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Enhancing the ecological value of oil palm agriculture through set-asides

In the format provided by the authors and unedited

Contents

Supplementary Note 1

Three key standards determine the kinds of conservation values that oil palm agriculture should endeavour to minimize impacts upon, and these standards also directly affect set-aside configurations and levels in oil palm landscapes – RSPO, HCV and HCS. One of the primary environmental aims of the RSPO (Round Table on Sustainable Palm Oil) is to "protect, conserve and enhance ecosystems and the environment" (Principle 7, RSPO 2018; https://rspo.org/principles-and-criteria-review). The integrated High Conservation Value (HCV; https://hcvnetwork.org/) and High Carbon Stock (HCS; http://highcarbonstock.org/) set-aside Approaches have, since 2018 been adopted by the RSPO to address biodiversity losses, with RSPO certified oil palm growers required to conserve and manage areas of forest that are identified as HCV or HCS within their plantations. There is also a requirement to manage, protect, and enhance rare, threatened, and endangered species identified within RSPO certified plantations.

The HCS Approach distinguishes forest areas for protection from degraded lands with low carbon and biodiversity values that if converted, are likely to result in fewer negative environmental consequences than areas with higher ecological values. The methodology aims to be a practical, transparent, robust and scientifically credible approach to implement commitments to halt deforestation in the tropics, while ensuring the rights and livelihoods of local peoples are respected. The amount of carbon and biodiversity stored within an area of land is assumed to vary according to the type of vegetative cover. Vegetation cover is stratified into six different classes based on analysis of satellite data and ground survey measurements: High Density Forest, Medium Density Forest, Low Density Forest, Young Regenerating Forest, Scrub and Cleared/Open Land. The first four classes are considered potential High Carbon Stock forests, with carbon values greater than 35 C t/ha (http://highcarbonstock.org/), below which is often considered to be non-forest. To understand how HCS classes mapped onto our study landscape, we used the HCS approach to classify forests, using the same above-ground carbon dataset used in the analyses. The classes in the study landscape reflected carbon content with medians of 108 C t/ha (SD=60) for Dense Forest; 32 (SD=42) for Young Regenerating Forest; 27 (SD=41) for Scrub; and 12 (SD=35) for Cleared/Open Land. Most of the set-asides in our landscape were Young Regenerating Forests, with some Dense Forest and Scrub. For comparison, above-ground carbon values for Malaysian oil palm range from 2 to 60 C t/ha, depending on palm age[1].

The HCV Approach is a tool designed to help deliver on a number of UN Sustainable Development Goals, for meeting corporate sustainability commitments and as a mechanism to ensure responsible investments in forestry and agriculture globally. High Conservation Value Areas (HCVAs) are natural habitats deemed to be of outstanding significance or critical importance due to their high biological, ecological, social, or cultural values, which require appropriate management. HCVAs are identified on a case-by-case basis, through field surveys, a decision tree, stakeholder consultations and use of spatial datasets. Whilst HCS classification includes a fragment size criteria, set-asides that lead to fragments do not.

Maximum slope for cultivation

In Malaysia and Indonesia, as well as in RSPO standards, the maximum slope for cultivation is 25° (equivalent to ~46%). In some cases terracing must be undertaken to allow cultivation on slopes between 20° and 25°, or on particularly vulnerable soils[2].

Riparian reserve width

RSPO standards take an incremental approach to determining riparian reserve width, depending on the size of the river. Smaller rivers (1–5 m wide) need to be buffered on both sides by 5 m riparian reserves, while larger rivers need to be buffered by riparian reserves of up to 100 m wide (Supplementary Table 1;[3]).

Rivers in Sabah State are protected by the Department of Irrigation and Drainage (DID). All permanent water courses more than >3 m wide need a riparian reserve of >20 m, whereas rivers <3 m require 5 m wide riparian reserves. Further, the Sabah EPD "takes into consideration EIA findings of proposed areas whereby environmentally sensitive, wildlife and steep areas" may require "provisions of 50–100 metres of river reserves"

Riparian reserve regulations in Peninsular Malaysia and Sarawak State differs from Sabah, varying depending on river width. Rivers less than 5 m wide have a 5 m reserve, rivers 5 – 10 m wide have a 10 m reserve, rivers 10–20 m have a 20 m reserve, rivers 20–40 m have a 40 m reserve and finally rivers larger than 40 m have a 50 m reserve (www.water.gov.my).

In Indonesia, riparian reserve width is 50 m for rivers less than 30 m wide, and 100 m for rivers more than 30 m wide.

Supplementary Note 2

Additional results on the impacts of set-asides on cultivation area

In isolation, riparian reserve set-aside alone comprised between 0.5 and 10% of the landscape (depending on the width of the reserve), while set-aside based on maximum slope for cultivation alone accounted for 4 to 30% (depending on maximum slope angle). Each fivemeter increase in riparian reserve width results in an increase in set-aside of just 0.44–0.52% of total landscape 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).

Supplementary Note 3

Optimization of trade-offs

We formulated a mixed integer linear programing (MILP) model to optimize set-aside approaches 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 amount of 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:

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

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

The MILP formulation of our 'variable' approach is then:

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

$s.t.$

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

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

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

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

Model (S1)-(S4) is a modified version of what is known in the site selection literature as a "maximum coverage" problem[4]. 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 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.

Our model can be viewed as a multi-objective problem involving the maximization of ecological outcome protection ($\max Z_1 = \sum_{i \in I} w_i y_i$) and maximization of the landscape available for oil palm cultivation or, alternatively, minimization of set-aside area ($\min Z_2 = \sum_{j \in J} \sum_{k \in K} \sum_{\ell \in L} c_{jk\ell} x_{jk\ell}$). The second objective is incorporated as a constraint in the model, as opposed to the common approach of combining both objectives into a single weighted objective function ($\max \alpha_1 Z_1 + \alpha_2 Z_2$, with $\alpha_1 \geq 0$ and $\alpha_2 \leq 0$ being the weights for objectives Z_1 and Z_2, respectively). To assess trade-offs between the two objectives, we systematically varied the amount of land in set-asides, in order to produce Pareto curves of the percentage of the landscape cultivated versus the proportion of ecological outcomes in set-asides. This approach is more formally known as the ε-constraint method for solving multi-objective problems[4].

To impose a 'uniform' approach for riparian reserve width and maximum slope for cultivation across all plantations, we introduce $u_{k\ell}$, 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:

$$\sum_{k \in K} \sum_{\ell \in L} u_{k\ell} = 1 \qquad \text{(S6)}$$

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

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

We implemented our landscape set-aside optimizations in the OPL modeling language using CPLEX studio version 12.9.0[5], 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 regulations in Malaysia and Indonesia. We then plotted where these lie on top of the Pareto-optimal curves.

Supplementary Note 4

At maximum efficient cultivation levels, all species had increased occurrence under the variable approach. Among the taxonomic groups, the greatest gains in species occurrence achieved by the variable approach at maximum efficient planting was seen for birds (Fig. 4A-D,G,H). This included Borneo endemics, such as the bold-striped tit-babbler (*Mixornis bornensis;* 38% relative increase in occurrence) and dusky munia (*Lonchura fuscans;* 27% mean relative increase), the IUCN Red List Endangered greater green leafbird (*Chloropsis sonnerati;* 14% mean relative increase), and Critically Endangered helmeted hornbill (*Rhinoplax vigil;* 14% mean relative increase), as well as species threatened by trade like the oriental magpie-robin (*Copsychus saularis;* 54% mean relative increase). All non-volant mammals were better-off under the variable approach. This included notable species of conservation concern such as the Critically Endangered Bornean orangutan (*Pongo pygmaeus*; 11% relative increase), the Vulnerable sun bear (*Helarctos malayanus;* 8% mean relative increase), Bornean bearded pig (*Sus barbatus;* 12% relative increase), and sambar deer (*Rusa unicolor;* 9% mean relative increase), and high-quality forest specialists such as the banded civet (*Hemigalus derbyanus;* 8% mean relative increase). Among the bats the variable approach benefitted all species, including Rohu's bat (*Philetor brachypterus;* 49% mean relative increase), while the restricted range and Vulnerable Ridley's leaf-nosed bat (*Hipposideros ridleyi*; 5% mean relative increase). All dung beetles were better-off from the variable approach including two Borneo endemics (*Proagaderus wantanabei;* 13% mean relative increase, and *Catharsius dayacus;* 12% mean relative increase).

The impact on dung nutrient cycling varied, with slight improvements observed for the variable approach when less than ~80% of the landscape is cultivated (Fig. 4F,G,H). When more of the landscape is cultivated, however, small reductions in nutrient cycling were observed. A likely explanation for this pattern is that areas characterized by more rugged topography, which make up a greater proportion of set-asides in variable approach configurations, have lower dung nutrient cycling rates because they tend to be at high elevations where temperatures are lower (Supplementary Figs. 6-7).

