

$$\sum_{j \in J} \sum_{k \in K} \sum_{\ell \in L} c_{jk\ell} x_{jk\ell} \le \theta b \tag{S2}$$

$$\sum_{k \in K} \sum_{\ell \in L} x_{jk\ell} = 1 \qquad \forall j \in J \tag{S3}$$

$$y_i \le \frac{1}{A_i} \sum_{j \in J} \sum_{k \in K} \sum_{\ell \in L} a_{ijk\ell} x_{jk\ell} \qquad \forall i \in I \tag{S4}$$

$$x_{jk\ell} \in \{0,1\} \qquad \forall j \in J \tag{S5}$$

Model (S1)-(S4) is a modified version of what is known in the site selection literature as a "maximum covering" problem *(57)*. The objective (S1) maximizes the weighted proportional ecological outcome within set-asides. Constraint (S2) sets an upper limit (aka budget) on total set-aside area across the landscape. Parameter θ is a user-specified value that can be adjusted up/down to increase/decrease the set-aside area budget. Equalities (S3) require selection of exactly one policy for riparian reserve width and maximum slope for cultivation for each plantation j. Inequalities (S4), meanwhile, determine the fraction of each ecological outcome i

within set-aside areas. Given the structure of the optimization model, constraints (S4) could be written as equalities, since each variable y_i will automatically equal the value on the right-hand-side. Finally, constraints (S5) impose binary restrictions on the $x_{jk\ell}$ variables for selecting riparian reserve widths and maximum slopes for cultivation.

To impose a uniform policy for riparian reserve width and maximum slope for cultivation across all plantations, we introduce variable $u_{k\ell}$ equal to one if riparian reserve width k and maximum slope for cultivation ℓ is selected as a standard, zero otherwise, and the following side constraints:

$$\sum_{k\in K}\sum_{\ell\in L} u_{k\ell} = 1 \tag{S6}$$

$$x_{jk\ell} = u_{k\ell} \qquad \forall j \in J, k \in K, \ell \in L \tag{S7}$$

Equality (S6) requires selection of a uniform policy for riparian reserve width and maximum slope for cultivation, while equalities (S7) stipulate that all plantations j must adopt the same policy.

We implemented our landscape set-aside optimizations in the OPL modeling language using CPLEX studio version 12.9 *(58)*, which employs branch-and-cut methods to solve MILPs. The largest problem instance we solved had 237 continuous variables, 880 binary variables, and 243 constraints. We performed secondary optimization runs assuming a uniform maximum slope for cultivation of 25°. We also ran a set of optimizations of specific combinations of riparian reserve width and maximum slope for cultivation to test existing policies in Malaysia and Indonesia. We then plotted where these lie on top of the Pareto-optimal curves.

Estimating improvements to palm oil cultivation across Borneo

To calculate the area of Borneo suitable for oil palm cultivation, we clipped the dataset of global oil palm suitability created by *(44)* to Borneo and then extracted and summed the area of 'Suitable', 'High', and 'Perfect' categories across the island. We then revised this figure by removing existing protected areas (from https://protectedplanet.net/) and existing oil palm plantations (from https://atlas.cifor.org/). We then intersected the remaining area with all areas falling between 15–25° slopes (at a 90 m resolution), by following the same procedure described above for assessing slopes across the study landscape. We estimated the area of Borneo within 100 m of a perennial river using river networks created by Milieux Environnementaux, Transferts et Interactions dans les Hydrosystèmes et les Sols (METRIS; https://www.metis.upmc.fr/en/node/375). To calculate the potential average additional oil palm trees across Borneo from optimizing plantations (Table 1), we applied a value of 125 oil palm trees per planted hectare, based on data from plantations C and D. To calculate the potential average additional crude palm oil (CPO) yield over 20 years, we applied an average yield value of 4.1 metric tonnes of CPO per hectare, per year assuming an oil extraction rate of 25%, and average fresh fruit bunch yield of 16.4 tonnes per hectare per year (data from plantations C and D and are close to the average for Malaysia which is 4.2 tonnes of CPO per hectare per year (http://www.fao.org/faostat/ and *60*).

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Author contributions

JEB led manuscript writing, conducted the landscape and Borneo wide set-aside analyses, species, above-ground carbon storage and dung nutrient cycling modelling, created the figures and undertook the oil palm producer consultations. ZGD and MJS conceived the study concept and analytical framework, contributed to the research design and co-wrote the manuscript. JRO'H, with JEB, developed and ran the optimization framework. PRA advised on the study concept and optimization methodology. EMS, NJD, SLM, DHB and VK provided biodiversity data, and EMS additionally provided nutrient cycling data. ALA, ZGD, EMS and GR helped with the design and delivery of the oil palm producer consultations. DAC contributed towards the estimates of above-ground carbon. SJR and OTL contributed to research design and helped secure funding. All authors provided editorial input on the manuscript.

Competing interests

Authors declare no competing interests.

Data availability

DOIs for the ecological data are listed in Supplementary Table 5.

