WePlan
FORESTS

WEPLAN - FORESTS:
A DECISION SUPPORT PLATFORM FOR SPATIAL PLANNING OF FOREST ECOSYSTEM RESTORATION

REPORT ON THE TROPICS

IIS INTERNATIONAL INSTITUTE FOR SUSTAINABILITY AUSTRALIA

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Convention on Biological Diversity

WePlan

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REPORT ON THE TROPICS: CENTRAL AFRICAN REPUBLIC

Contents

WePlan – Forests

This project is developed by the International Institute for Sustainability Australia and International Institute for Sustainability Rio, in partnership with the Convention on Biological Diversity (CBD) Secretariat as part of the implementation of the Forest Ecosystem Restoration Initiative with the financial assistance of the Korea Forest Service of the Government of the Republic of Korea and the European Union.

The aim of this project is to offer to all developing countries Party to the CBD with tropical forest in their territories a decision support platform for restoration planning and implementation in forest ecosystems. Additionally, it aims to support countries in the formulation of more ambitious, realistic, and specific forest ecosystem restoration plans and targets within their global commitments.

WePlan – Forests is a decision support platform for spatial optimisation planning of forest ecosystem restoration that can significantly enhance the outcomes of policies, programs and projects for biodiversity conservation, sustainable development, climate change mitigation and poverty alleviation.

The platform consists of a user-friendly web-based interface that automates the technical and computing requirements of complex spatial analyses and allows users without GIS and spatial modelling know-how to explore a broad range of results and scenarios. The details of all underlying processes and data would be available so that procedures are transparent.

Platform development

The platform is built using best available spatial data and contemporary approaches to mathematical optimisation of systematic spatial planning problems to develop evidence-based decision support for forest ecosystem restoration. As new data becomes available the platform will be updated to reflect better information, other objectives, higher resolution datasets, and broader coverage.

Version 1 was a demonstration version of the analysis that reflected biodiversity conservation and climate change mitigation benefits, while accounting for opportunity and establishment costs. Improvements in the quantification of these benefits and

costs, and other improvements to the formulation of the decision support problem, that were incorporated into Version 2 are summarised in Table 1.

Version	v001 (Dec 2020)	v002 (Apr 2021)
Biodiversity conservation (reduction in mean extinction risk)	SPARC dataset (c.45,000 species representing best performing models only), equal weighting among species	SPARC dataset (c.103,000 species representing all models weighted by performance), balanced weights among plants and animals
Climate change mitigation (carbon sequestration)	E. Broadbent (U Florida) Nov 2020 estimates	E. Broadbent (U Florida) Nov 2020 estimates
Opportunity cost	IIS 2020 estimates	Vincent & Yi 2021 estimates
Establishment cost	IIS 2020 estimates, does not account for potential for natural regeneration	Vincent, Kaczan, et al. 2021 estimates
Accounts for potential for natural regeneration	No	Yes
Resolution, projection and mapping	1km; Mollweide; binary maps	1km; Mollweide; maps of ranked priorities

Table 1: Comparison between the components of the first and second editions of the WePlan – Forests restoration planning analyses.

Disclaimer

The designations employed and the presentation of the material in this document do not imply the expression of any opinion whatsoever on the legal status of any country, territory, city or area or of its authorities, or concerning the delimitation of its frontiers or boundaries. Every effort is made to ensure these data are free of errors but there is no warrant that these data, or the maps and graphs resulting from this analysis, are accurate or fit for any particular purpose.

Acknowledgments

Context

Forests are home to 80% of the world's biodiversity and stock high amounts of carbon relative to other ecosystems. However, substantial areas of forest have been cleared and, of the remaining forests, as much as 82% are now degraded to some extent as a result of human actions such as industrial logging, urbanization, agriculture and infrastructure (Watson *et al.*, 2018). Tropical forest restoration has the potential to counteract some of these negative impacts and deliver multiple benefits, such as climate change mitigation, biodiversity conservation, and provide sustainable livelihoods for people (Chazdon & Guariguata, 2016; Crouzeilles *et al.*, 2020).

The Strategic Plan for Biodiversity 2011-2020 adopted at the CBD COP 10 in 2011 established a set of twenty Aichi Biodiversity Targets. Target 5 stated that by 2020 degradation and fragmentation of habitat should be significantly reduced, and Target 15 referred to the need to restore at least 15% of degraded ecosystems. Country Parties to the CBD are expected to develop National Biodiversity Strategies and Action Plans (NBSAPs) that contribute to achieving the Aichi Biodiversity Targets.

An assessment conducted in 2016 concluded that many of the national targets adopted in response to the Aichi Biodiversity Target 15 lacked specificity (COP-13/CBD, 2016). The post-2020 Global Biodiversity Framework updated Zero Draft states as the 2050 vision: "By 2050, biodiversity is valued, conserved, restored and wisely used, maintaining ecosystem services, sustaining a healthy planet and delivering benefits essential for all people" (CBD 2020). The need to further develop the capacity of developing countries to undertake quantitative, spatially-explicit assessments of restoration opportunities was highlighted in the Pan-African Action Agenda on Ecosystem Restoration for Increased Resilience, adopted at the recent Africa Biodiversity Summit in the margins of the CBD COP 14 in 2018.

In response to the need thus identified, the "WePlan – Forests: A decision support platform for spatial planning of forest ecosystem restoration" was developed. The WePlan – Forests platform can help governments and other stakeholders to plan and implement forest restoration to cost-effectively achieve biodiversity conservation and climate mitigation benefits. WePlan – Forests also enables users to explore the potential of certain areas to sustain natural forest regrowth, a restoration intervention that is often the most cost-effective and provides substantial benefits for biodiversity and climate (Crouzeilles *et al.*, 2017).

7

Guiding questions and overview

WePlan – Forests (Fig. 1) can help to inform restoration planning and implementation within tropical forest ecosystems at the national scale for developing countries Party to the CBD by answering five different key questions:

1. Where are the priority areas for restoration that maximise multiple benefits, while minimising costs?

2. What benefits are likely to be achieved over an area to be restored and what are the costs?

3. How do trade-offs between benefits and costs affect restoration priorities?

4. Where and when should actions be scheduled in space?

5. Where and how intensively restoration actions should be implemented?

The problem formulation achieves a range of potential objectives (benefits and costs) within a given percentage of deforested land to be restored:

1. Maximising benefits for biodiversity conservation

2. Maximising benefits for climate change mitigation

3. Minimising restoration establishment costs (while accounting for the potential for natural forest regrowth)

4. Minimising costs
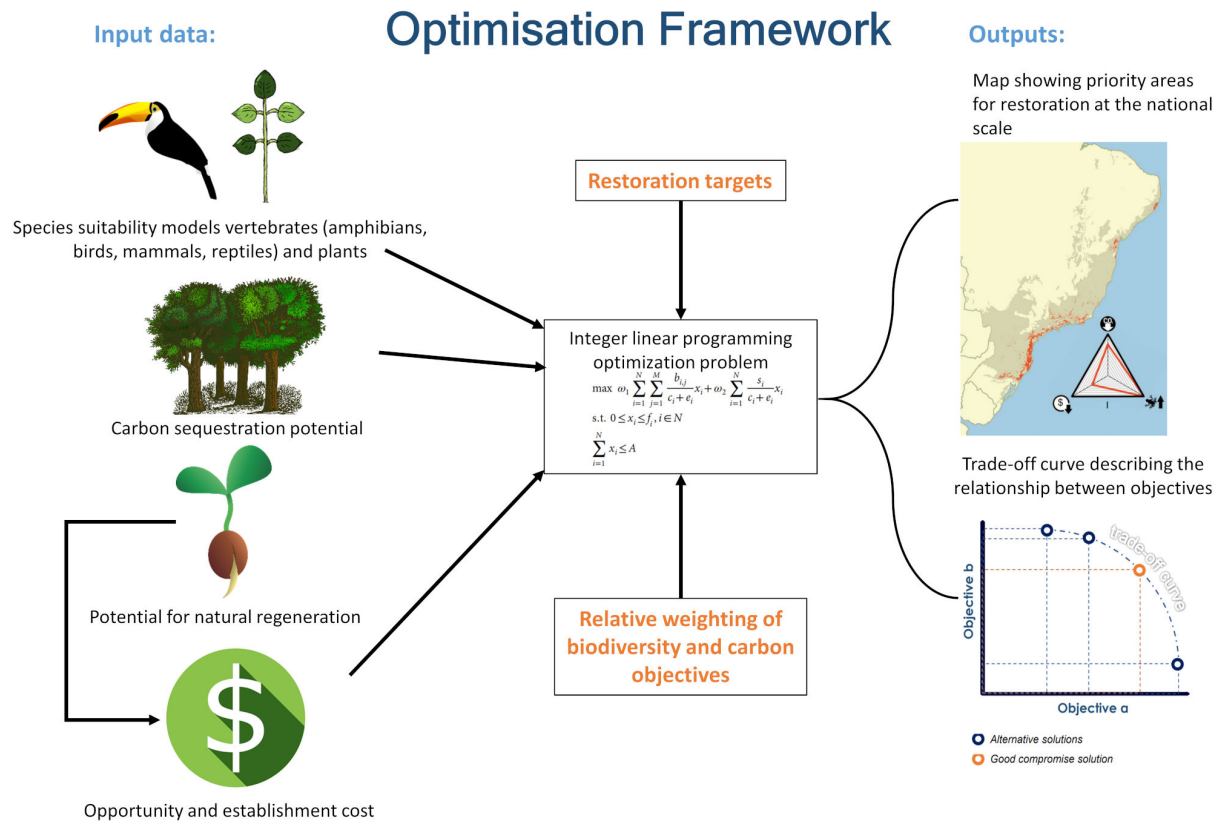
Figure 1: Conceptual overview of the WePlan – Forests spatial optimisation framework for planning forest restoration in forest ecosystems at the national scale for developing countries Party to the CBD.

WePlan – Forests allows for four main outputs:

1. Identification of priority areas for forest restoration

2. Quantification of objectives (benefits and costs)

3. Comparisons of the impacts of a variety of alternative scenarios (including cost-effective solutions)

4. Quantification of trade-offs among objectives

For further information, online training material is available by following this link. This training material was developed during a webinar series in 2020 to promote the uptake of the science in which the WePlan – Forests is based by potential users. During the webinars feedback was solicited from the participants to improve the WePlan – Forests interface and the training itself, and to tailor the platform to the needs of users. It also aimed to produce training material that is available within the WePlan – Forests platform for future users, and to showcase the platform.

Results

Analysis overview and interpretation

WePlan – Forests is a spatially explicit, forest restoration planning tool that evaluates a range of alternative scenarios, reporting the benefits, costs and spatial distribution of restoration priorities for each one. It considers two objectives: (i) climate change mitigation benefit, estimated as the change in carbon sequestration that would arise from forest restoration, and (ii) biodiversity conservation benefit, estimated as the average reduction in local (national) extinction risk among all forest-associated species. The analysis also considers opportunity and implementation costs of forest restoration. Analyses occur at a 1 km^2 resolution on a national basis, for countries containing tropical and subtropical forests within ± 25 degrees latitude.

Four main types of analysis are presented: (i) optimal solutions that maximise cost-effectiveness (benefit / cost); (ii) optimal solutions that maximise benefit, ignoring costs; (iii) optimal reference solutions that minimise total costs, ignoring benefits; and (iv) reference solutions that randomise restoration. The first two analyses also involve evaluation of the trade-off between climate change mitigation and biodiversity conservation benefits. Trade-off curves are described by solving the optimisation problem across a range of relative weights of the two objectives, which provides decision-makers with information on the strength of the trade-off and helps to identify possible scenarios representing good compromises between the objectives. Planning solutions were developed for five area targets, representing 10, 20, 30, 40, and 50% of the area available for forest restoration.