For the high level set-aside (70% cultivated) scenario, the 'variable' approach delivers an average 4.7% net increase in species occurrence, 3.0% more above-ground carbon storage (at time point zero) and a 1.3% reduction in dung nutrient cycling (Fig. 3D,F; Supplementary Table 3). Efficiencies gained from an optimized 'variable' approach for business-as-usual (90% cultivated) correspond to an average 5.1% net increase in species occurrence, 2% more above-ground carbon storage and a 0.7% reduction in dung nutrient cycling. Framed another way, the same level of species occurrence under the high level set-aside and business-as-usual scenarios could only be achieved under the ‘uniform’ approach by planting 5.3% and 3.5% less of the landscape with oil palm respectively (Supplementary Table 4).

Supplementary Note 5

Trade-off curves of 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 (as a result of set-aside configurations), 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 $b_0, \dots, b_3$ 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.

In general, species trade-offs were non-linear (Fig. 4; Supplementary Fig. 8) and this is due to three factors. First, some species are more associated with steep slopes, while others are more associated with riparian reserve forest habitats. Second, changes to maximum slope for cultivation has an exponential effect on set-aside area. Third, as the proportion of the landscape in set-aside increases, the chances of an area of forest being both retained because it is both on a slope and in a riparian reserve rises. This therefore effects different species in different ways, because riparian reserves are driving changes in the amount of set-aside above 83% of the landscape cultivated, whereas maximum slope is the primary driver at lower percentages of the landscape cultivated. Non-linearity was highest for dung-beetles, whose trade-off curves often levelled off above 83% of the landscape cultivated.

Supplementary Tables 1-8

Supplementary Table 1. Minimum riparian reserve widths either side of rivers for RSPO and HCV. From rspo.org[3].

River width	1-5 m	5-10 m	10-20 m	20-40 m	40-50 m	>50 m
RSPO generic guidelines for minimum width of riparian reserve on both banks	5	10	20	40	50	100
Waterways which supply the water and food needs of local communities and plantation workers (HCV5)	30	30	30	40	50	100
Reserves that are upstream of conservation areas or are significant breeding grounds for fish and aquatic life (HCV1/5)	30	30	30	40	50	100
Reserves that are important wildlife corridors, support rare, threatened and endangered species of economic importance to local communities (HCV5)	30	70	>200	>200	>200	>200
Waterways, including small streams <1 m wide, which receive surface water runoff from steep and moderately steep oil palm cultivated slopes (9-25, HCV4)	Increase the width of any adjacent riparian reserves by 1 m for every 0.5° increase above 9° in the slope. Slopes >25° should not be planted under RSPO requirements.					
Seasonally flooded or unsuitable soil types for cultivating oil palm	It is recommended that these areas are not planted with oil palm or are reforested if planting has already taken place.					

Supplementary Table 2. Area (hectares), percentage area above 15°, and percentage area within 100 m of a river, for each plantation in the study landscape in Sabah, Malaysian Borneo.

Plantation Name	**Area (ha)**	**% area with slopes above 15°**	**% area within 100m of a river**
A	10,094	56	22
B	37,784	30	23
C	40,667	23	17
D	19,858	18	12
Across all four plantations	108,403	28	19

Supplementary Table 3. Differences in ecological outcomes (species occurrence, above-ground carbon storage, dung nutrient cycling) and the potential additional land available for cultivation and oil palm trees, between the 'variable' and 'uniform' approaches. These figures are at time point zero and so do not include carbon accumulation that may result. Estimated carbon accumulation values are included in Supplementary Table 4.

	Variable approach	Uniform approach	Difference	Net difference (%)
Maximum efficient (85% cultivated)				
Biodiversity (net % species occurrence, mean and range across all species)	65 (12 – 80)	54 (8 – 77)	-	8.8 (-8.1 – 17)
Above-ground carbon storage (tonnes) at time point zero	15,626,044	14,759,766	866,267	3.8
Dung nutrient cycling (g dung removed per 24 hrs)	7,389,178	7,780,458	-391,280	-1.0
Additional land available for cultivation (compared to 'uniform' approach)	-	-	9,214	8.5
Additional oil palm trees (compared to 'uniform' approach)	-	-	1,151,776	-
Business-as-usual (90% cultivated)				
Biodiversity (net % species occurrence, mean and range across all species)	53 (8 – 74)	47 (6 – 74)		5.6 (-10.3 – 13.8)
Above-ground carbon storage (tonnes) at time point zero	14,529,362	14,010,931	518,431	2.3
Dung nutrient cycling (g dung removed per 24 hrs)	5,767,622	6,098,705	-331,083	-0.9
Additional land available for cultivation (compared to 'uniform' approach)	-	-	4,878	4.5
Additional oil palm trees (compared to 'uniform' approach)	-	-	609,764	-
High level set-aside (70% cultivated)				
Biodiversity (net % species occurrence, mean and range across all species)	72 (24 – 85)	68 (19 – 83)	-	4.0 (-4.4 – 6.8)
Above-ground carbon storage (tonnes) at time point zero	17,380,733	16,860,087	652,647	2.4
Dung nutrient cycling (g dung removed per 24 hrs)	12,332,853	12,513,444	-180,591	-0.5
Additional land available for cultivation (compared to 'uniform' approach)	-	-	6,289	6.3
Additional oil palm trees (compared to 'uniform' approach)	-	-	853,670	-

Supplementary Table 4. Predicted above-ground carbon stored in the study landscape after 20 years, for both the 'variable' and 'uniform' approaches to implementing set-asides, following natural regeneration and active restoration of degraded forest. The estimates are based on carbon accumulation rates for Sabah, Malaysia (2.9 C t/ha yr^{-1} for natural regeneration and 4.4 t/ha yr^{-1} for actively restored forest)[64]. As edge effects are likely to impact carbon sequestration in small forest patches[52,65], these accumulation rates may be over-estimates. The percentage increase compared with time point zero are shown in parentheses.

	Variable approach at time point zero	Uniform approach at time point zero	Variable approach natural regeneration after 20 years	Uniform approach natural regeneration after 20 years	Variable approach actively restored after 20 years	Uniform approach actively restored after 20 years
Above-ground carbon storage (tonnes) at Maximum efficient (85% cultivated) planting levels	15,626,044	14,759,766	22,438,114 (+44%)	21,571,836 (+46%)	25,961,598 (+66%)	25,095,320 (+70%)
Above-ground carbon storage (tonnes) at Business-as-usual (90% cultivated) planting levels	14,529,362	14,010,931	21,341,432 (+47%)	20,823,001 (+49%)	24,864,916 (+71%)	24,346,485 (+74%)
Above-ground carbon storage (tonnes) at High level set-aside (70% cultivated) planting levels	17,380,733	16,860,087	24,192,803 (+39%)	23,672,157 (+50%)	27,716,287 (+59%)	27,195,641 (+61%)

Supplementary Table 5. Mean (weighted by plantation area) and range of configurations for riparian reserves widths and maximum slope for cultivation to achieve 85, 90 and 70% of the landscape cultivated under the uniform and variable approaches.

	Uniform approach riparian reserve widths	Variable approach riparian reserve widths	Uniform approach maximum slope for cultivation	Variable approach maximum slope for cultivation
Maximum efficient (85% cultivated)				
Mean	61 m	49 m	19°	23°
Range	5 – 100 m	5 – 100 m	19 – 25°	15 – 25°
Business-as-usual (90% cultivated)				
Mean	18 m	19 m	24°	24°
Range	5 – 30 m	5 – 100 m	23 – 25°	17 – 25°
High level set-aside (70% cultivated)				
Mean	63 m	70 m	17°	17°
Range	35 – 85 m	40 – 100 m	16 – 17°	15 – 22°

Supplementary Table 6. Potential for optimizing oil palm cultivation across Borneo

Impact of optimizing set-asides on potential palm oil production, scaled up for the whole of Borneo. On Borneo, an additional 30 million hectares (40% of the island) is bioclimatically suitable for oil palm cultivation and falls outside of protected areas[44]. Of this, we estimate 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 (Methods). Our analyses below are based on the numbers shown in Fig. 6 A-C (far left bars in yellow), the 'variable' approach to set-asides could either lead to increased ecological outcomes (as generally presented in this study), or, increased cultivation area without a net change in ecological outcomes. Under 'uniform' set-asides, all plantations in the landscape adopt the same riparian reserve widths and maximum slopes for cultivation, whereas under 'variable' set-asides there can be variability in riparian reserve widths and maximum slopes for cultivation between plantations. Figures are given for 70, 85 and 90% of the landscape cultivated.

	High level set-aside 70% of landscape cultivated	**Maximum efficient** 85% of landscape cultivated	**Business-as-usual** 90% of landscape cultivated
Potential percentage of additional land cultivated	6.3	8.5	4.5
Potential average additional oil palm trees[1]	236 million	330 million	169 million
Potential average additional CPO yield over 20 years (tonnes)[2]	156 million t	216 million t	111 million t

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

[2]Given average yield values of 4.1 tonnes 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 tonnes per hectare per year. Data from plantations C and D, which are close to the average of 4.2 tonnes of CPO per hectare per year for Malaysia (Methods).