List of Supplementary Information:

Supplementary Notes 1-3

Supplementary Tables 1 to 5

Supplementary Figs. 1 to 12

Figures

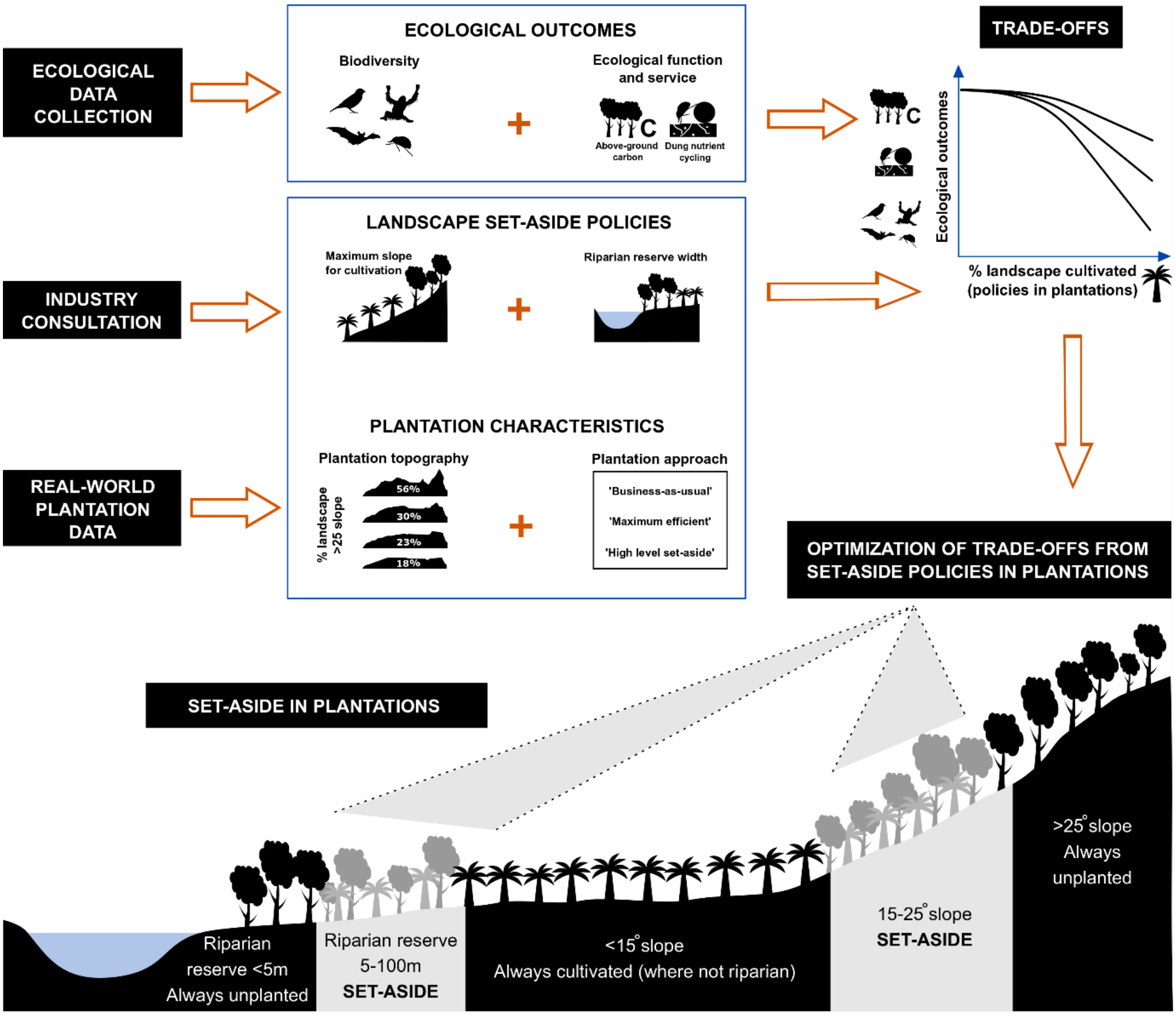

Fig. 1. Study workflow

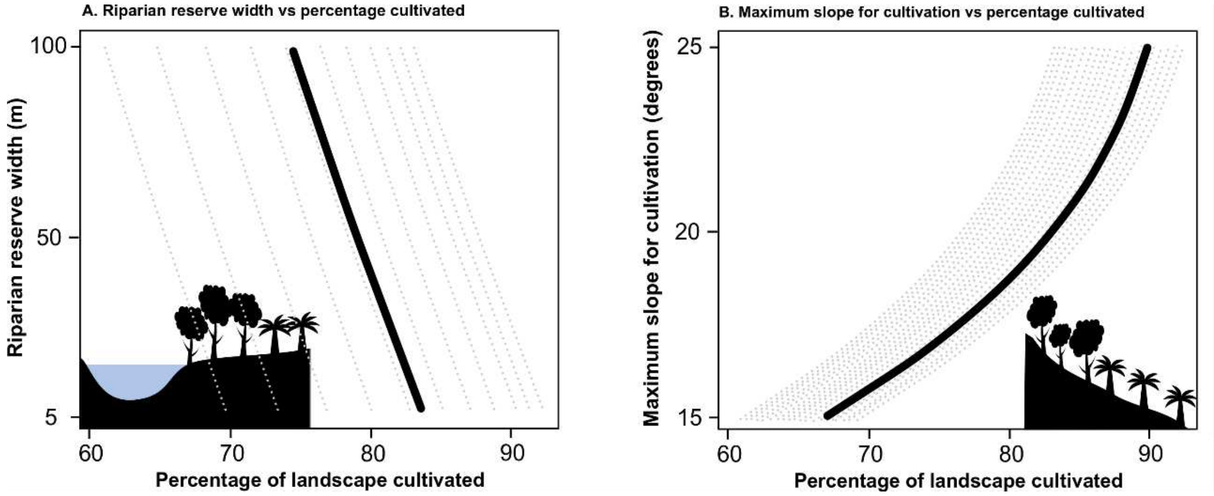

Fig. 2. Impacts of set-aside configurations on percentage of landscape cultivated