A number of general patterns that can typically be observed in these analyses:

- First, the cost-effectiveness analysis usually achieves somewhat lower returns than the maximum-benefit analysis, but at much lower cost. The cost-effective scenarios therefore provide the greatest return-on-investment and are the primary focus for forest restoration planning support.

- Second, there is usually some level of trade-off between climate change mitigation and biodiversity conservation benefits. Hence, it is usually not possible to achieve maximum benefits for both simultaneously and the trade-off curves WePlan – Forests describes help to identify solutions that are good compromises

between the two objectives.

- Third, as the area target increases the returns on climate change mitigation and biodiversity conservation benefits increase, but often not linearly. This implies that the return-on-investment per unit area changes depending on how much area is restored.

- Fourth, the minimum-cost solution identifies the cheapest solution for restoring forest for a given area target but typically performs poorly with respect to climate change mitigation and biodiversity conservation benefits.

- Fifth, the random solution often performs poorly with respect to both benefits and costs, usually providing the lowest returns-on-investment among all of the analyses for a given area target. The random scenario is likely to be a fair approximation of returns for any planning process that is based on other concerns and that does not consider these objectives explicitly.

The solutions generated by the WePlan – Forests analyses do not prescribe where restoration action should occur, but rather support and inform decisions about restoration planning. These analyses account for several key dimensions of restoration planning problems but they do not account for all relevant factors. Local-scale factors such as governance, land ownership and tenure, livelihoods, and local community objectives are also often important to consider in the decision-making process.

WePlan – Forests provides a quantitative, spatially-explicit, transparent and evidence-based framework for evaluating a range of restoration targets and scenarios to inform national-scale planning. The Weplan – Forests team can work with nations to develop bespoke analyses that reflect national policy and priorities.

This report provides an overview of the key results of the national WePlan – Forests analyses. The full range of scenarios and their associated climate change mitigation and biodiversity conservation benefits can be explored on the interactive WePlan – Forests solution explorer.

This section first presents a tabular and graphical summary of all scenarios evaluated across all area restoration targets. It then provides graphical and map-based overviews of the results for each target level separately.

Country	Central African Republic
Analysis version	v002
Number of scenarios evaluated	80
Area of country	62.3 M ha
Area within WePlan – Forests domain	62.3 M ha
Area available for forest restoration	1.6 M ha
Restoration targets considered (% of available)	10, 20, 30, 40, 50%
Number of species considered	4179
Number of plant species	3626
Number of bird species	350
Number of mammal species	160
Number of amphibian species	36
Number of reptile species	7

Table 2: Summary of country-level properties pertaining to the WePlan – Forests restoration planning analysis.

Scenarios	Target (%)	Carbon seq. (Gt)	Mean red. ext. risk (%)	Cost (millions US$)
Cost-effectiveness scenarios				
Biodiversity conservation focus	10%	3.2	1.4	285.6
Climate mitigation focus	10%	4.5	0.2	115
Balanced solution	10%	3.9	1	165
Biodiversity conservation focus	20%	6.4	1.9	615
Climate mitigation focus	20%	8.3	0.5	308.5
Balanced solution	20%	7.8	1.5	411.2
Biodiversity conservation focus	30%	9.3	2.1	900.5
Climate mitigation focus	30%	12.8	0.7	632.7
Balanced solution	30%	11.9	1.7	654.6
Biodiversity conservation focus	40%	12.3	2.3	1228.8
Climate mitigation focus	40%	17.2	1.1	1006.7
Balanced solution	40%	15.9	1.9	989.4
Biodiversity conservation focus	50%	16	2.5	1599.6
Climate mitigation focus	50%	21.4	1.4	1401.1
Balanced solution	50%	20	2.1	1361.1
Max-benefit scenarios				
Biodiversity conservation focus	10%	3.6	1.5	390.1
Climate mitigation focus	10%	5.2	0.4	437.2
Balanced solution	10%	4.8	1.2	439
Biodiversity conservation focus	20%	6.7	2	748.6
Climate mitigation focus	20%	10.1	0.7	849.5
Balanced solution	20%	9.2	1.7	831.2
Biodiversity conservation focus	30%	9.7	2.2	1122
Climate mitigation focus	30%	14.9	0.8	1229.8
Balanced solution	30%	13.1	2.1	1200.8
Biodiversity conservation focus	40%	12.9	2.4	1503.3
Climate mitigation focus	40%	19.5	1	1578.8
Balanced solution	40%	17.7	2.2	1583.5
Biodiversity conservation focus	50%	16	2.5	1842.8
Climate mitigation focus	50%	23.8	1.2	1928.9
Balanced solution	50%	22.2	2.2	1946.6

Table 3: Summary of benefits to climate change mitigation (carbon sequestration) and biodiversity conservation (mean reduction in extinction risk among forest-associated species) and costs arising from a subset of WePan – Forests restoration planning scenarios at each of the area restoration targets evaluated. The climate mitigation and biodiversity conservation focused scenarios maximise only single objectives, and any benefit to the other objective is incidental. The balanced solution refers to a solution on the trade-off curve that provides good returns on both objectives.
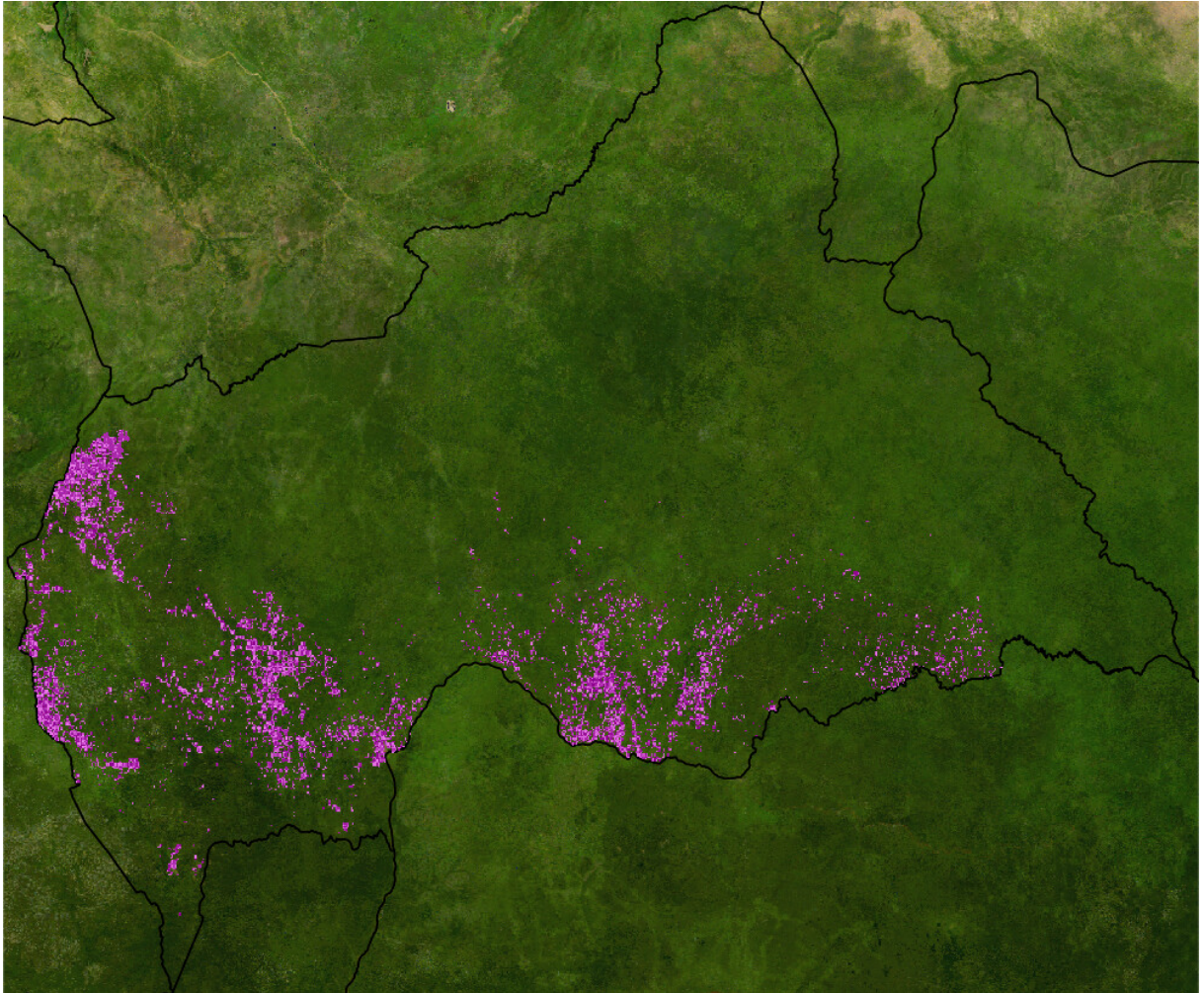
Area deemed available for forest restoration

Figure 2: **Area deemed available for forest restoration.** Areas in purple indicate the 1 km^2 planning units that were assessed to have potential for forest restoration given (see Methods for details). The shading of cells from light to dark purple is proportional to the area within each planning unit available for forest restoration.

Combined results for restoration of 10-50% of deforested lands

Figure 3: **Restoration of 10, 20, 30, 40 & 50% of deforested lands.** Performance of a range of forest restoration prioritisation scenarios (points) with respect to climate change mitigation benefit (x axis), measured as above-ground carbon sequestration, and biodiversity conservation benefit (y axis), measured as the mean percent reduction in extinction risk among all species. Cost-effective scenarios (solid line) maximise return-on-investment (benefit/cost) and are likely to represent the most feasible restoration planning options. For reference, maximum-benefit scenarios (dashed line) that maximise returns irrespective of cost are also presented. The point circled in black represents a potential good compromise solution. Two further reference scenarios are also presented in which restoration is allocated randomly (triangle) or to minimise costs irrespective of benefit (square). For all scenarios the colour represents the total cost of the solution (see legend). The following figures show results from each of the restoration area targets separately. An interactive version of this figure is available online.