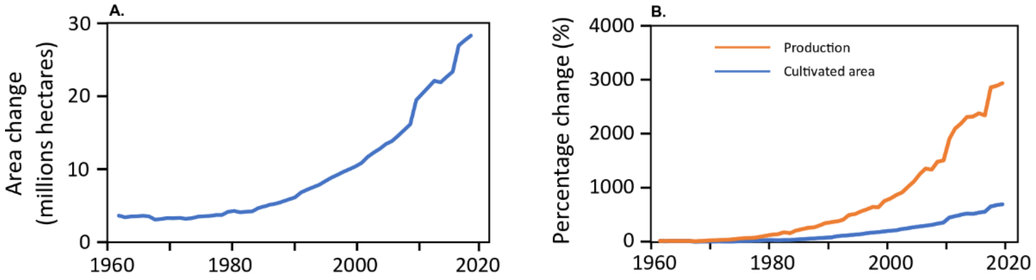
Supplementary Table 7. DOIs and other sources for ecological data used in the analyses

Ecological data	**DOI and other sources**
Dung beetle assemblage	https://doi.org/10.5281/zenodo.3247494; and https://doi.org/10.1002/fee.2473; and https://doi.org/10.1111/1365-2664.13784; and https://doi.org/10.1111/1365-2664.14049; and https://doi.org/10.1111/1365-2656.13655
Dung nutrient cycling	https://doi.org/10.5281/zenodo.3247494
Bat community	https://doi.org/10.5281/zenodo.3247465; and https://doi.org/10.1111/mec.16153
Non-volant mammal community	https://doi.org/10.5285/62774180-ae72-4873-9482-e8be3935f533; and https://doi.org/10.1002/fee.2473
Bird community	https://doi.org/10.5061/dryad.kn251r8; and https://kar.kent.ac.uk/76185/; and https://doi.org/10.1002/fee.2473
Above-ground carbon LiDAR	See https://doi.org/10.1016/j.biocon.2017.10.020

Supplementary Table 8. Ground truthed rivers in the study landscape in Sabah, Borneo

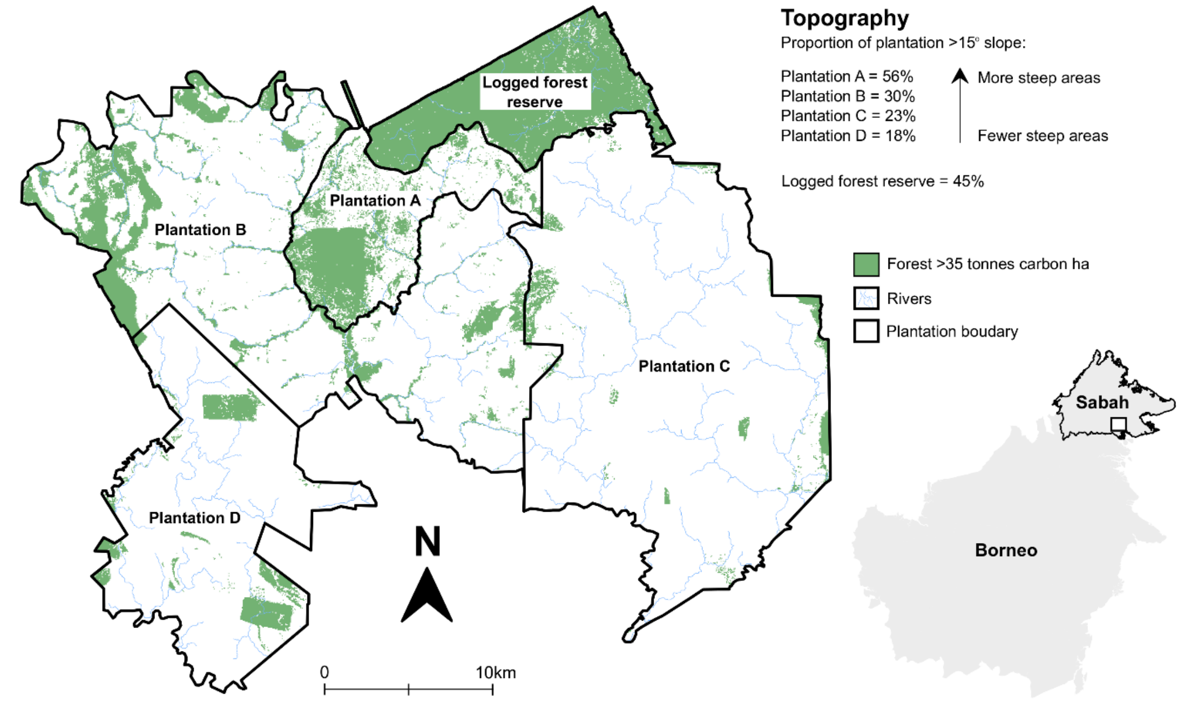
River channel width (mean)	Riparian reserve width (mean either side of the river)
5.77	137.47
13.70	74.60
5.60	36.45
7.06	59.87
5.77	137.47
25.00	61.50
60.00	496.25
11.50	46.60
8.24	15.78
9.50	49.25
12.68	59.96
11.73	42.89
18.00	98.40
8.36	0.00
7.91	0.00
5.94	0.00
17.73	50.00
9.96	0.00
2.00	0.00
2.00	0.00

Supplementary Figures 1-15



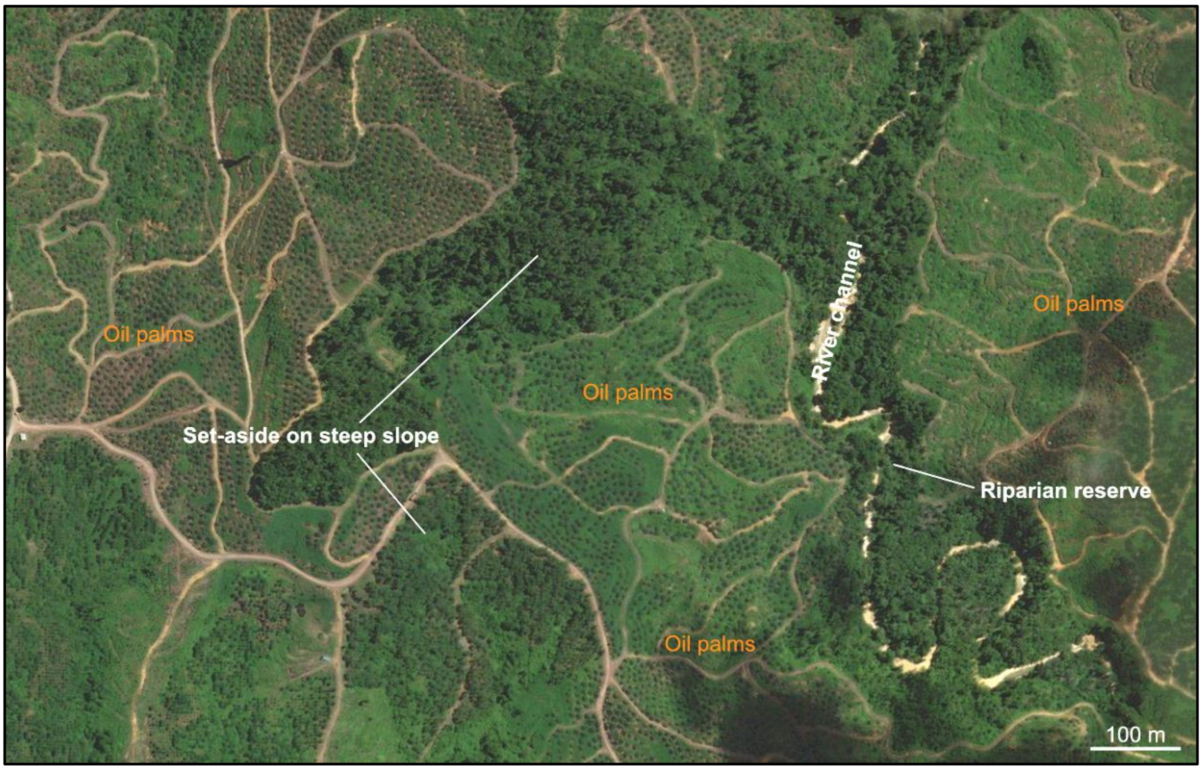
Supplementary Fig. 1. Oil palm trends

Global change in oil palm cultivation between 1961 and 2019. **(A)** area in millions of hectares, and; **(B)** percentage. Percentage change includes cultivated area, and production (i.e. yield). This indicates an overall rise in intensification, because production is increasing at a greater rate than changes in cultivation area. Data from http://www.fao.org/faostat/.