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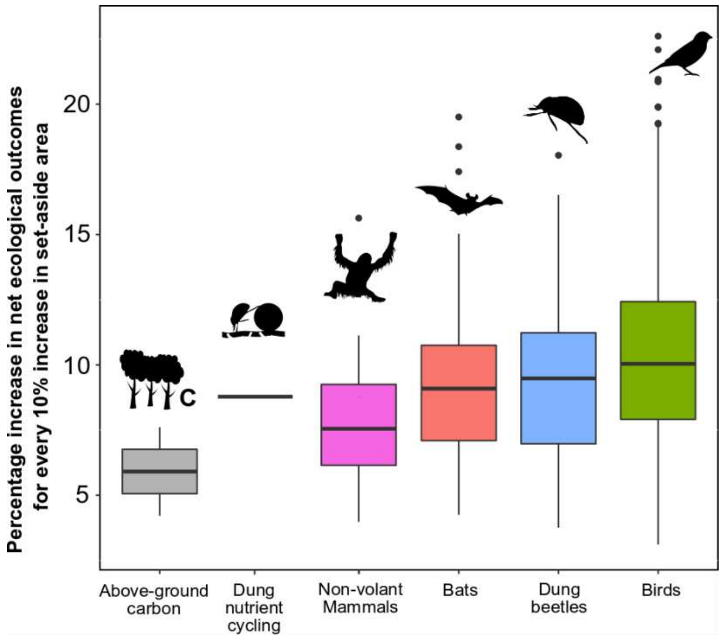


Fig. 3. Percentage increase in net ecological outcomes for each 10% uniform increase in set-aside area

Boxplots of all taxonomic groups, above-ground carbon storage and dung nutrient cycling showing the percentage increase in net ecological outcomes for each 10% uniform increase (under landscape scenarios that range from 61-92% cultivated) in set-aside area across the landscape.