Results for restoration of 10% of deforested lands
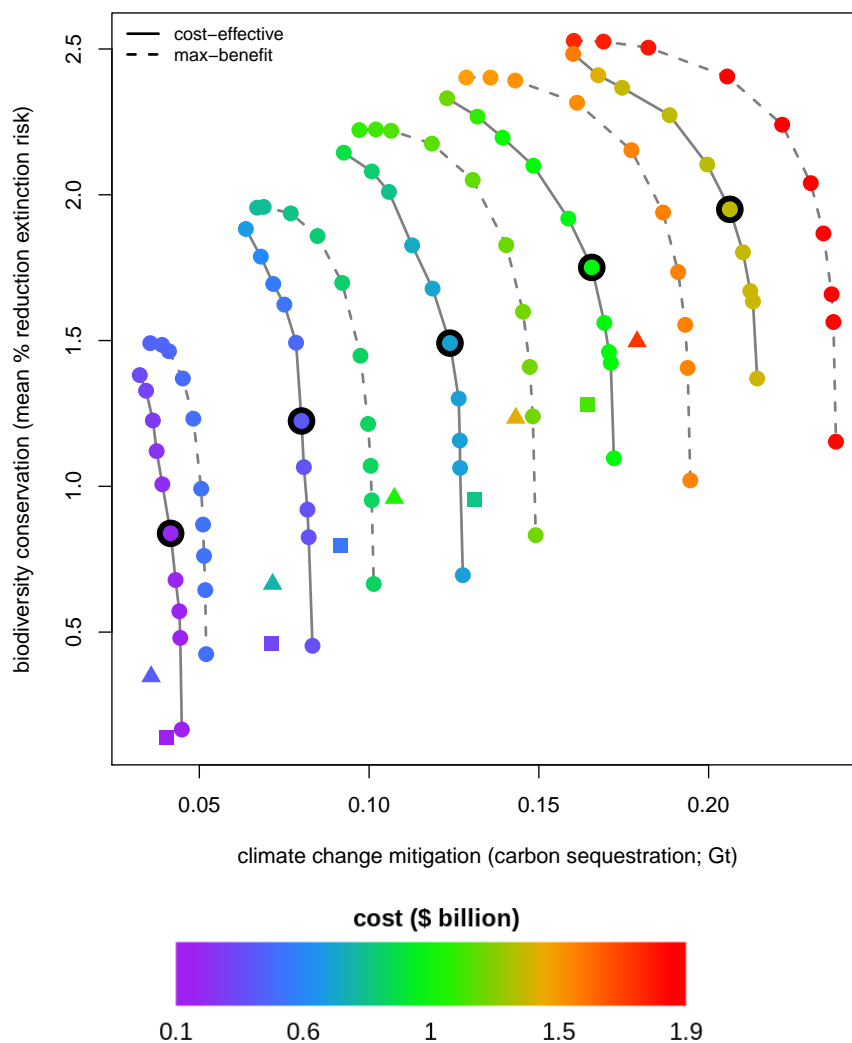

Figure 4: **Restoration of 10% of deforested lands.** Performance of a range of forest restoration prioritisation scenarios (points) with respect to climate change mitigation benefit (x axis), measured as above-ground carbon sequestration, and biodiversity conservation benefit (y axis), measured as the mean percent reduction in extinction risk among all species. Cost-effective scenarios (solid line) maximise return-on-investment (benefit/cost) and are likely to represent the most feasible restoration planning options. For reference, maximum-benefit scenarios (dashed line) that maximise returns irrespective of cost are also presented. The point circled in black represents a potential good compromise solution. Two further reference scenarios are also presented in which restoration is allocated randomly (triangle) or to minimise costs irrespective of benefit (square). For all scenarios the colour represents the total cost of the solution (USD; see legend). Maps of the locations associated with several of these solutions are included in the following two figures.

Figure 5: **Restoration of 10% of deforested lands.** Priority locations for restoration (cyan) for a solution that represents a balance between climate change mitigation and biodiversity conservation objectives while maximising cost-effectiveness (benefit/cost).

(a) cost-effective: climate change mitigation   (b) cost-effective: biodiversity conservation

(c) max-benefit: climate change mitigation   (d) max-benefit: biodiversity conservation

Figure 6: **Restoration of 10% of deforested lands.** Priority locations for restoration (cyan), under four scenarios: maximising cost-effectiveness for climate change mitigation only (a) and biodiversity conservation only (b), versus maximising benefit irrespective of cost for climate change mitigation only (c) and biodiversity conservation only (d). These figures illustrate how priority location change across the four scenarios.
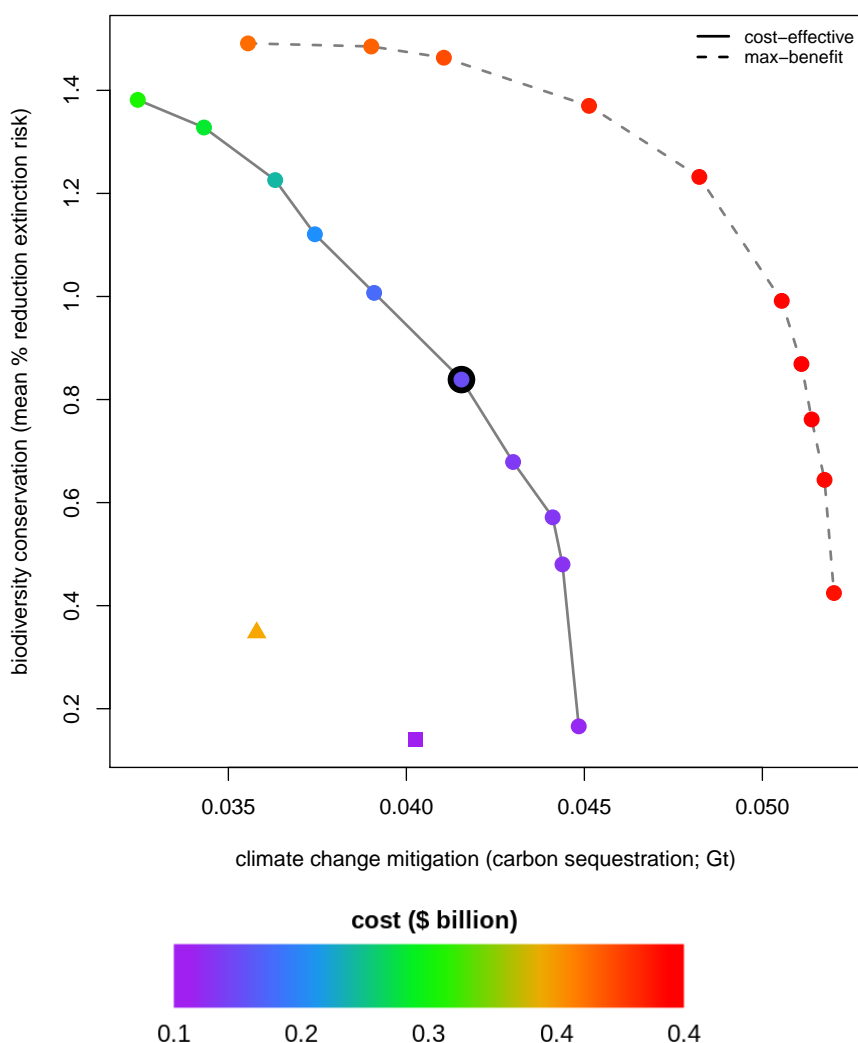
Results for restoration of 20% of deforested lands

Figure 7: **Restoration of 20% of deforested lands.** Performance of a range of forest restoration prioritisation scenarios (points) with respect to climate change mitigation benefit (x axis), measured as above-ground carbon sequestration, and biodiversity conservation benefit (y axis), measured as the mean percent reduction in extinction risk among all species. Cost-effective scenarios (solid line) maximise return-on-investment (benefit/cost) and are likely to represent the most feasible restoration planning options. For reference, maximum-benefit scenarios (dashed line) that maximise returns irrespective of cost are also presented. The point circled in black represents a potential good compromise solution. Two further reference scenarios are also presented in which restoration is allocated randomly (triangle) or to minimise costs irrespective of benefit (square). For all scenarios the colour represents the total cost of the solution (USD; see legend). Maps of the locations associated with several of these solutions are included in the following two figures.
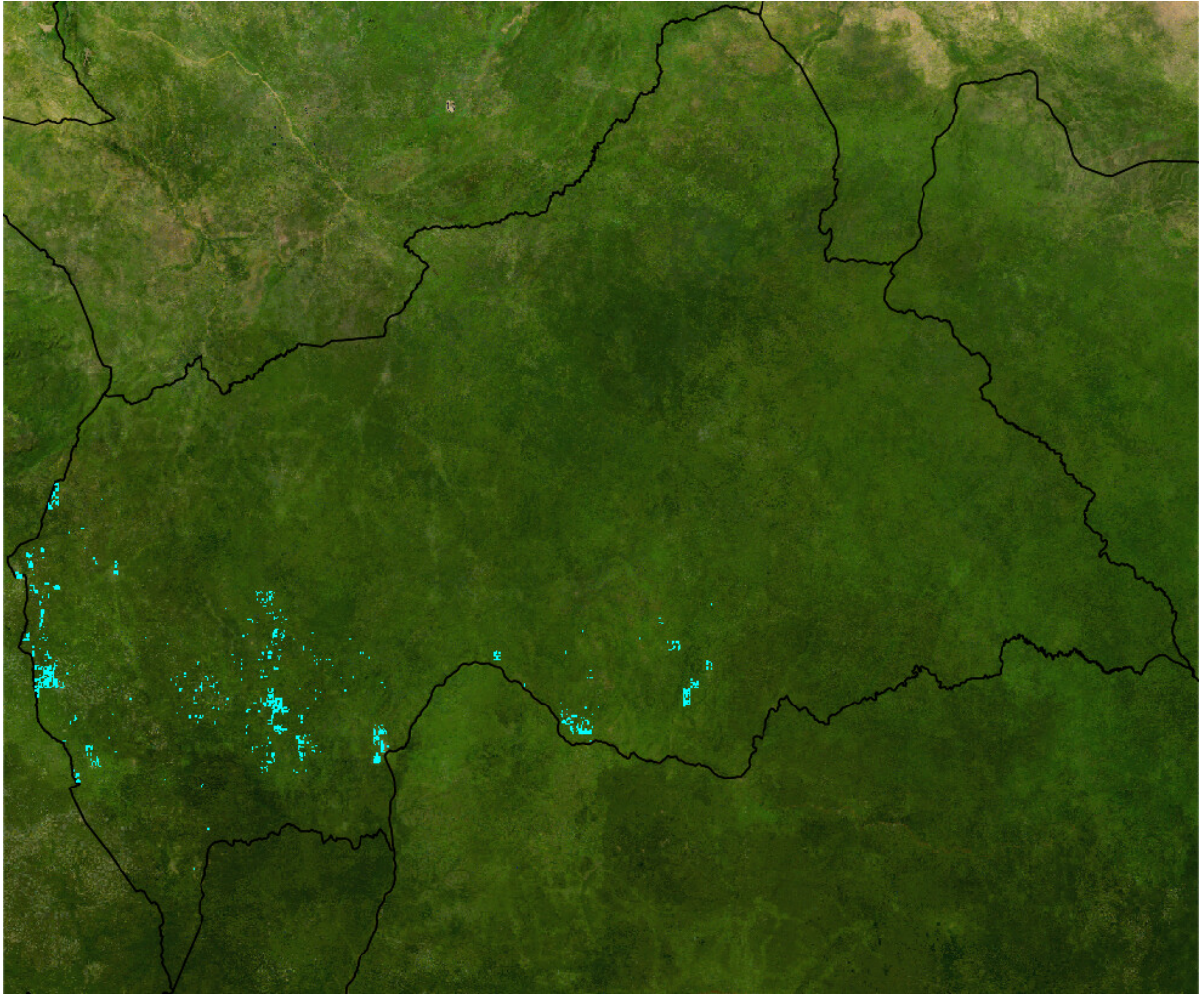
Figure 8: **Restoration of 20% of deforested lands.** Priority locations for restoration (cyan) for a solution that represents a balance between climate change mitigation and biodiversity conservation objectives while maximising cost-effectiveness (benefit/cost).
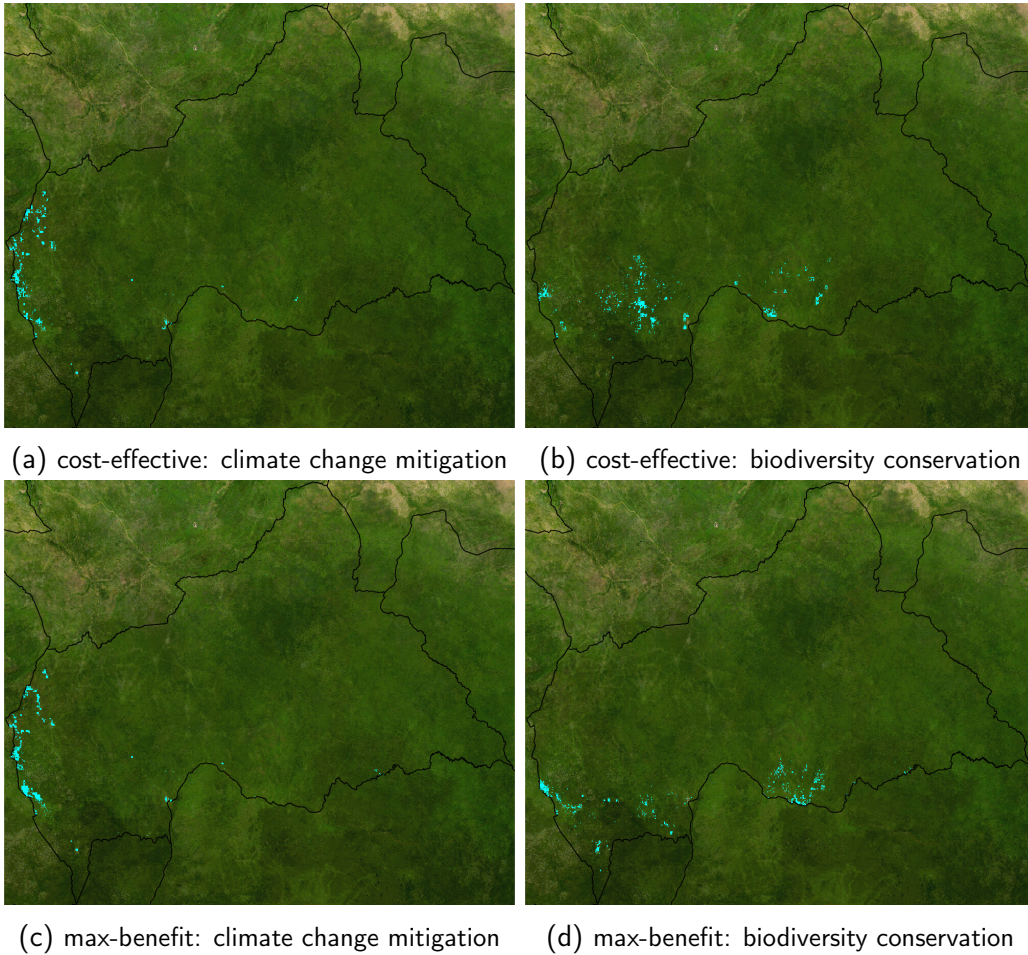
(a) cost-effective: climate change mitigation (b) cost-effective: biodiversity conservation