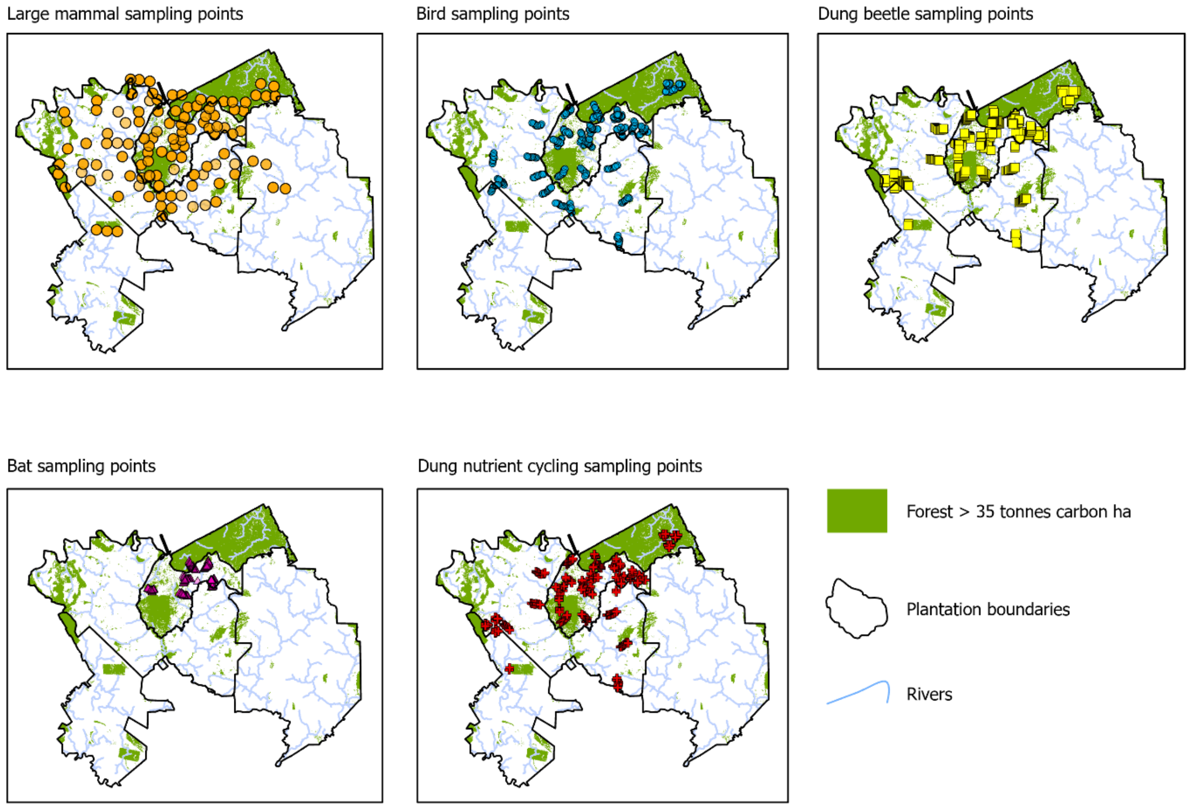


Supplementary Fig. 2. Study landscape in Sabah, Malaysian Borneo

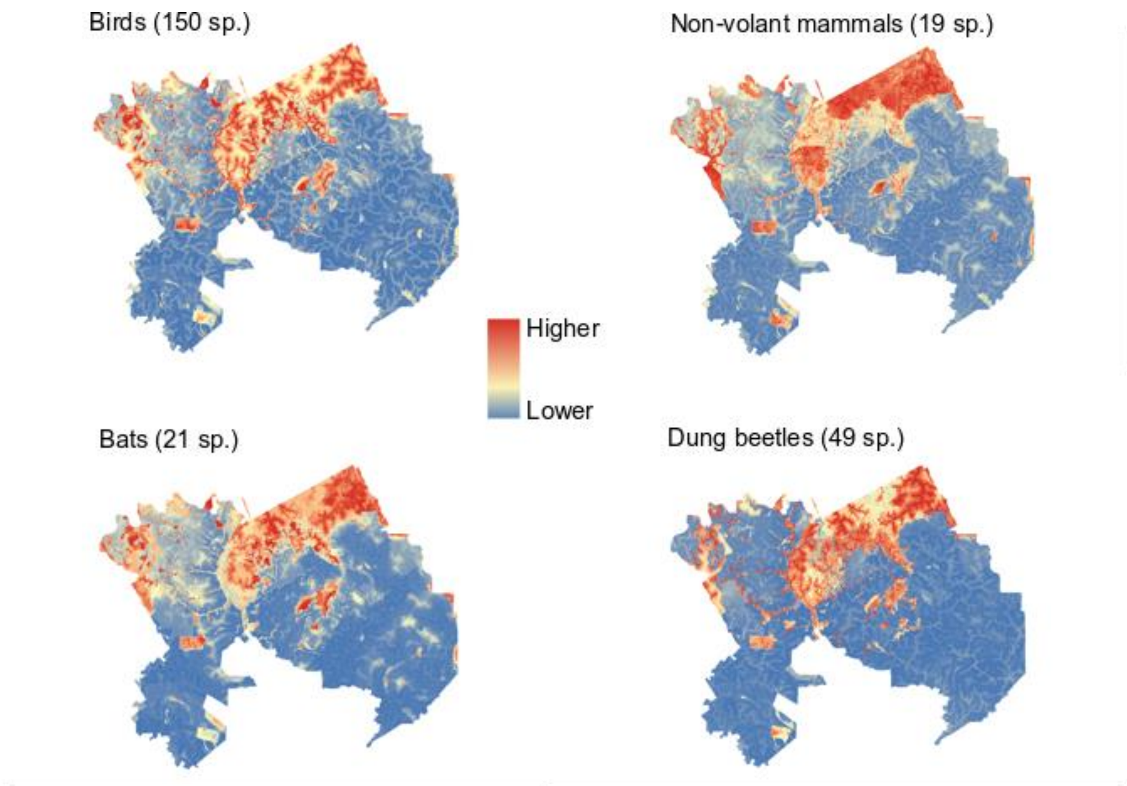
Four plantations and the forest reserve. Green shows forested pixels that have greater than 35 tonnes of above-ground carbon stored per hectare. Only rivers with channels wider than ~5 m are shown and included in the analyses. Inset map shows the Malaysian state of Sabah on the island of Borneo. White square shows the location of the study system.



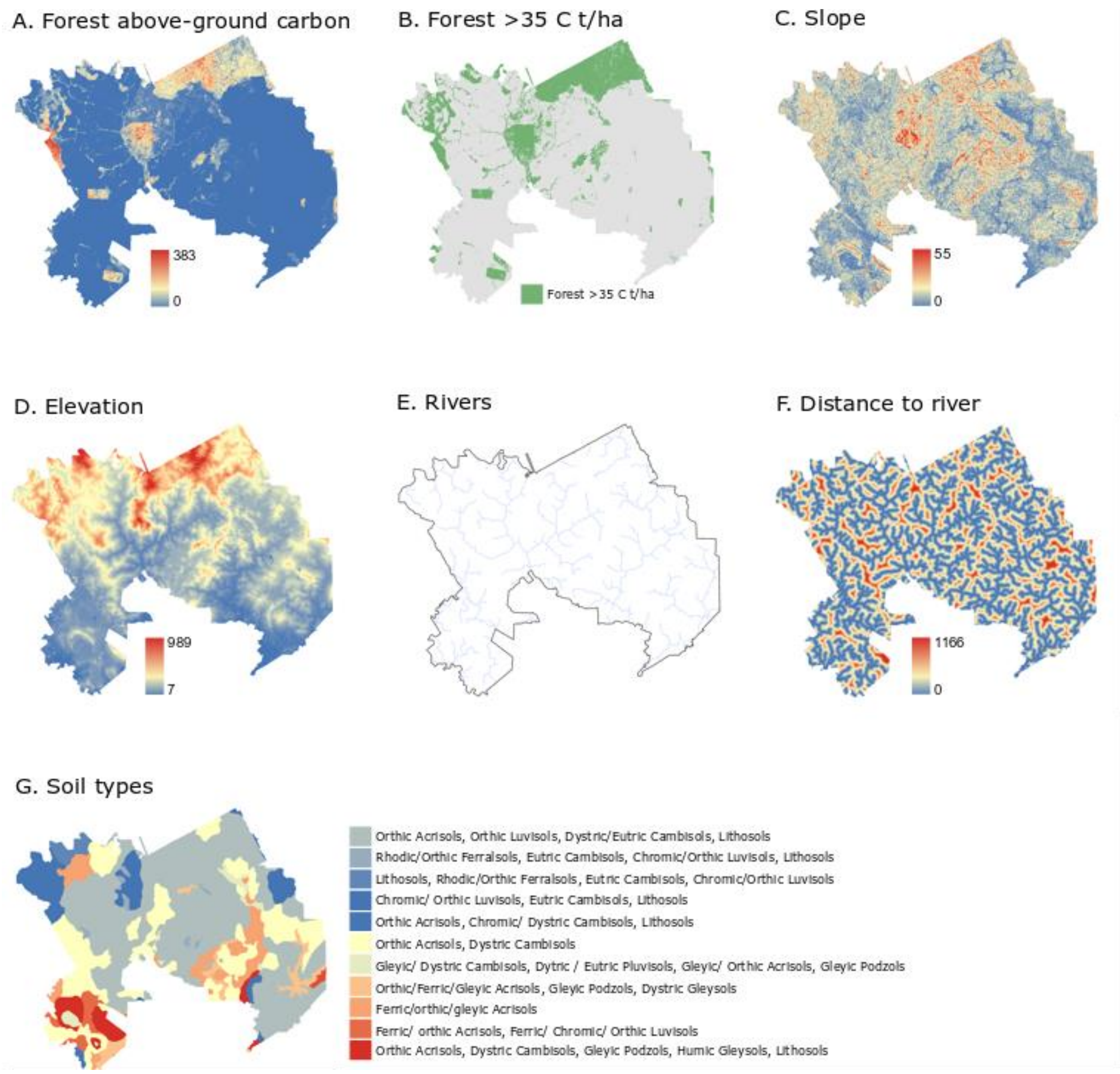
Supplementary Fig. 3. Aerial view of part of the study landscape, showing the agricultural matrix of oil palms, remnant forest set-aside on steep slopes, set-aside in riparian reserves, and the river channel. Imagery curtesy of Microsoft/Bing Maps