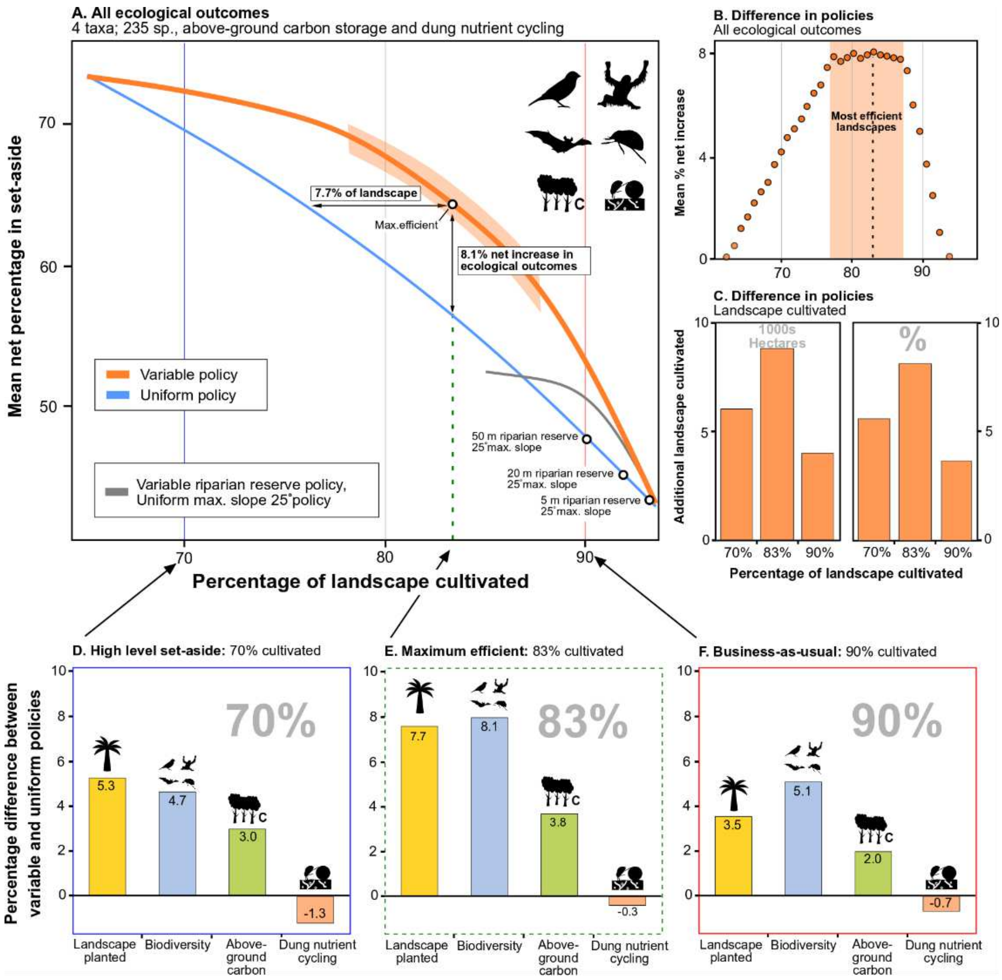


Fig. 4. Ecological outcomes under variable and uniform set-aside policies

(A) Percentage of net ecological outcomes (species occurrence, above-ground carbon storage and dung nutrient cycling) against the percentage of the landscape cultivated under variable (orange line) and uniform (blue line) policies. Under the uniform policy, all plantations in the landscape apply the same policies for riparian reserve width and maximum slope for cultivation, whereas under the variable policy these two components can vary among plantations. The 'most efficient landscapes' show gains from the variable policy that are obtained when set-aside configurations that result in 77–87% of the landscape cultivated (upper quartile of the difference between uniform and variable policies), with the maximum difference achieved when 83% of the landscape is cultivated ('max. efficient' black and white dot). The current legislation in Sabah, Malaysia (25° maximum slope for cultivation, 20 m riparian reserve width) and Indonesia (25° maximum slope for cultivation slope, 50 m riparian reserve width) are shown with labelled dots. Grey curve shows variable riparian policies with a uniform maximum slope for cultivation of 25°. Curves use local polynomial regression for locally estimated scatterplot smoothing (LOESS). **(B)** Percentage change in net ecological outcomes (species occurrence, above-ground carbon storage and dung nutrient cycling) under the variable policy, at all levels of the landscape cultivated. As in A, the most efficient landscapes show the upper quartile of all comparisons between the policies. **(C)** Additional cultivation area (absolute in hectares and as a percentage of the landscape) gains from adopting the variable policy at 70, 83 and 90% of the landscape cultivation, i.e. possible ecological gains for equivalent ecological outcomes. **(D-F)** Net percentage gains for landscape cultivated, species occurrence, above-ground carbon storage, and dung nutrient cycling from adopting the variable policy at 70, 83 and 90% of the landscape cultivated.

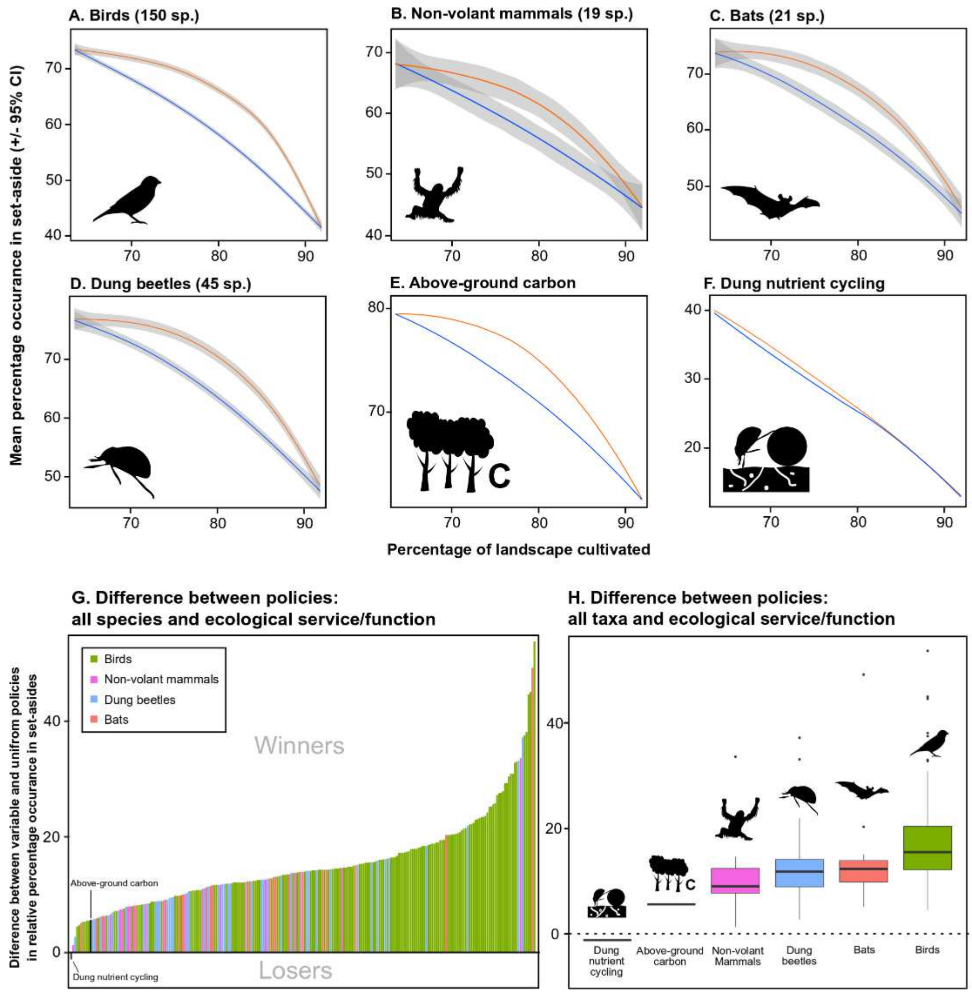


Fig. 5. Taxon and ecological service/function specific ecological outcomes under variable and uniform set-aside policies