(c) max-benefit: climate change mitigation (d) max-benefit: biodiversity conservation

Figure 9: **Restoration of 20% of deforested lands.** Priority locations for restoration (cyan), under four scenarios: maximising cost-effectiveness for climate change mitigation only (a) and biodiversity conservation only (b), versus maximising benefit irrespective of cost for climate change mitigation only (c) and biodiversity conservation only (d). These figures illustrate how priority location change across the four scenarios.

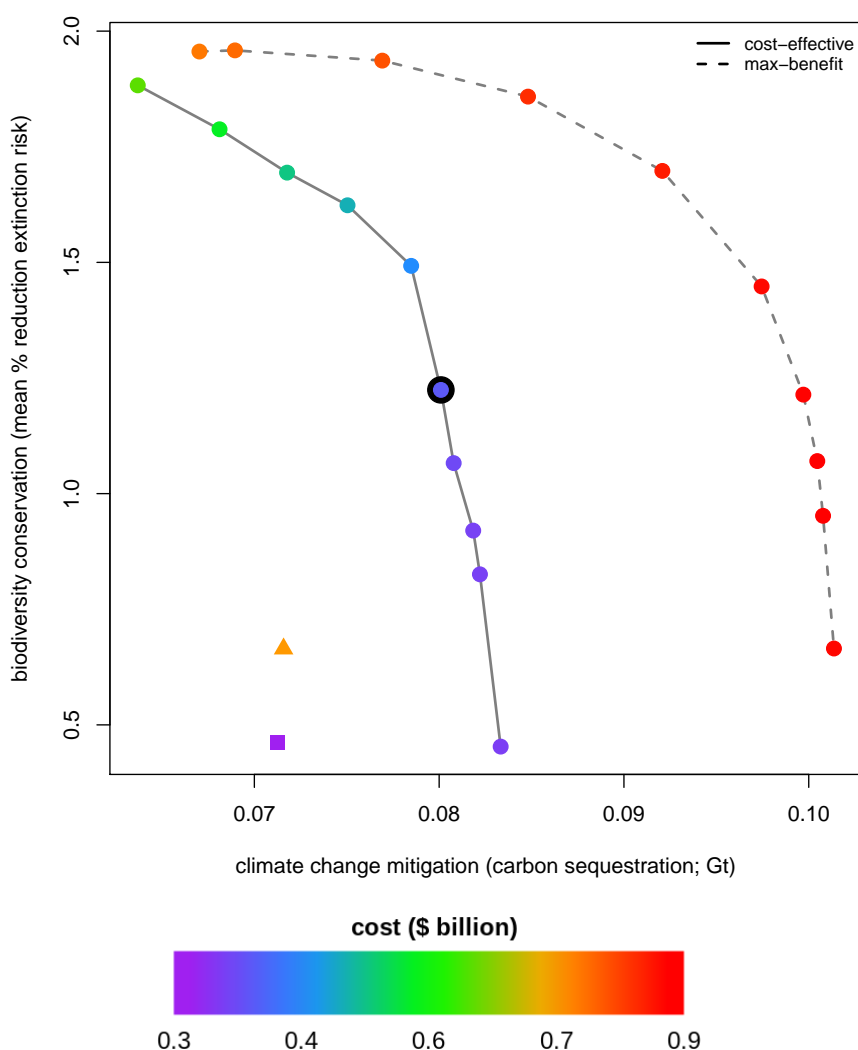## Results for restoration of 30% of deforested lands

Figure 10: **Restoration of 30% of deforested lands.** Performance of a range of forest restoration prioritisation scenarios (points) with respect to climate change mitigation benefit (x axis), measured as above-ground carbon sequestration, and biodiversity conservation benefit (y axis), measured as the mean percent reduction in extinction risk among all species. Cost-effective scenarios (solid line) maximise return-on-investment (benefit/cost) and are likely to represent the most feasible restoration planning options. For reference, maximum-benefit scenarios (dashed line) that maximise returns irrespective of cost are also presented. The point circled in black represents a potential good compromise solution. Two further reference scenarios are also presented in which restoration is allocated randomly (triangle) or to minimise costs irrespective of benefit (square). For all scenarios the colour represents the total cost of the solution (USD; see legend). Maps of the locations associated with several of these solutions are included in the following two figures.
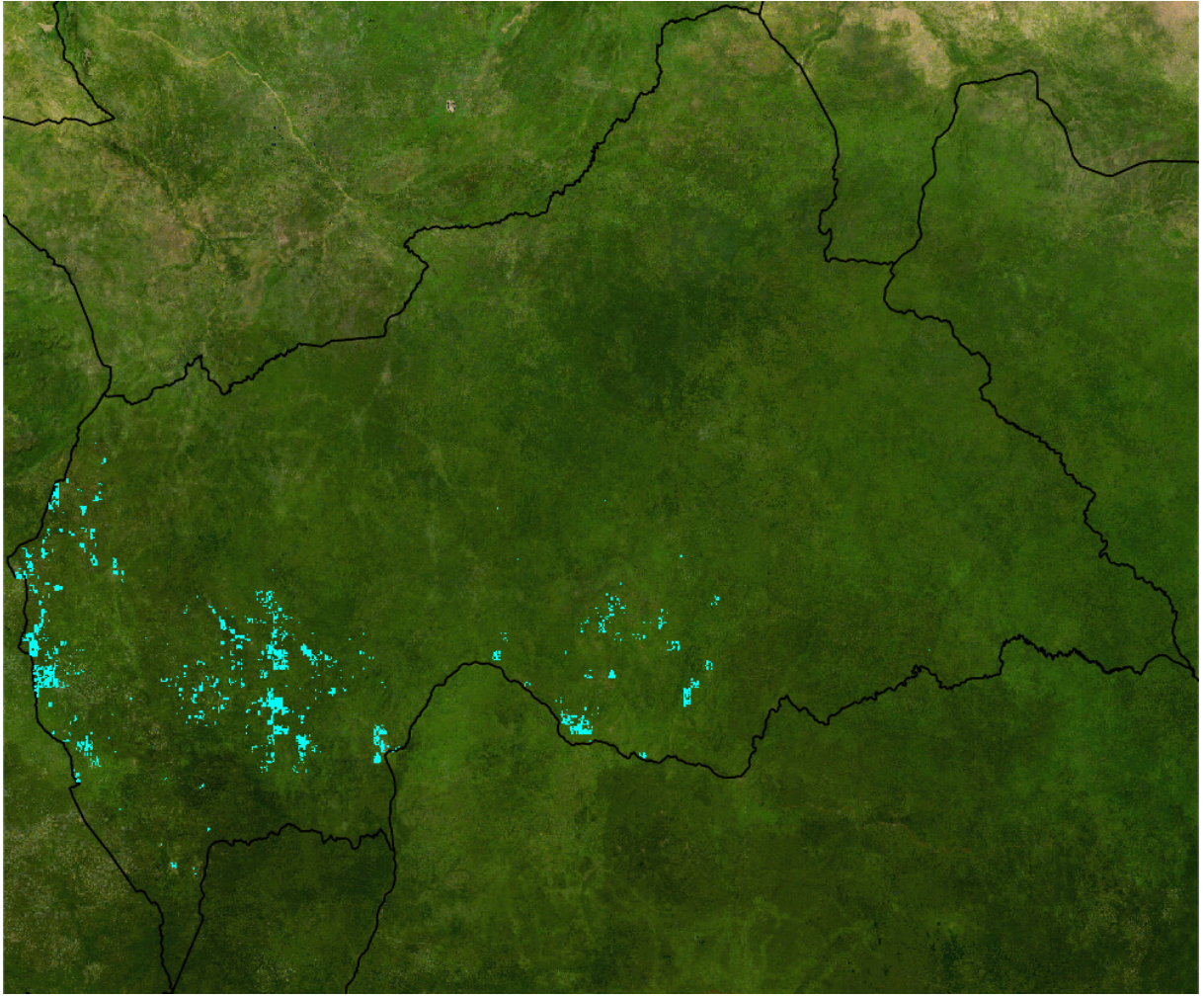
Figure 11: **Restoration of 30% of deforested lands.** Priority locations for restoration (cyan) for a solution that represents a balance between climate change mitigation and biodiversity conservation objectives while maximising cost-effectiveness (benefit/cost).
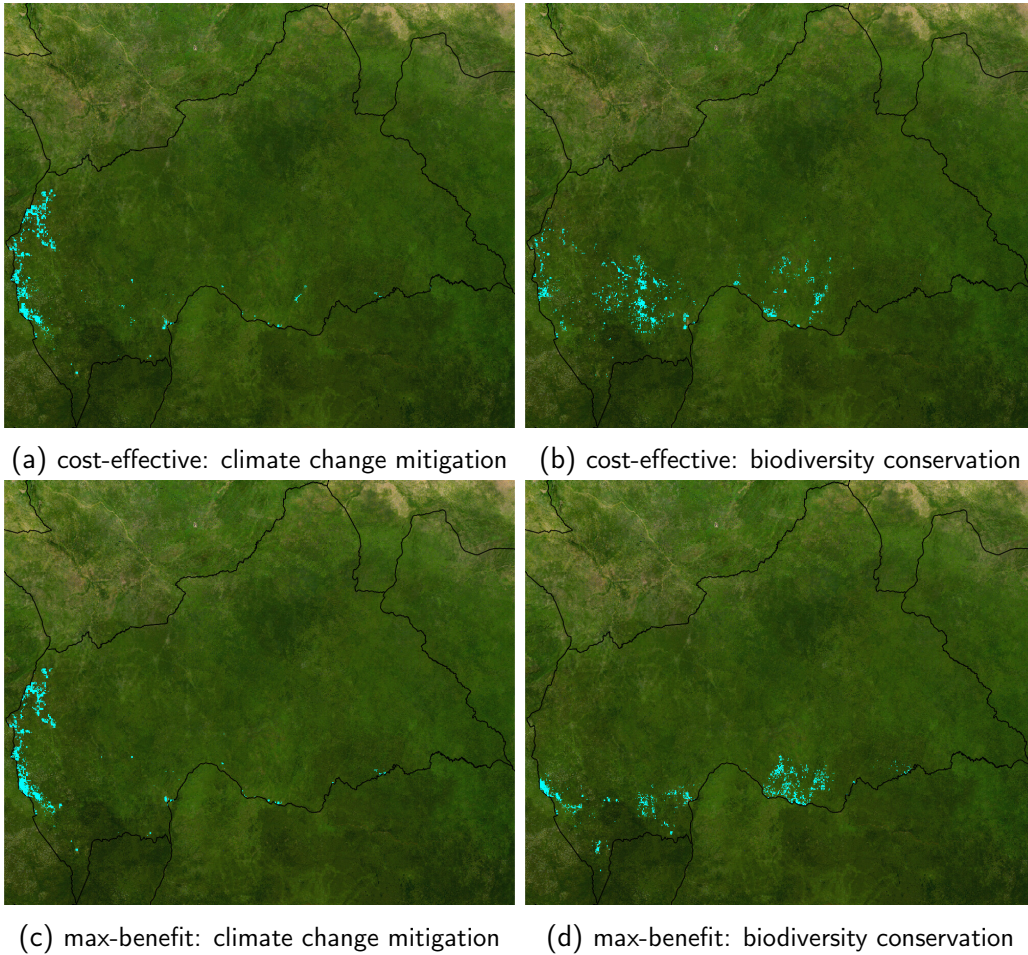
(a) cost-effective: climate change mitigation