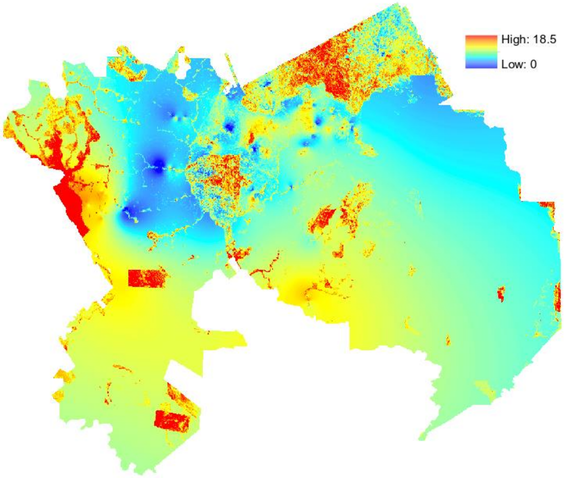
Supplementary Fig. 4. Sampling points across the landscape for each taxonomic group and dung nutrient cycling. Above-ground carbon storage was measured across the entire landscape.



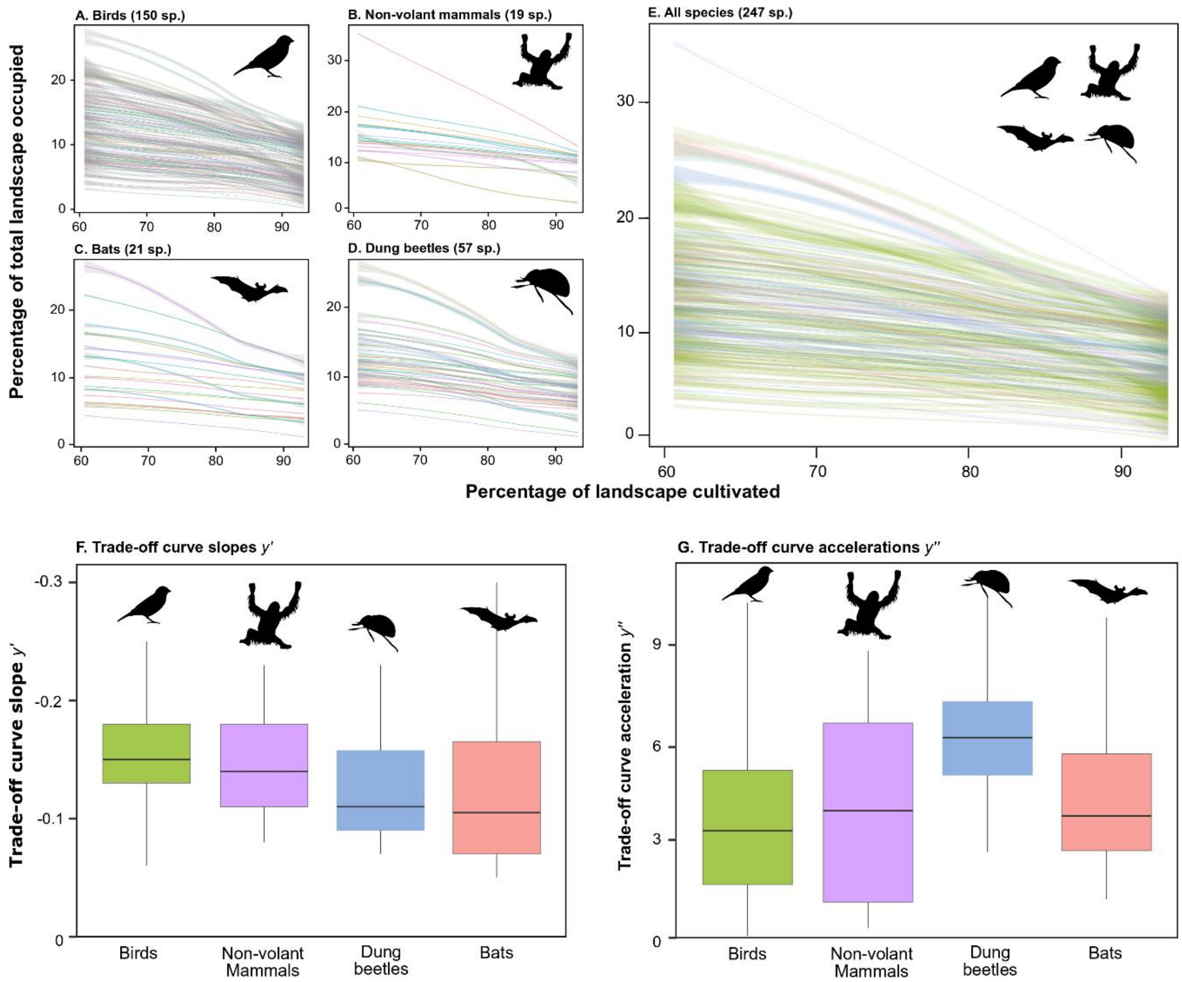
Supplementary Fig. 5. Species richness from SDMs (see Methods) across the study landscape for the four taxonomic groups.



Supplementary Fig. 6. Landscape variables used in the study. A. Above-ground carbon density in forests (tonnes of carbon per hectare); B. Forest cover above 35 tonnes of carbon per hectare; C. Slope (degrees), derived from SRTM. D. Elevation from SRTM; E. Perennial rivers (> 5 m bank to bank on average; from SRTM and ground-truthing); F. Euclidean distance to rivers; G. Soil types (from national database of Malaysia).

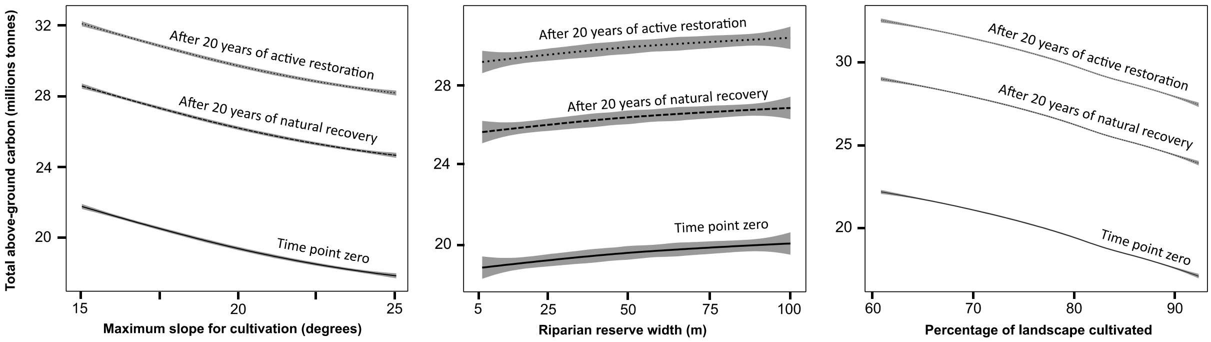


Supplementary Fig. 7. Dung nutrient cycling (grams of dung removed per 24 hours) estimated across the study landscape by regression kriging (see Methods).