(A-F) Trade-off curves of the percentage change in net ecological outcomes (species occurrence, above-ground carbon storage and dung nutrient cycling) in set-aside (mean ± 95% CI) against the percentage of landscape cultivated. Under the uniform policy, all plantations in the landscape apply the same policies for riparian reserve width and maximum slope for cultivation. For the variable policy, these two components can vary between plantations. All curves use local polynomial regression for locally estimated scatterplot smoothing (LOESS). **(G-H)** Difference between policies at the 'maximum efficient' level (83% of the landscape cultivated) in terms of relative percentage occurrence in ecological outcomes **(G)**, and boxplots for all ecological outcomes **(H).**

Table 1. Potential for optimizing oil palm cultivation across Borneo

Impact of optimizing set-asides on potential palm oil production across Borneo for 70, 83 and 90% of landscape cultivated, comparing uniform and variable policies. Under the uniform policy, all plantations in the landscape apply the same policies for riparian reserve width and maximum slope for cultivation. For the variable policy, these two components can vary between plantations.

	High level set-aside 70% of landscape cultivated	**Maximum efficient** 83% of landscape cultivated	**Business-as-usual** 90% of landscape cultivated
Potential percentage of additional land cultivated	5.3	7.7	3.5
Potential additional bio-physically suitable land cultivated on Borneo		30 million hectares	
Potential average additional oil palm trees[1]	199 million	288 million	131 million
Potential average additional CPO yield over 20 years (metric tons)[2]	130 million t	189 million t	86 million t

[1]Given 125 trees per planted hectare (data from plantations C and D).

[2]Given average yield values of 4.1 metric tons of crude palm oil (CPO) per hectare per year, assuming an oil extraction rate of 25%, and average fresh fruit bunch yield of 16.4 metric tons per hectare per year. Data from plantations C and D, which are close to the average of 4.2 metric tons of CPO per hectare per year for Malaysia (Methods).

Figures

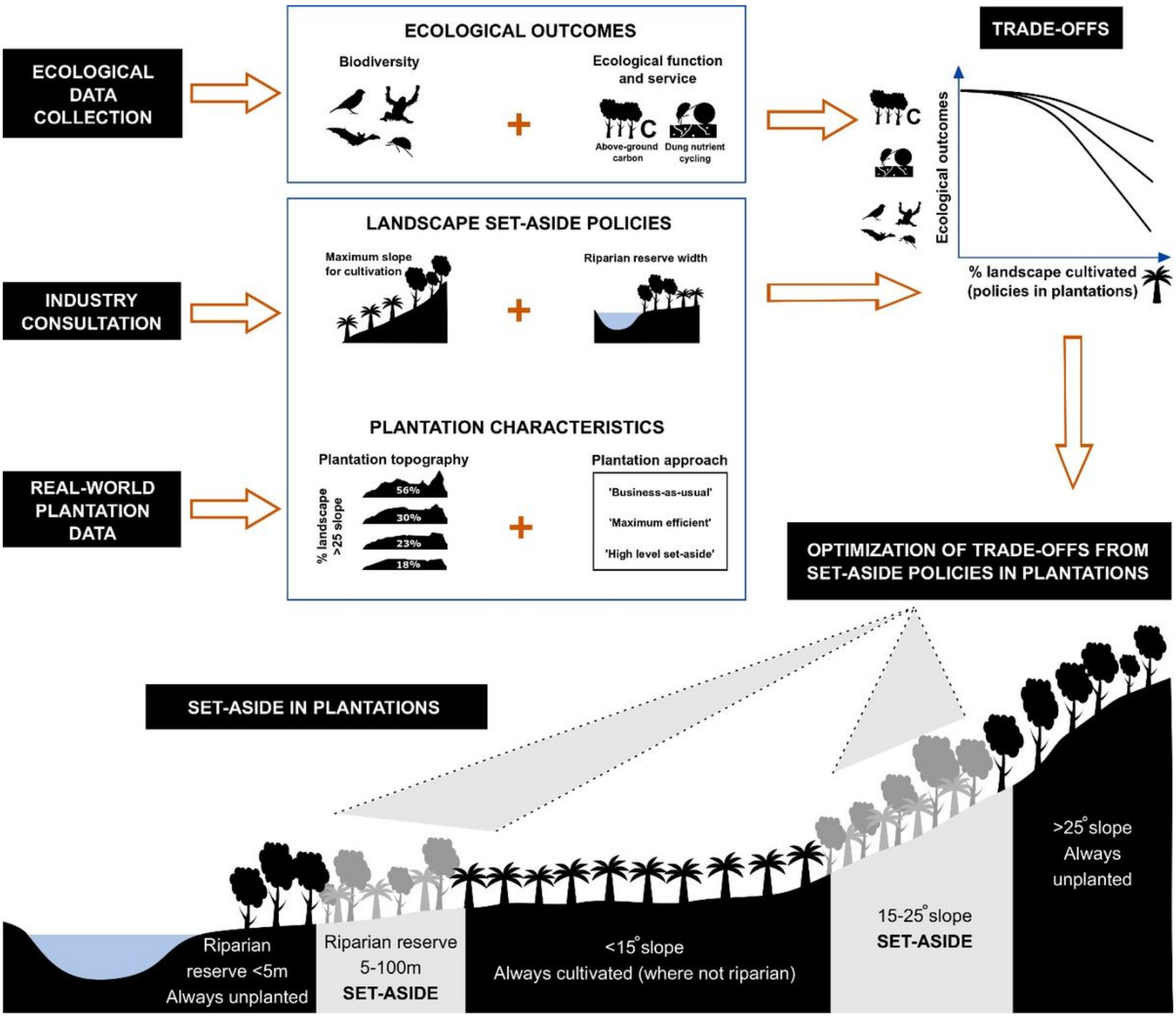
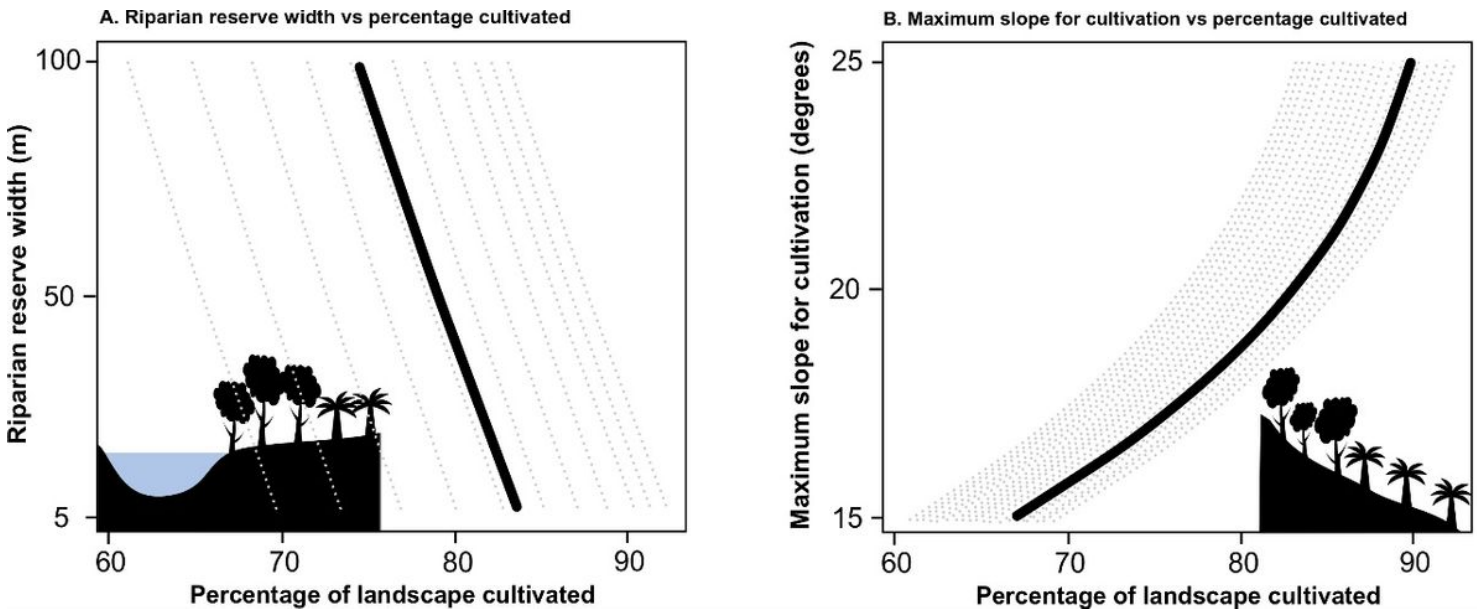