(b) cost-effective: biodiversity conservation

(c) max-benefit: climate change mitigation

(d) max-benefit: biodiversity conservation

Figure 12: **Restoration of 30% of deforested lands.** Priority locations for restoration (cyan), under four scenarios: maximising cost-effectiveness for climate change mitigation only (a) and biodiversity conservation only (b), versus maximising benefit irrespective of cost for climate change mitigation only (c) and biodiversity conservation only (d). These figures illustrate how priority location change across the four scenarios.

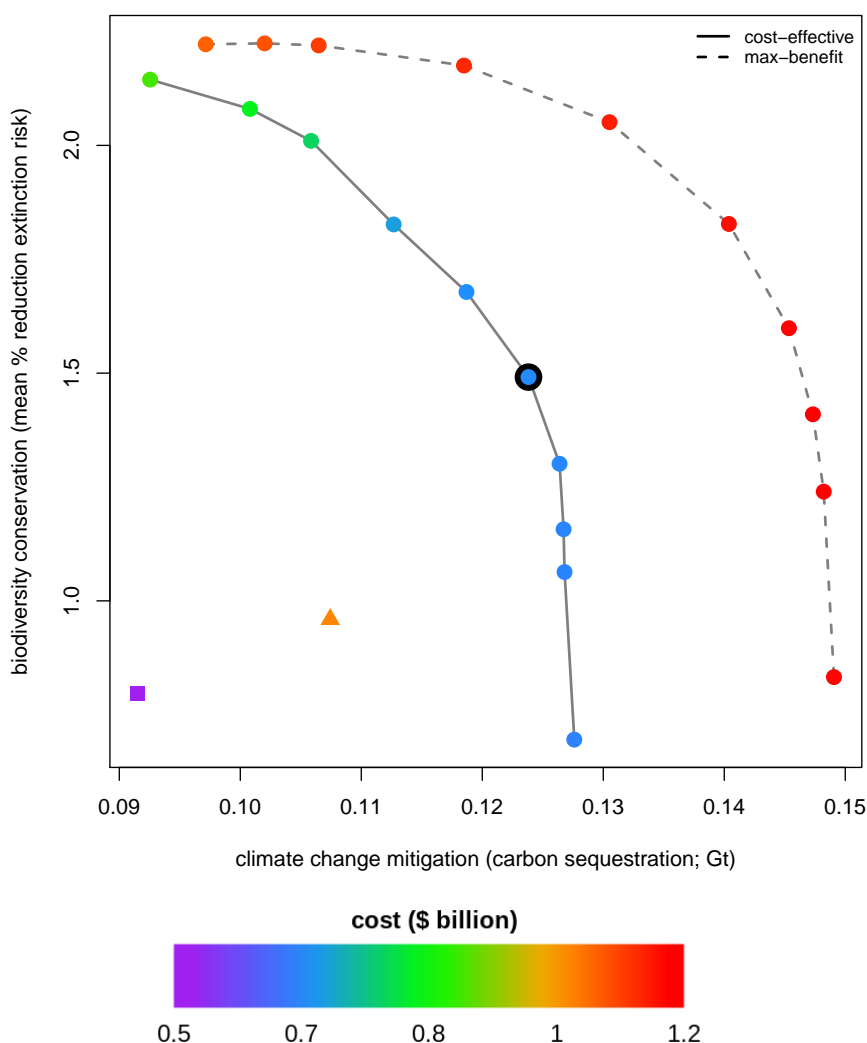# Results for restoration of 40% of deforested lands

Figure 13: **Restoration of 40% of deforested lands.** Performance of a range of forest restoration prioritisation scenarios (points) with respect to climate change mitigation benefit (x axis), measured as above-ground carbon sequestration, and biodiversity conservation benefit (y axis), measured as the mean percent reduction in extinction risk among all species. Cost-effective scenarios (solid line) maximise return-on-investment (benefit/cost) and are likely to represent the most feasible restoration planning options. For reference, maximum-benefit scenarios (dashed line) that maximise returns irrespective of cost are also presented. The point circled in black represents a potential good compromise solution. Two further reference scenarios are also presented in which restoration is allocated randomly (triangle) or to minimise costs irrespective of benefit (square). For all scenarios the colour represents the total cost of the solution (USD; see legend). Maps of the locations associated with several of these solutions are included in the following two figures.
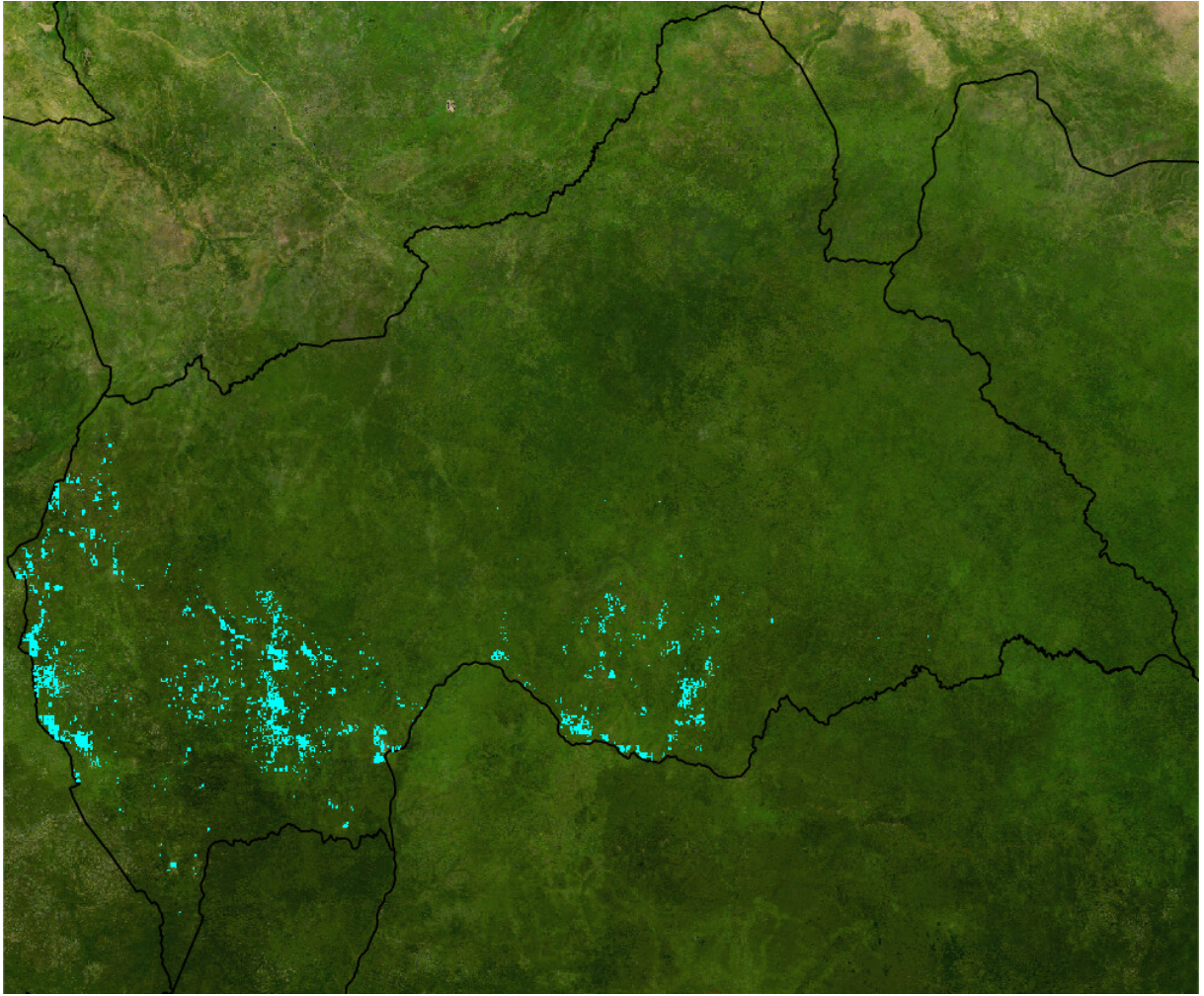
Figure 14: **Restoration of 40% of deforested lands.** Priority locations for restoration (cyan) for a solution that represents a balance between climate change mitigation and biodiversity conservation objectives while maximising cost-effectiveness (benefit/cost).
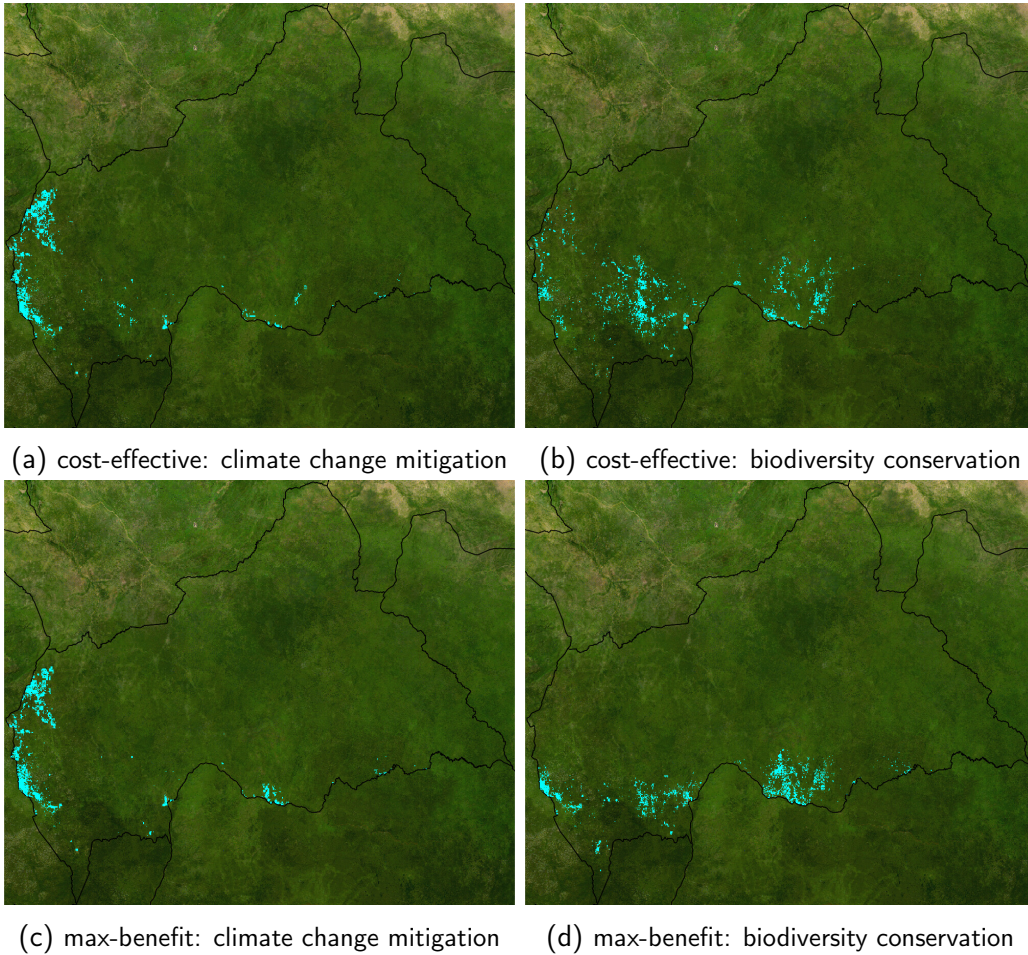
(a) cost-effective: climate change mitigation