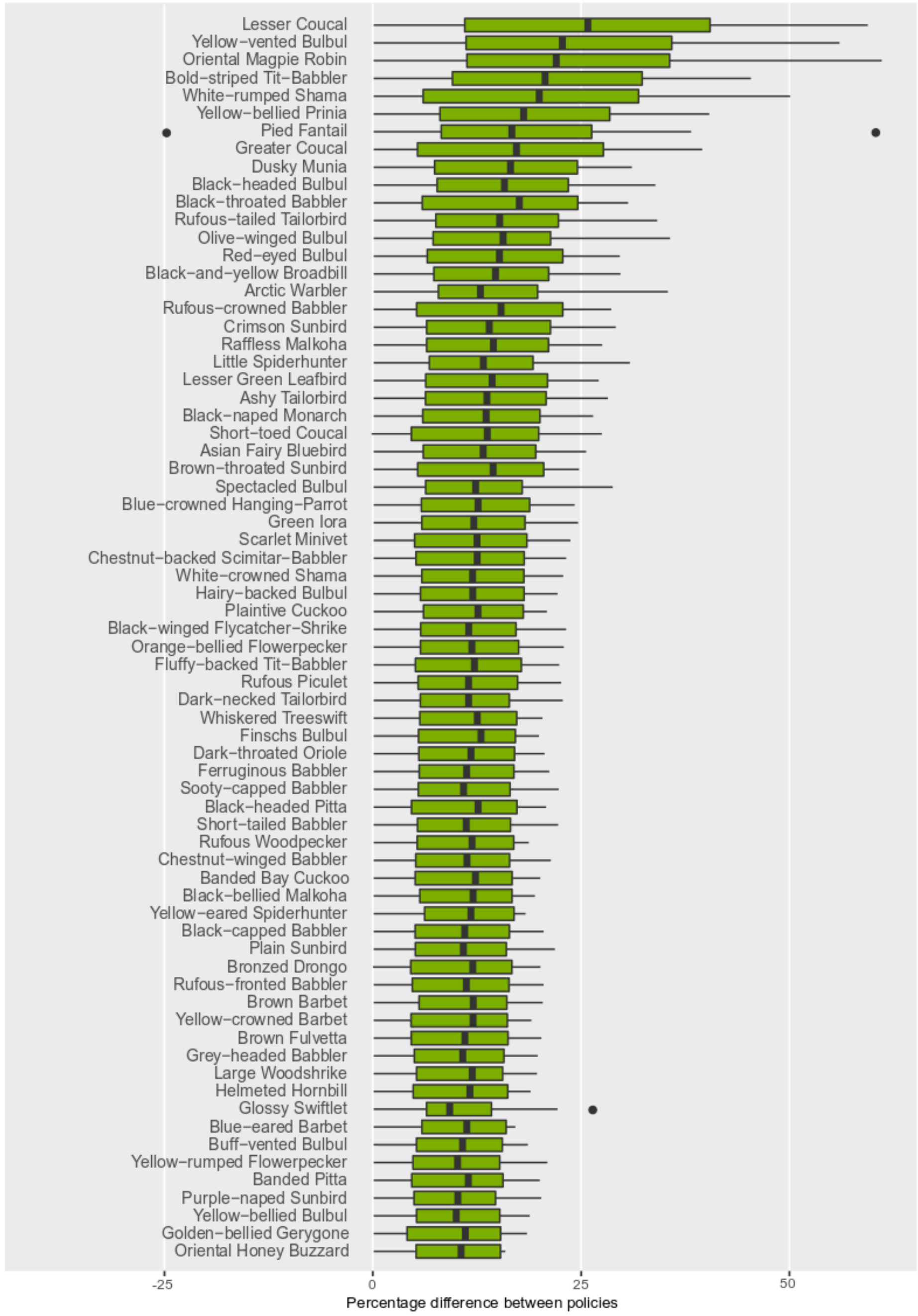


Supplementary Fig. 8. Trade-off curves, slopes and acceleration for each taxon and ecological outcome.

(A-E) Species specific trade-off curves showing the percentage of the total landscape occupied (±95% CI), and percentage of the landscape cultivated under 220 landscape set-aside configurations for **(A)** birds, **(B)** non-volant mammals, **(C)** bats, **(D)** dung beetles, and **(E)** all species. **(F)** Boxplots (bold horizonal line = median; box = 25^{th} and 75 percentiles; whiskers = largest and smallest values within 1.5 times the interquartile range) of trade-off curve slope (y') for each taxa. **(G)** Boxplots of trade-off curve accelerations (y'') for each taxa. Acceleration provides an approximation of the linearity of a curve, with larger accelerations being less linear. All curves use local polynomial regression for locally estimated scatterplot smoothing (LOESS). Based on 247 species (150 birds, 21 bats, 19 non-volant mammals, and 57 dung beetles)

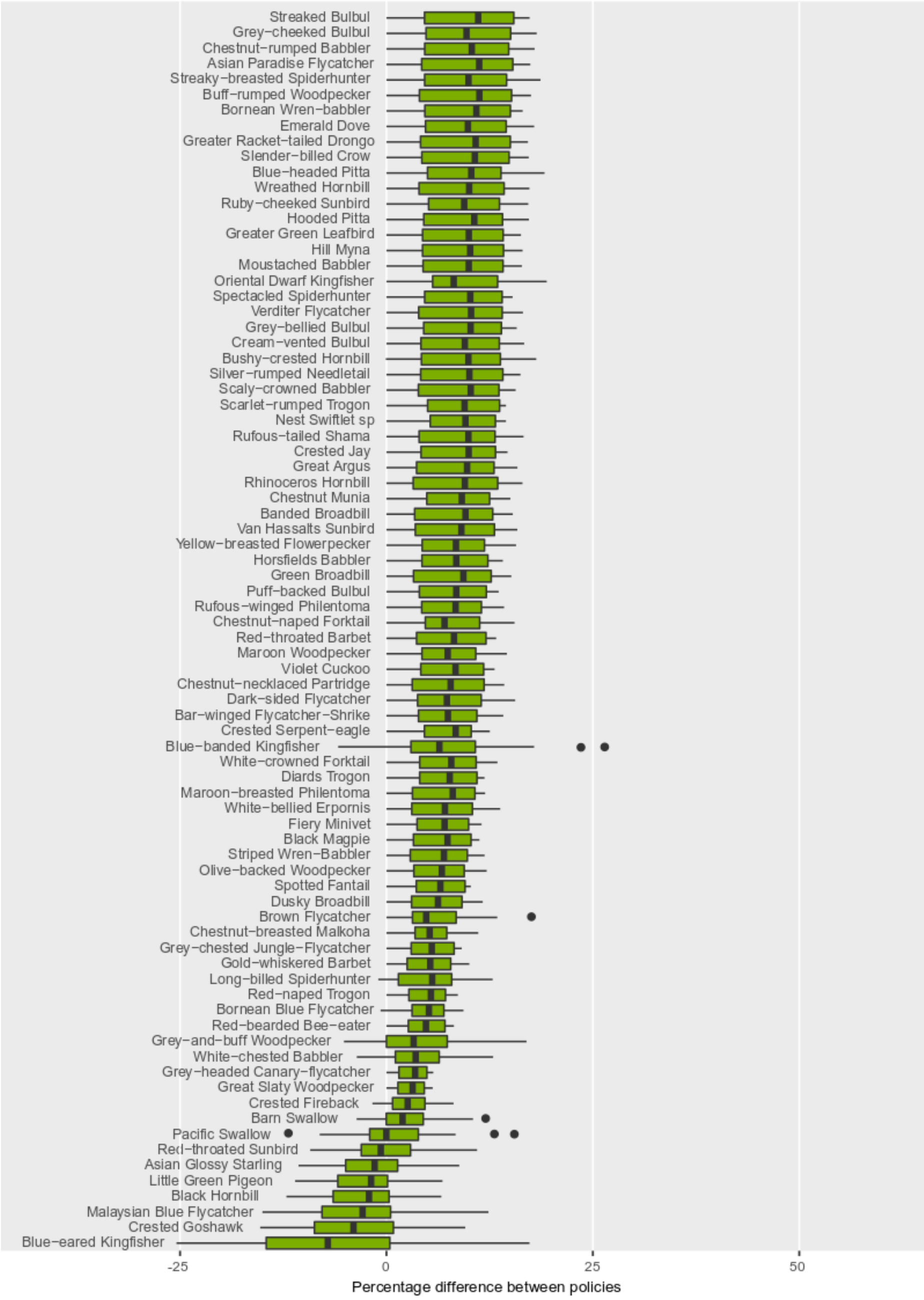


Supplementary Fig. 9. Relationship between above-ground forest carbon storage, maximum slope for cultivation, riparian reserve width and the percentage of the landscape cultivated. The bottom curve shows carbon at time point zero in the study landscape, the middle curve shows the predicted carbon after 20 years of natural restoration, and the top curve show the predicted carbon after 20 years of active restoration. Shading indicates 95% confidence intervals. All curves use local polynomial regression for locally estimated scatterplot smoothing (LOESS).