Figure 1

Study workflow



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Impacts of set-aside configurations on percentage of landscape cultivated (A) Relationship between riparian reserve width and the percentage of the landscape cultivated. (B) Relationship between maximum slope for cultivation and percentage of the landscape cultivated. Dashed lines show all potential landscape set-aside configurations, and bold lines show the mean.

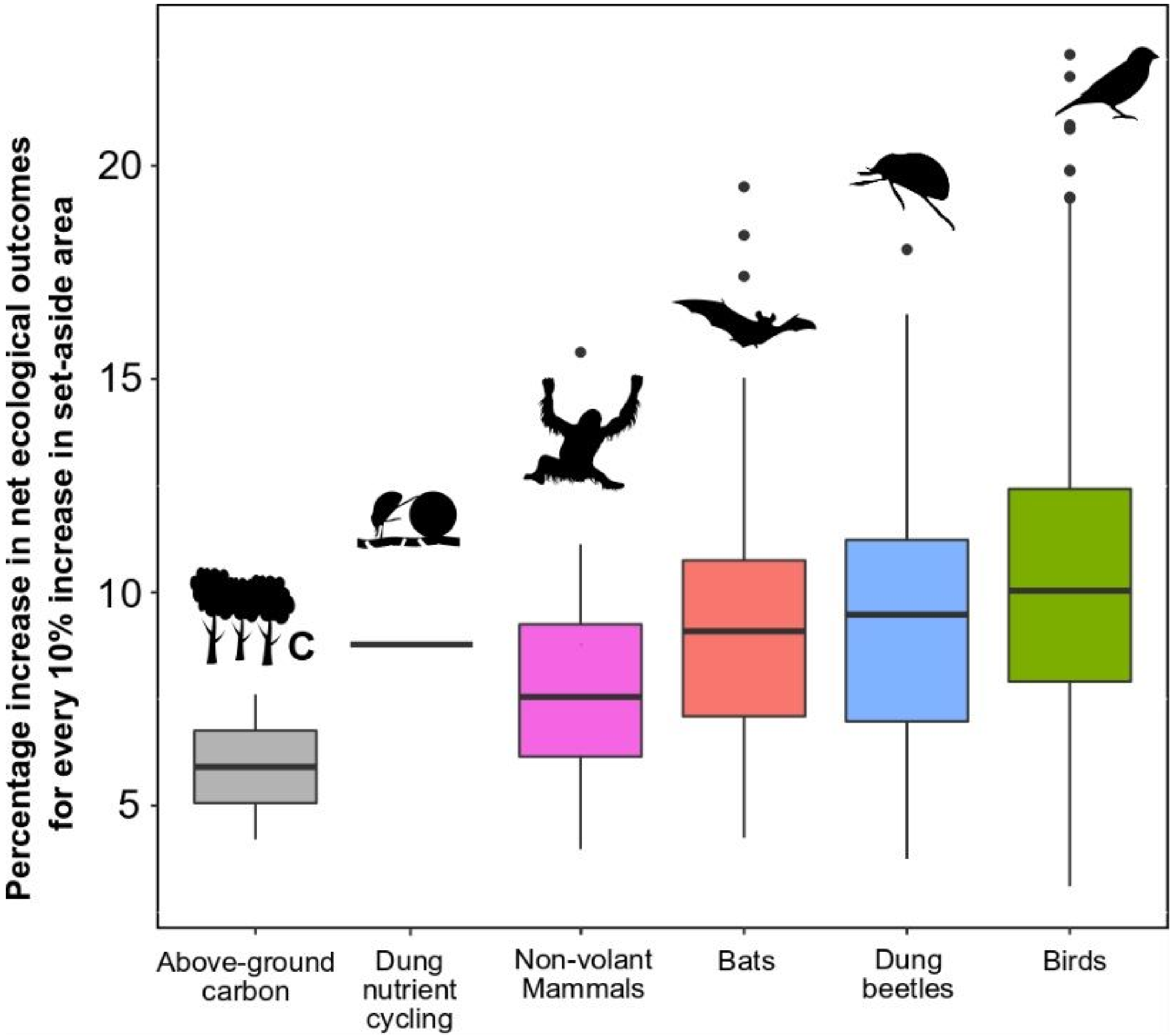

Figure 3

Percentage increase in net ecological outcomes for each 10% uniform increase in set-aside area Boxplots of all taxonomic groups, above-ground carbon storage and dung nutrient cycling showing the percentage increase in net ecological outcomes for each 10% uniform increase (under landscape scenarios that range from 61-92% cultivated) in set-aside area across the landscape.