(b) cost-effective: biodiversity conservation

(c) max-benefit: climate change mitigation

(d) max-benefit: biodiversity conservation

Figure 15: **Restoration of 40% of deforested lands.** Priority locations for restoration (cyan), under four scenarios: maximising cost-effectiveness for climate change mitigation only (a) and biodiversity conservation only (b), versus maximising benefit irrespective of cost for climate change mitigation only (c) and biodiversity conservation only (d). These figures illustrate how priority location change across the four scenarios.

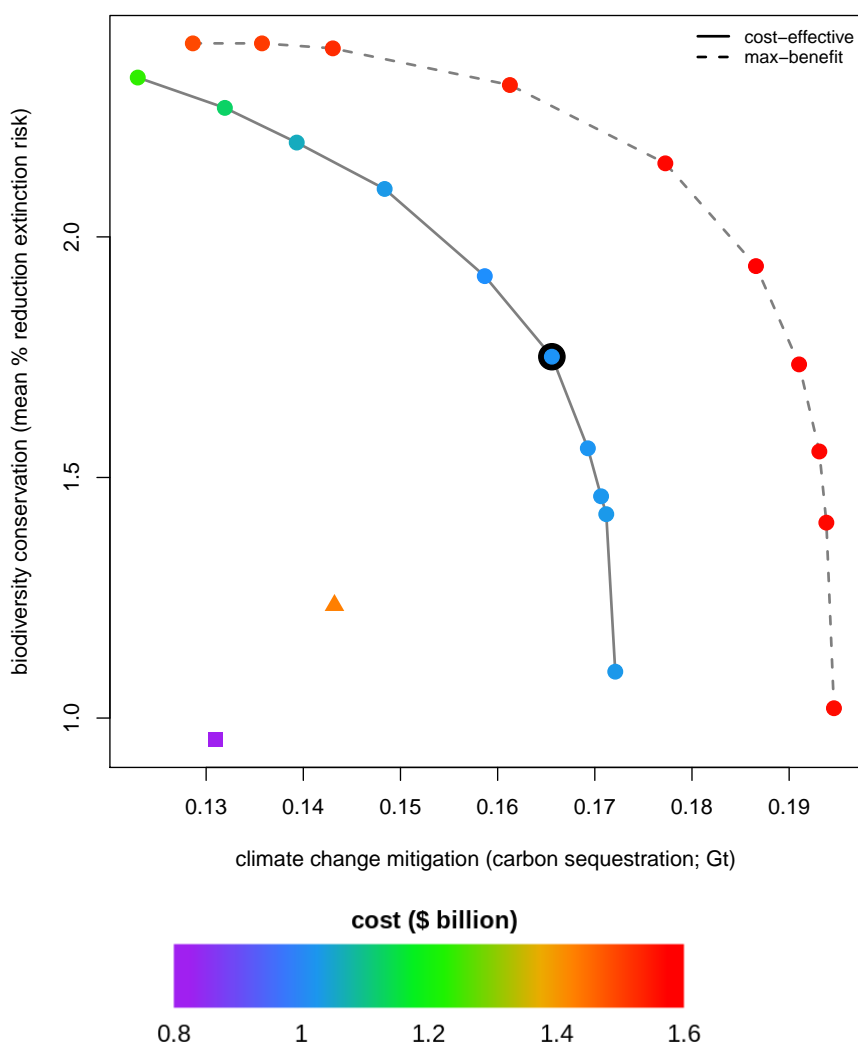# Results for restoration of 50% of deforested lands
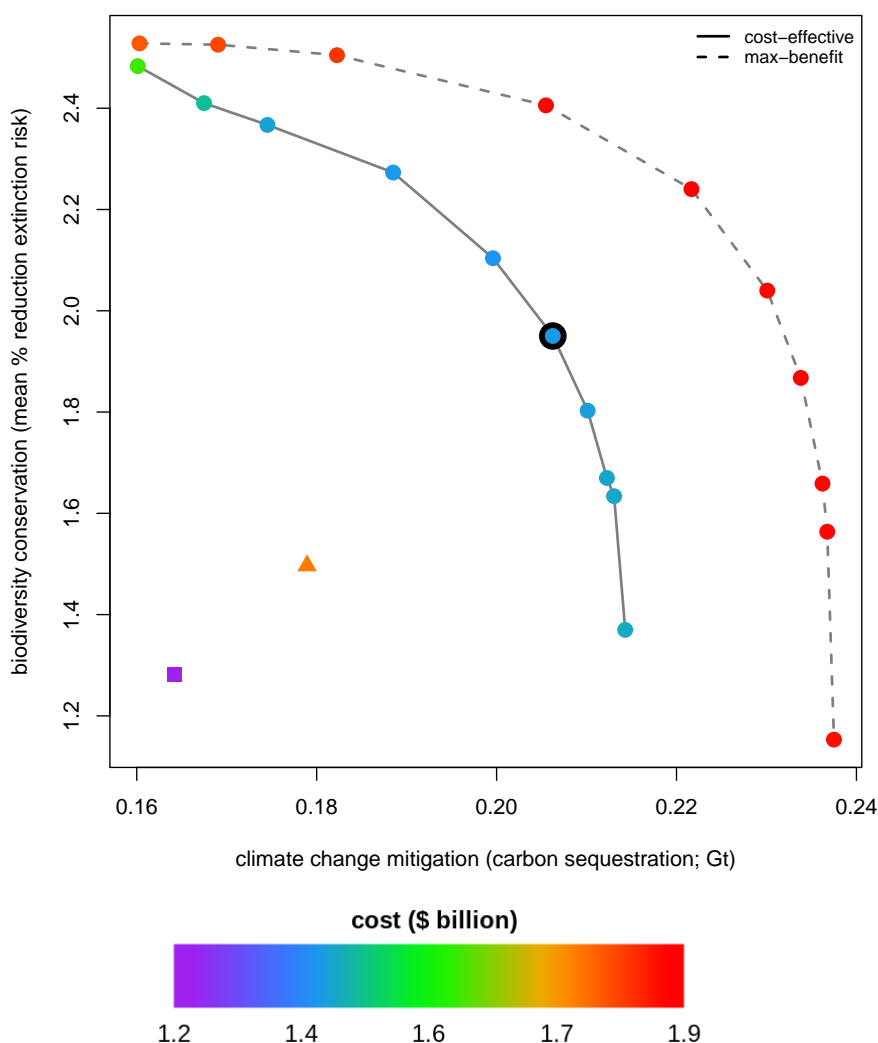
Figure 16: **Restoration of 50% of deforested lands.** Performance of a range of forest restoration prioritisation scenarios (points) with respect to climate change mitigation benefit (x axis), measured as above-ground carbon sequestration, and biodiversity conservation benefit (y axis), measured as the mean percent reduction in extinction risk among all species. Cost-effective scenarios (solid line) maximise return-on-investment (benefit/cost) and are likely to represent the most feasible restoration planning options. For reference, maximum-benefit scenarios (dashed line) that maximise returns irrespective of cost are also presented. The point circled in black represents a potential good compromise solution. Two further reference scenarios are also presented in which restoration is allocated randomly (triangle) or to minimise costs irrespective of benefit (square). For all scenarios the colour represents the total cost of the solution (USD; see legend). Maps of the locations associated with several of these solutions are included in the following two figures.
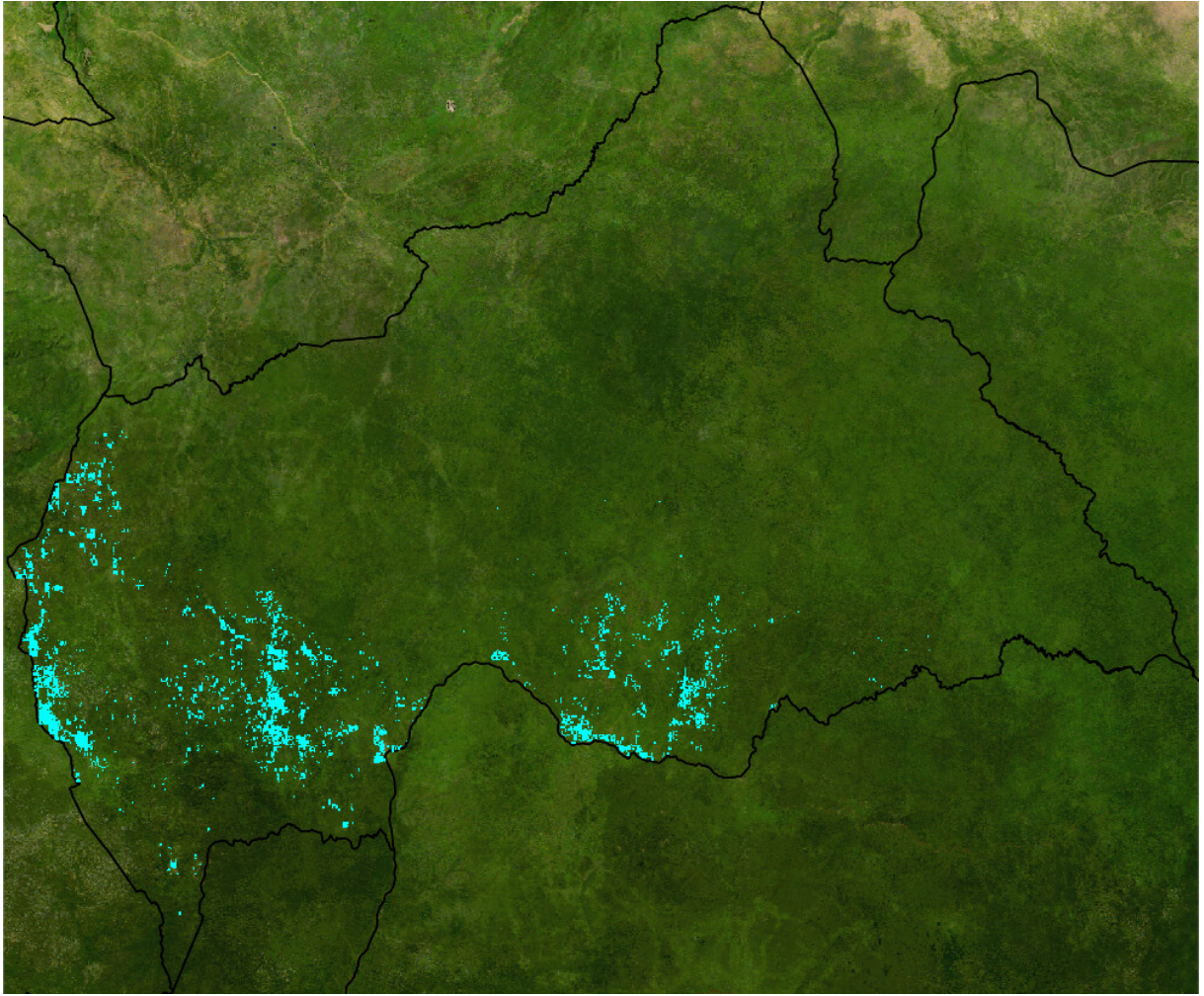
Figure 17: **Restoration of 50% of deforested lands**. Priority locations for restoration (cyan) for a solution that represents a balance between climate change mitigation and biodiversity conservation objectives while maximising cost-effectiveness (benefit/cost).
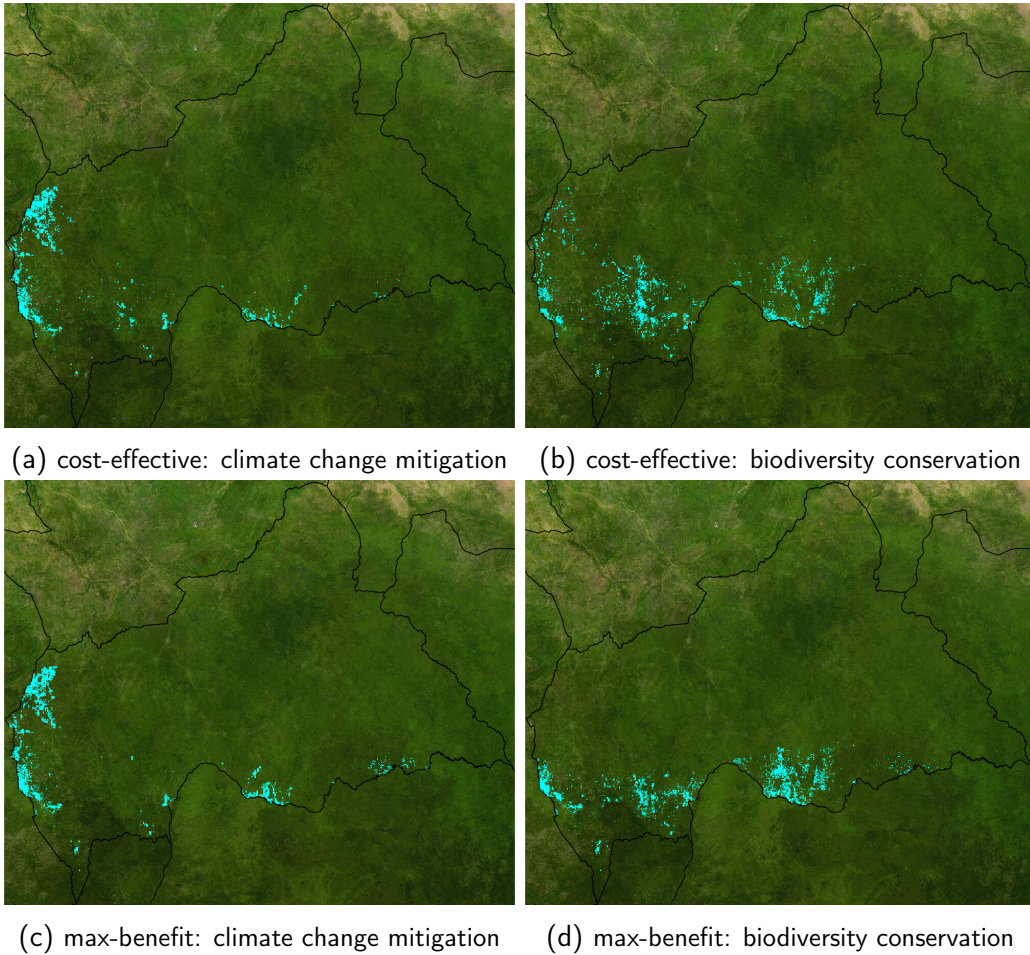
(a) cost-effective: climate change mitigation