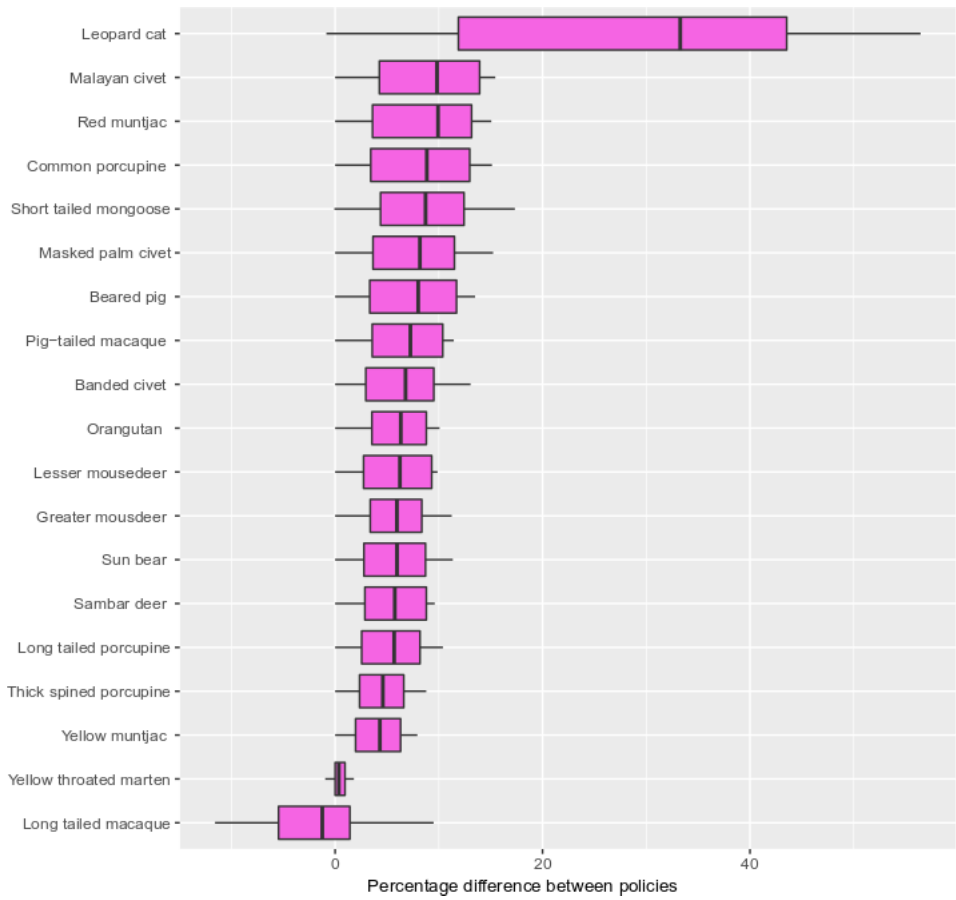
Supplementary Fig. 10i. Relative difference in species occurrence between approaches for all birds

Boxplots (bold horizonal line = median; box = 25th and 75 percentiles; whiskers = largest and smallest values within 1.5 times the interquartile range) of the net difference between the ‘uniform’ and ‘variable’ approaches in terms of the relative percentage occurrence in set-aside, across all percentages of the landscape cultivated under 220 landscape set-aside configurations, for each species of bird.



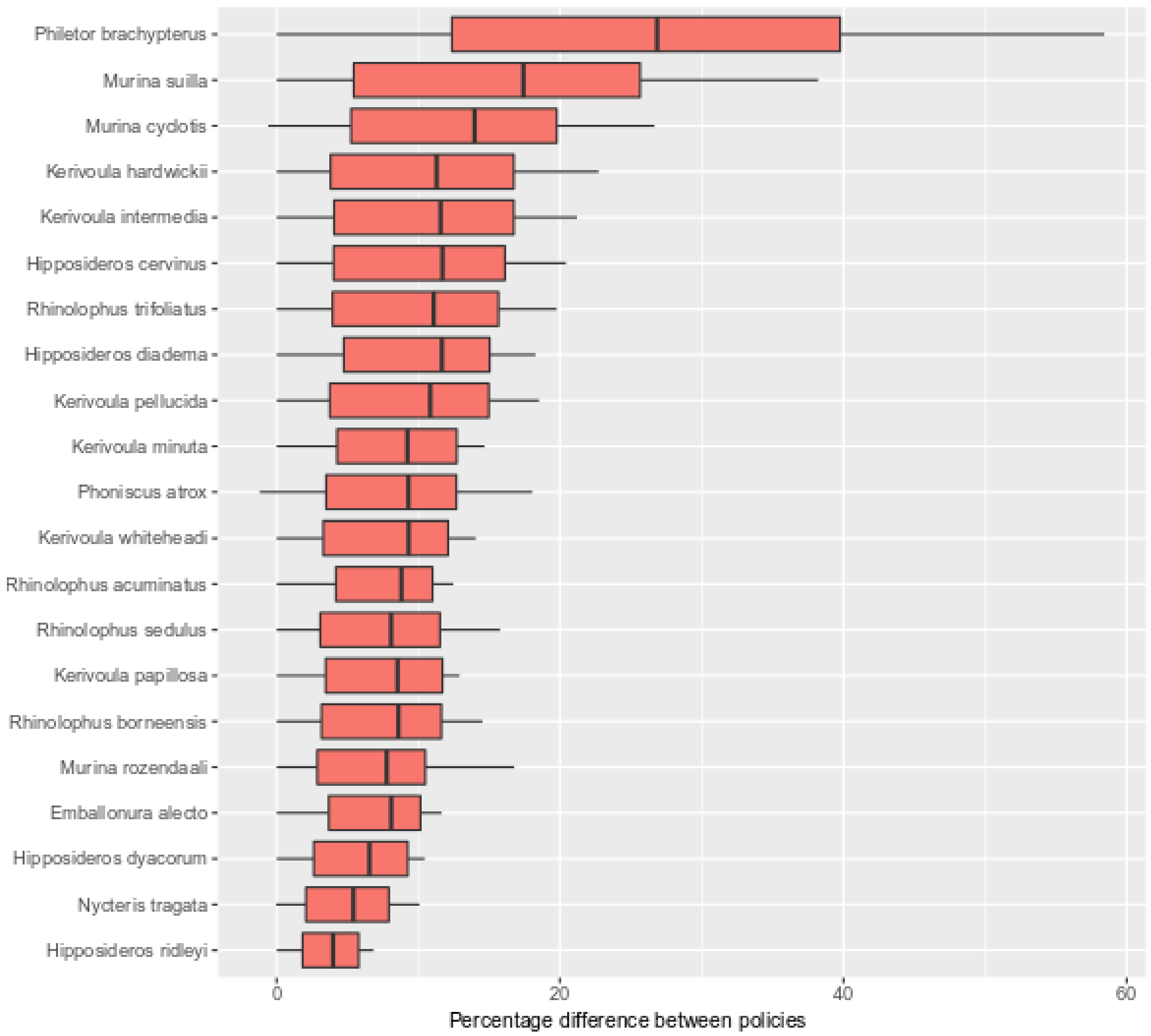
Supplementary Fig. 10$_{ii}$. Relative difference in species occurrence between approaches for all birds

Boxplots (bold horizonal line = median; box = 25th and 75 percentiles; whiskers = largest and smallest values within 1.5 times the interquartile range) of the net difference between the ‘uniform’ and ‘variable’ approaches in terms of the relative percentage occurrence in set-aside, across all percentages of the landscape cultivated under 220 landscape set-aside configurations, for each species of bird.