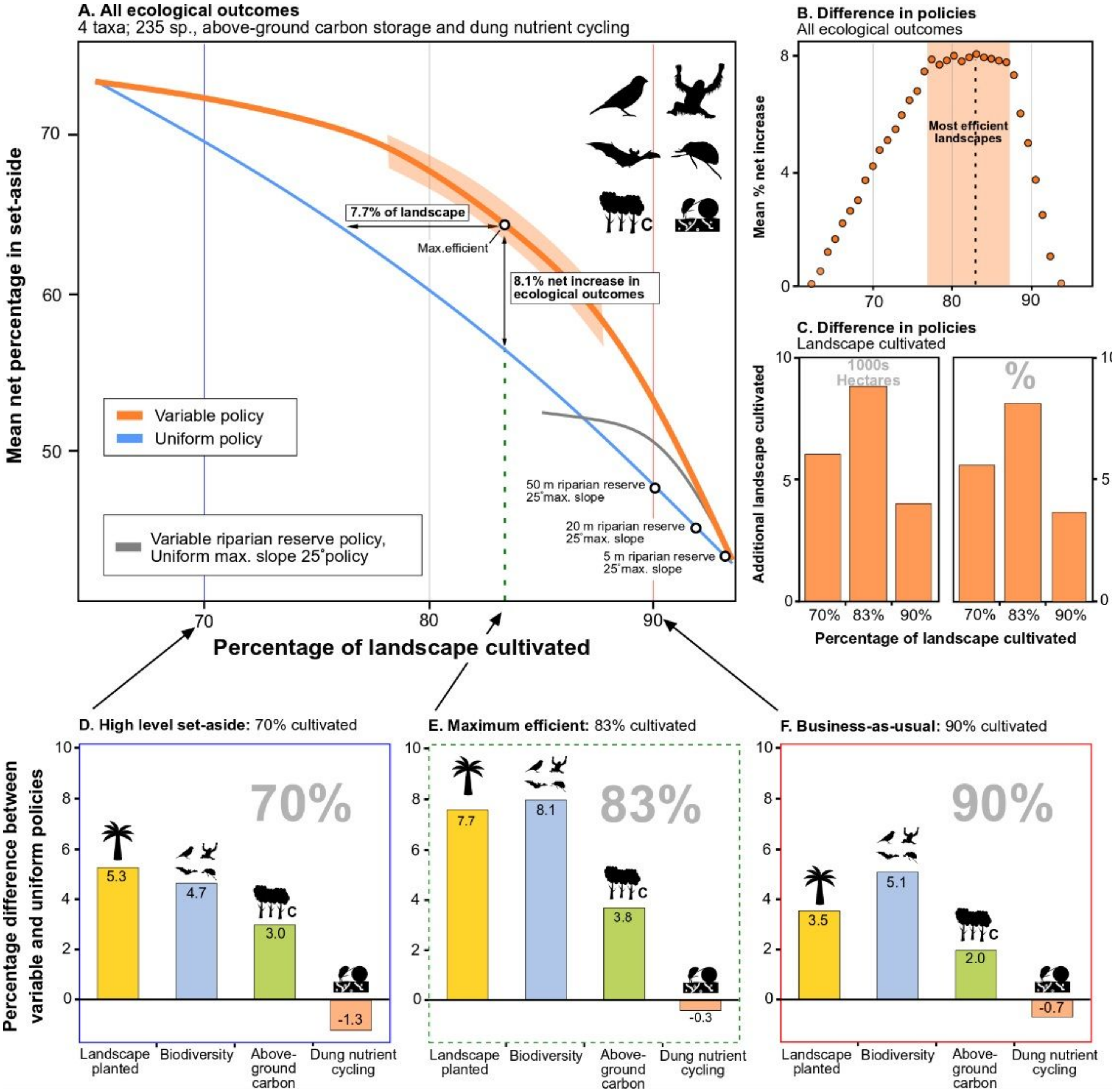

Figure 4

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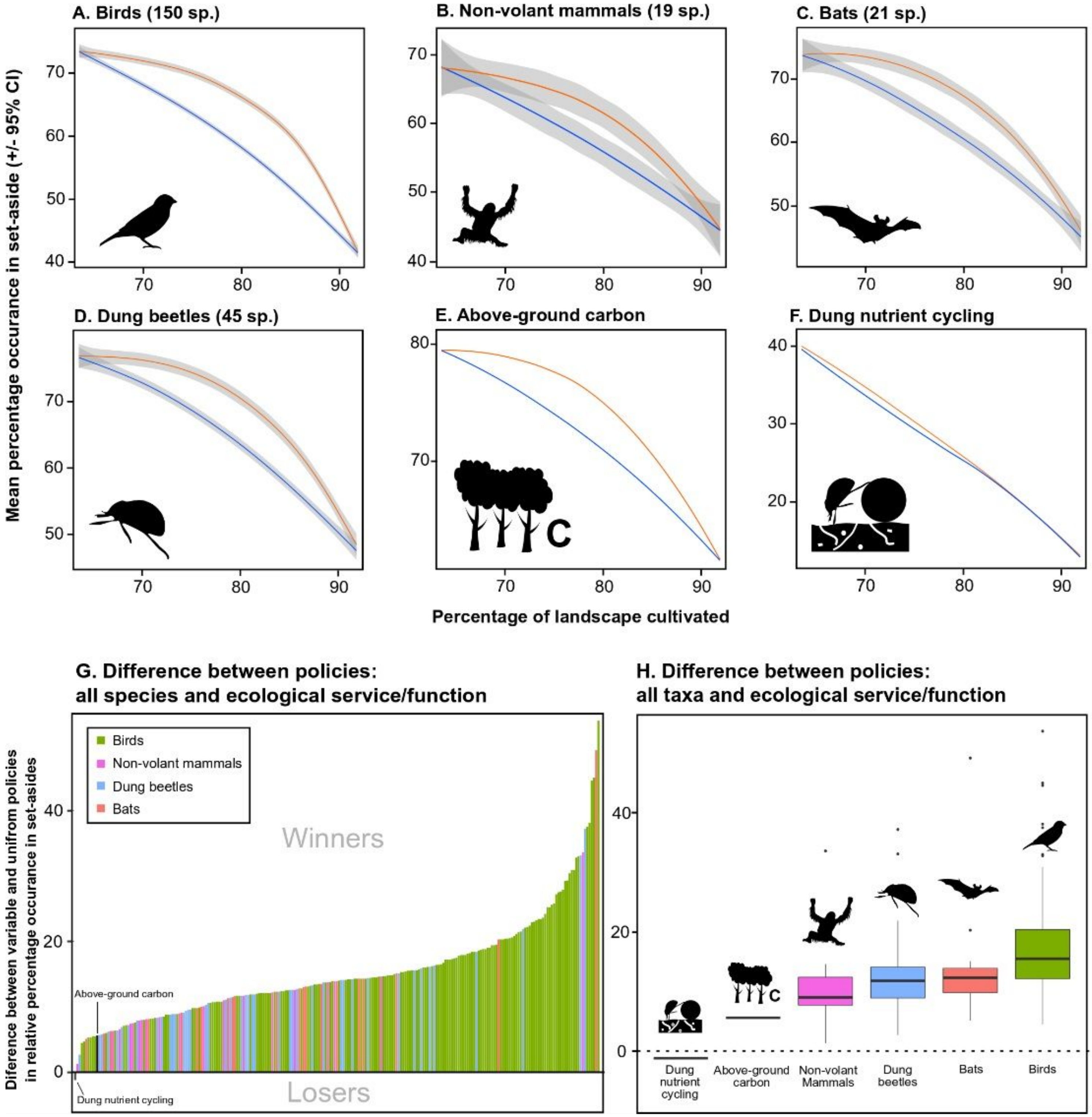

Figure 5

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Supplementary Files

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- BicknelletalSupplementaryInformation.pdf