(b) cost-effective: biodiversity conservation

(c) max-benefit: climate change mitigation

(d) max-benefit: biodiversity conservation
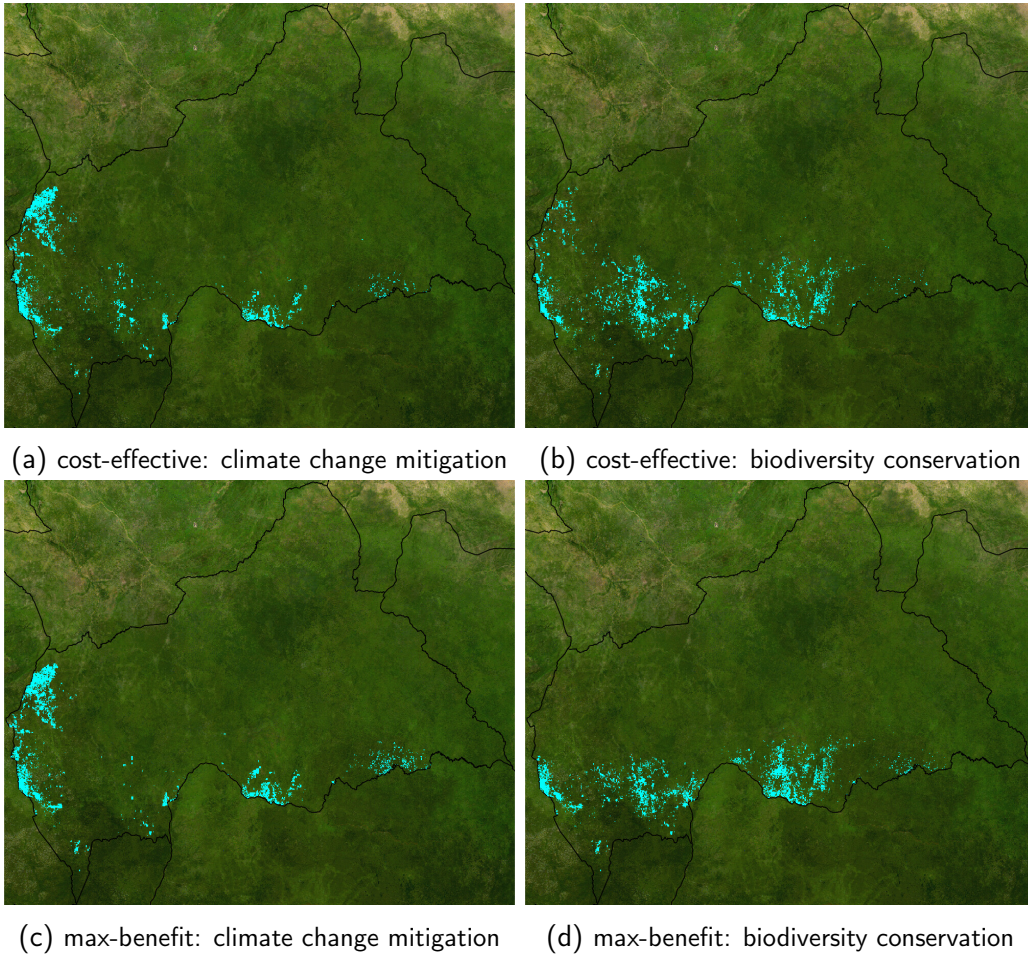
Figure 18: **Restoration of 50% of deforested lands.** Priority locations for restoration (cyan), under four scenarios: maximising cost-effectiveness for climate change mitigation only (a) and biodiversity conservation only (b), versus maximising benefit irrespective of cost for climate change mitigation only (c) and biodiversity conservation only (d). These figures illustrate how priority location change across the four scenarios.

Applying the results to planning and practice

Decision support platforms that are simple to understand and use are more likely to be adopted, provided they are clearly documented, published, and validated. **WePlan – Forests benefit governments, NGOs, investors, and restoration practitioners**. First, regional and national governmental agencies can integrate these data products into policy and planning. Second, NGOs and conservation organisations can use the data products to prioritise restoration activities. Third, restoration practitioners, local communities and landowners could use the data products to inform local-scale restoration activities. Finally, the CBD has identified value in this project to support country-level restoration planning and implementation to reach its restoration targets.

Decision support platforms inform but do not prescribe decisions. In our framework the judgment of decision-makers remains an essential part of the planning and decision process. The outputs presented here need to be integrated in a broader decision-making process that is inclusive. Recommendations for the design of such processes were discussed at the first training webinar, which can be accessed by following this link.

Methods

The spatial optimization restoration planning framework (WePlan – Forests) allows for comparisons of multiple scenarios through the quantification of restoration outcomes and trade-off curves at the national scale for all developing countries Party to the Convention on Biological Diversity (CBD) with tropical forest ecosystems. These scenarios are based on criteria that reflect biodiversity conservation, climate change mitigation, implementation costs, and opportunity costs.

Area available for restoration

Our study area comprises all Tropical & Subtropical coniferous forest, Tropical & Subtropical Dry Broadleaf Forests, Tropical & Subtropical Moist Broadleaf Forests, and Tropical & Subtropical Grasslands, Savannas & Shrublands (which contains some forested ecosystems) within +25 to -25 degree latitudes, excluding Australia. Using the Copernicus 2019 land cover raster (Buchhorn *et al.*, 2020) we defined areas available for restoration as classes 121 (Open forest, evergreen needle leaf), 123 (Open forest, deciduous needle leaf), 122 (Open forest, evergreen broad leaf), 124 (Open forest, deciduous broad leaf), 125 (Open forest, mixed), 126 (Open forest, unknown), 20 (Shrubs), 30 (Herbaceous vegetation), and 40 (Cultivated and managed vegetation/agriculture (cropland)) (Buchhorn *et al.*, 2020). This is summarised as the proportion of land available for restoration within each 1km^2 resolution planning unit. All other classes were considered as unavailable for restoration.

The definition of the areas that are deemed available for restoration can have a profound impact on the spatial distribution of areas selected for forest restoration, and this issue is a key consideration for planning and policy related to large-scale forest restoration. The definition is uncontentious for the tropical and subtropical forest biomes where areas that were once forested but are no longer forced can be defined reliably, and where areas associated with land uses that are not available for forest restoration (e.g. urban areas, water, wetlands) can be excluded. However, it is more difficult to define areas available for forest restoration in other biomes. For example, the Tropical & Subtropical Grasslands, Savannas and Shrublands biome contains 58 ecoregions including woodlands, savannah, forest-savannah, pine forests, bushlands, shrublands, grasslands, and other types, and spanning montane, tropical, subtropical and xeric conditions.

There is a legitimate concern that including non-forest ecoregions such as savannahs in forest restoration planning could be perceived as promoting, or lead to, afforestation of these systems. However, there are three reasons we argue some of these ecoregions should not be unilaterally excluded from forest restoration planning. First, tree cover is an important component of several of these ecoregions and they may, therefore, represent areas that could support some level of forest restoration without compromising their ecological integrity.

Second, ecoregions and biomes are coarsely mapped and may contain a range of other ecosystem types at smaller scales. As some of the ecoregions are large (e.g. the Cerrado), excluding them may result in a substantial impact on the area considered available for forest restoration. Furthermore, transitions between ecoregions can sometimes be gradual, hence the boundaries are subjectively defined. For large ecoregions, error in the mapping of boundaries can substantially alter the area of the ecoregion and hence the area deemed available for forest restoration. For example, a ±1 km distance error in the definition of the boundary of the Cerrado translates to a potential $\pm38,000$ km^2 (3.8 M ha) variation in the ecoregion area (estimated using an inner and outer buffer of the Cerrado ecoregion polygon).