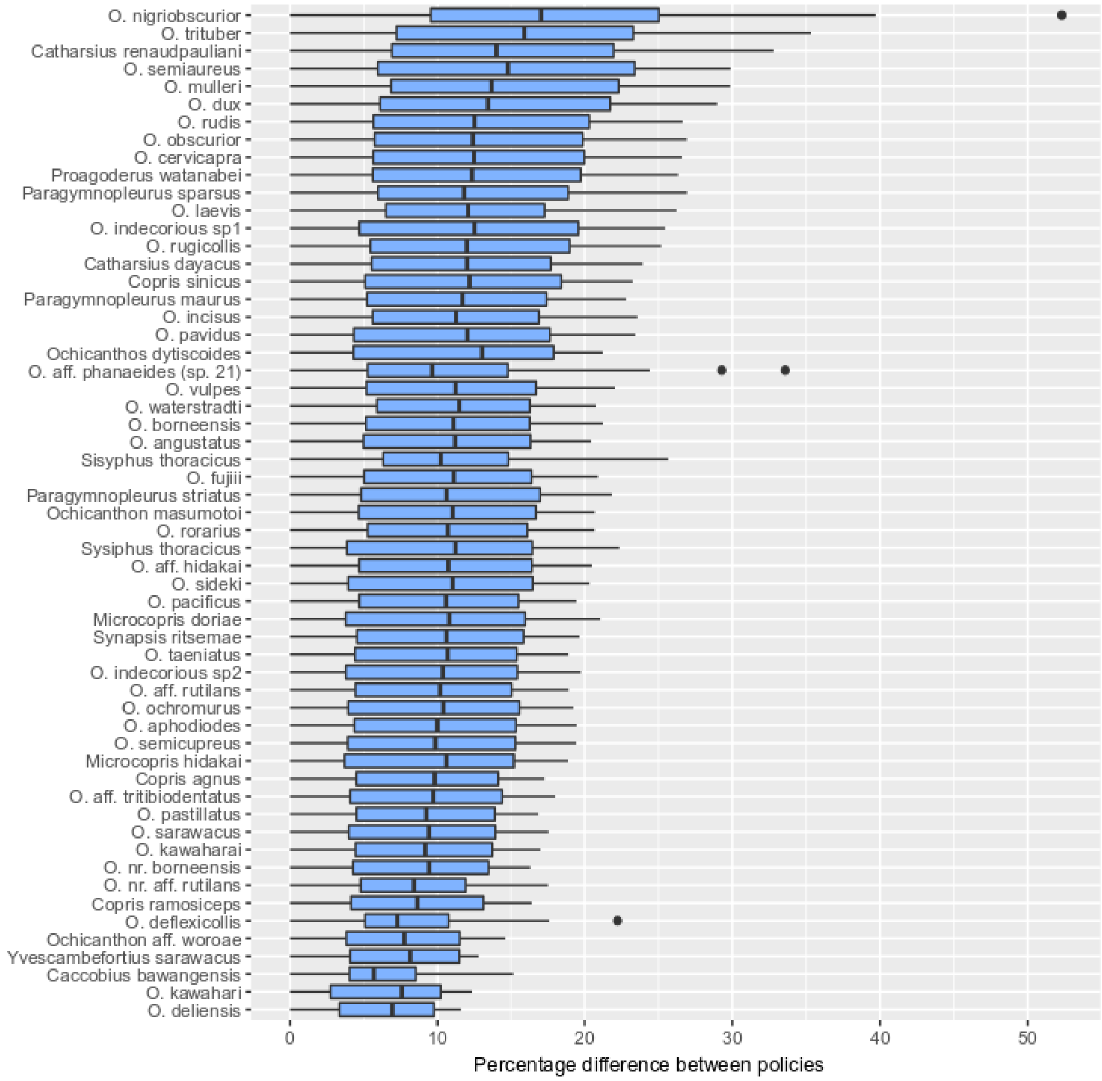
Supplementary Fig. 11. Relative difference in species occurrence between approaches for all non-volant mammals

Boxplots (bold horizonal line = median; box = 25th and 75 percentiles; whiskers = largest and smallest values within 1.5 times the interquartile range) of the net difference between the ‘uniform’ and ‘variable’ approaches in terms of the relative percentage occurrence in set-aside, across all percentages of the landscape cultivated under 220 landscape set-aside configurations, for each species of non-volant mammal.



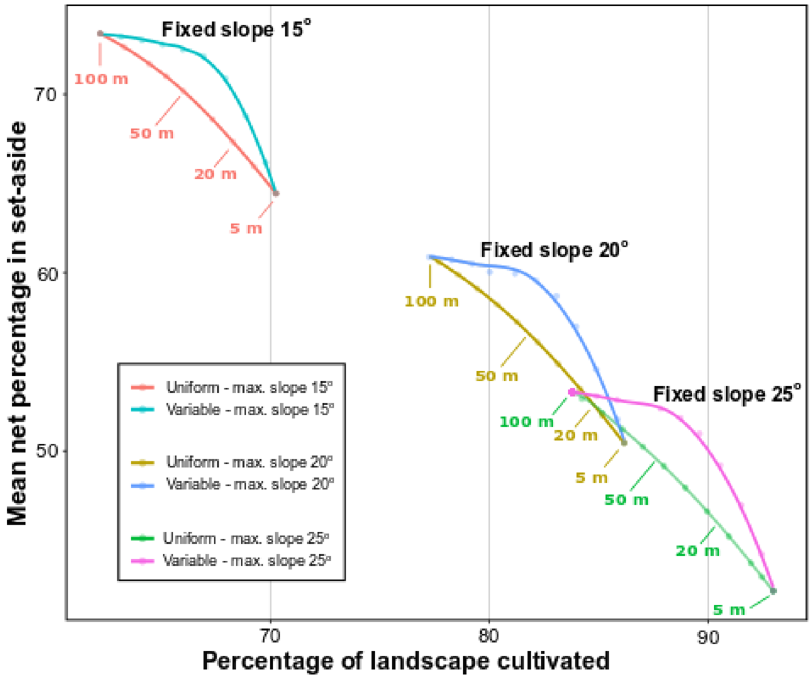
Supplementary Fig. 12. Relative difference in species occurrence between approaches for all bats

Boxplots (bold horizonal line = median; box = 25th and 75 percentiles; whiskers = largest and smallest values within 1.5 times the interquartile range) of the net difference between the 'uniform' and 'variable' approaches in terms of the relative percentage occurrence in set-aside, across all percentages of the landscape cultivated under 220 landscape set-aside configurations, for each species of bat.



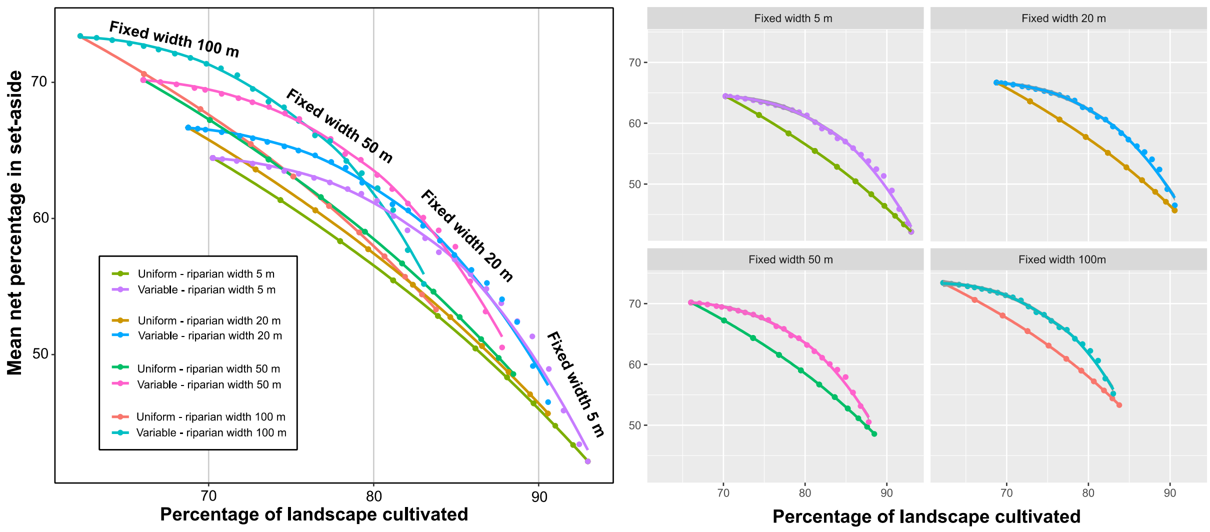
Supplementary Fig. 13. Relative difference in species occurrence between approaches for all dung beetles

Boxplots (bold horizonal line = median; box = 25th and 75 percentiles; whiskers = largest and smallest values within 1.5 times the interquartile range) of the net difference between the 'uniform' and 'variable' approaches in terms of the relative percentage occurrence in set-aside, across all percentages of the landscape cultivated under 220 landscape set-aside configurations, for each species of dung beetle. O = *Onthophagus*



Supplementary Fig. 14. Ecological outcomes under 'variable' and 'uniform' set-aside approaches when maximum slope for cultivation is fixed

Percentage of net ecological outcomes (species occurrence, above-ground carbon storage and dung nutrient cycling) against the percentage of the landscape cultivated under and 'uniform' approach when maximum slope for cultivation is fixed at 15, 20 and 25°. Under the 'uniform' approach, all plantations in the landscape apply the same riparian reserve width, whereas under the 'variable' approach riparian reserve width can vary among plantations. Riparian reserve widths are labelled on the 'uniform' approach, but vary their location on the curve under the 'variable' approach. All curves use local polynomial regression for locally estimated scatterplot smoothing (LOESS).



Supplementary Fig. 15. Ecological outcomes under 'variable' and 'uniform' set-aside approaches when riparian reserve width is fixed

Percentage of net ecological outcomes (species occurrence, above-ground carbon storage and dung nutrient cycling) against the percentage of the landscape cultivated under and 'uniform' approach when riparian reserve width is fixed is 5, 20, 50 and 100 m. Under the 'uniform' approach, all plantations in the landscape apply the same maximum slope for cultivation, whereas under the 'variable' approach maximum slope for cultivation can vary among plantations. All curves use local polynomial regression for locally estimated scatterplot smoothing (LOESS).

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