Third, there are many ecosystems that appear to be at risk of transitioning to alternative states as anthropogenic pressures have altered some of the biophysical processes (e.g. fire regimes, climate change, elephant abundance) that maintain some ecoregions in a non-forested, or partially forested, state. Climate change in particular has the potential to drive substantial changes in the distribution of some ecosystems over the coming decades. In that context, there may be some ecoregions that are currently non-forested, but fostering a transition to a forest ecosystem may be deemed appropriate if there is a high likelihood the current ecosystem would be lost anyway.

There is considerable subjectivity and uncertainty in the definition of areas deemed available for restoration. Many of the decisions are subjective, are sensitive to error in datasets, and may not be robust to climate change impacts. Ultimately, it is likely to fall to individual nations to make these decisions though science could play an important role in informing those decisions. There is a research need to produce a high resolution (e.g. 30m-100m) estimate of the areas that could be deemed available for restoration under a variety of assumptions, based on a range of ecological and biophysical data, and that provides an assessment of risk in the context of climate change. Also needed is a spatially explicit assessment of the potential for perverse outcomes to arise from forest restoration.

Problem formulation

We formulate the problem of where to restore forest to maximise benefits, quantified in a range of ways among the scenarios, as a linear programming problem (a formal, mathematical optimisation framework). Specifically, the objective considers biodiversity conservation and climate change mitigation, while accounting for implementation and opportunity costs. The objective function is:

$$
\begin{aligned}
\max \quad & w_s \sum_i^{N_p} x_i \frac{s_i}{c_i + e_i} + w_b \sum_i^{N_p} \sum_j^{N_s} x_i \frac{b_{ij}}{c_i + e_i} \\
\text{subject to} \quad & \sum_i^{N_p} x_i A_i \leq T \\
& 0 \leq x_i \leq u_i \quad \forall i \in N_p
\end{aligned}
\tag{1}
$$

where x is a vector of decision variables representing the proportion of each planning unit to restore; s is the expected change in carbon sequestration resulting from forest regeneration relative to current land cover conditions; b is the expected benefit to biodiversity conservation, summed across all species, following restoration (described in detail below); and c and e are the opportunity and establishment costs associated with restoration, respectively. Carbon sequestration, biodiversity and cost metrics are quantified as rates per unit area of restoration. The relative contribution of climate change mitigation and biodiversity conservation objectives is determined by the weights w_s and w_b. They are required because the equivalence of objectives with different units is a subjective decision that must be made by decision-makers.

The two components of the objective function represent the returns (benefits divided by costs) of forest restoration to biodiversity conservation (b/(c + e); US\$$^{-1}$ km^{-2}) for each species j; climate change mitigation (s/(c + e); tonnes US\$$^{-1}$ km^{-2}), where the total cost of forest restoration is the sum of the opportunity costs (c; US\$$^{-1}$ km^{-2}) and the establishment costs (e; US\$$^{-1}$ km^{-2}). N_p is the total number of planning units and N_s is the total number of species.

The first constraint limits the total restoration area to target T. The second constraint limits the proportion of each planning unit that can be restored, where u (range: 0-1) is determined by calculating the proportion of each planning unit containing cover types that are not available for restoration (e.g. water and urban areas).

This equation represents the cost-effectiveness scenario. For comparison a maximum-benefit formulation was also calculated in which the cost denominator is removed. Two other reference solutions were also calculated that did not involve optimisation. The random allocation solution iteratively selected planning units, restoring each one up to the total available area for restoration (u), until the total restoration area target (T) had been achieved. This was repeated 100 times and the average returns calculated. The minimum cost solution restored forest in planning units in order of ascending cost until the target was achieved. The benefits and costs associated with these two references scenarios were then calculated.

We implement this problem formulation separately for each nation, as that is the scale at which planning is translated into implementation.

Quantifying biodiversity conservation benefit

Biodiversity conservation was quantified as the estimated mean reduction in extinction risk among all forest-associated species resulting from forest restoration. This estimation is based on the extinction risk model of (Thomas *et al.*, 2004): $e = 1 - (a/A_0)^z$, where a is the current habitat area, or future projected habitat area following restoration, A_0 refers to the original habitat area, corresponding to presettlement conditions, and z determines how extinction risk increases as habitat is lost (here, $z = 0.25$). The benefit to biodiversity conservation (B) of forest restoration among species is then estimated as: $B = \sum_i^{N_s}(e_c - e_r)$, where e_c is the extinction risk based on current habitat area, e_r is the projected extinction based on the habitat area following restoration, and N is the number of species included in the model.

Estimating the area parameters requires spatially explicit estimates of the species range and habitat within the range for each species of interest. We use the Spatial Planning for Area Conservation in Response to Climate Change (SPARC) dataset (Hannah *et al.*, 2020; Marquet *et al.*, 2020), which modelled the ranges of approximately 103,000 species in the Neotropics, the Afrotropics and the Indo-Malayan tropics. Benefits of the SPARC dataset over other species range collections is that a large number of species are represented including a strong representation of plants, and the ranges are modelled in a consistent manner.

The SPARC project modelled current species distributions on the basis of species

location data sourced from multiple datasets (e.g. BirdLife, GBIF, VertNet, BIEN) with filtering to exclude records with missing, duplicated, or errant location data (see Hannah *et al.*, 2020; Marquet *et al.*, 2020, for details). Distributions were modelled for species with at least 10 occurrence records, with the domain of the predictions limited to within 500 km of occurrence records. The environmental covariates used related to bioclimatic conditions (mean annual temperature, mean diurnal temperature range, seasonality of temperature, minimum temperature of the coldest month, mean annual precipitation, seasonality of precipitation; WorldClim v1.4, www.worldclim.org), an accumulated aridity index (Marquet *et al.*, 2020), and soil variables (depth to bedrock, pH, clay proportion, silt proportion, bulk density; all means within the top 1m) (Soilgrids; www.soilgrids.org).

The climate and soil variables used in the distribution modelling are likely to be associated with the *potential* distribution of habitat. While these SPARC SDM ranges are expected be less extensive than Extent of Occurrence (EOO) ranges because they may already partially reflect the distribution of habitat through the proxies of climate and soil variables, they are expected to be more extensive than Area of Habitat (AOH; also referred to as Extent of Suitable Habitat - ESH) range estimates because they do not explicitly reflect the distribution of habitat (for a discussion of EOO and AOH see Brooks *et al.*, 2019).

Quantifying what constitutes habitat for each species is a challenging problem. Species-habitat associations have been defined for 9,932 of the SPARC species (IUCN), through a process of assessment by experts. For the remaining species we use the empirical location data for each species to estimate the habitat association using a map of the IUCN habitat types (Jung *et al.*, 2020). Specifically, we calculate the proportion of occurrence records occurring within each of the Level 1 IUCN habitat classes, and identify the threshold that maximises the sensitivity and specificity of the predicted habitat associations for the 9,932 species with defined habitat associations. As our focus is on forest restoration we restrict our analysis to the subset of species with forest associations, which could be predicted with 81.6% accuracy.

Following Strassburg *et al.* (2020), we simplify the IUCN habitat categories into six general habitat types (forest, savannah, shrubland, natural grassland, wetland, desert) for which the presettlement distributions were estimated. The area of original habitat (A_0) is derived by identifying area of the intersection between the species distribution models and the presettlement habitat distributions for each species. Current habitat area was determined by intersecting the species distribution models with an estimate of

the current distribution of these five habitat types derived by reclassifying a contemporary 100 m resolution map of the IUCN habitat types (Jung *et al.*, 2020).

The contribution of forest restoration in each cell to the reduction in extinction risk among all species is calculated using a weighted sum of the expected rates of change in extinction risk. Specifically, for each planning unit the set of species that would benefit from forest restoration at that location is identified using the SDM. The expected reduction in extinction risk arising from forest restoration is the tangent to the extinction risk function at the current level of habitat throughout the range, and is calculated numerically. Forest restoration in any cell changes the benefit of restoration in other cells. We therefore solve the optimisation problem in increments, updating the extinction risk benefit calculation after each increment.

The contribution of each species to the extinction risk reduction benefit is determined by a species weighting scheme that assigns equal total weights between plants and animals (0.5 to each) and for animals then assigns equal weights among mammals, birds, reptiles and amphibians (0.125 total weight to each). Within each of those taxonomic groups the total weight is divided equally among all species in that group. The weights sum to unity among all species. Without a weighting scheme plants would have a disproportionately large influence on the solution due to their disproportionately high representation among the set of species included in SPARC.

Quantifying climate change mitigation benefit

Climate change mitigation, measured here as potential carbon sequestration (PCS) in aboveground biomass (AGB), is one of the benefits that can inform spatial restoration planning for tropical forest ecosystems. Restored tropical forests contribute to the reduction of CO_2 in the atmosphere through carbon sequestration and, thus, to mitigate global climate change (Brancalion *et al.*, 2019b; Strassburg *et al.*, 2019). A map of predicted old-growth forest aboveground biomass (OGF-AGB) was created at 100m resolution using an iterative Random Forest model in Google Earth Engine. To do so, a large number of potential predictor variables, including topographic, edaphic, and bioclimatic, were tested, and predictor variables that did not add to the power of the model were removed. The final model estimated OGS-AGB to within 20 Mg/ha for a global validation sample of several thousand points. We then calculated the difference between the year 2017 AGB at 100m resolution and then excluded pixels

having more than 50% OGF-AGB as those would be less suitable for restoration. The remaining restoration suitable pixels provided 100m resolution PCS-AGB, which were then summed to create a 1x1 km estimate of PCS-AGB for each pixel. Our approach provides a minimum and maximum bounded uncertainty for PCS-AGB through the incorporation of the standard error AGB uncertainty maps available in our input 100m AGB maps (CCI AGB 100m). The workflow and maps were developed by Dr. Eben Broadbent and Almeyda Zambrano of the Spatial Ecology and Conservation Lab (www.speclab.org) at the University of Florida (publication in preparation).

Quantifying costs

WePlan – Forests accounts for both opportunity costs and restoration implementation costs. Accounting for opportunity costs is important to reduce conflict between agricultural productivity and forest restoration as it increases the likelihood that forest restoration will be concentrated into areas of marginal agricultural productivity. Opportunity cost may also be linked to the probability of long-term success of forest restoration (Brancalion *et al.*, 2019a). Accounting for establishment costs is important in order to maximise the return on investment from restoration activities.

Establishment costs were estimated using a statistical model that was based on forest restoration project data ($n = 234$ observations) extracted from 50 World Bank project reports spanning 24 countries (Vincent, Kaczan, et al., in prep.). The criteria for inclusion were that the area and costs, or the cost per unit area, of restoration must have been explicitly reported. The dataset excluded observations from Eastern Europe as they are not relevant to the context of tropical forest restoration, and excluded unusual special-purpose activities (e.g. mangrove restoration, tree-planting along highways, planting bamboo, etc) as they are not representative of the type of activities most relevant to tropical forest restoration. A distinction was made between afforestation, referring to forest regeneration on land where the most recent use was not forest (typically agriculture), and reforestation, referring to regeneration of forest land that recently lost its tree cover due to harvesting, wildfire, or some other source of damage. Costs included all expenditures associated with regeneration until the new stand was 'free to grow' (approx. 3-5 years, depending on project and site).

The dependent variable in the statistical model was the natural log of establishment costs per hectare expressed in 2011 US$. The independent variables included GDP per

capita (natural log transformed), a binary variable distinguishing between afforestation and reforestation, a binary variable distinguishing between natural and active regeneration, a binary variable indicating whether the project was initiated pre- or post-2010, a continuous variable representing the proportion of the country associated with temperate/boreal biomes, a binary variable indicating whether the cost accounted for overhead costs or not, and the total area of forest regeneration (natural log transformed). The model explained approximately half of the variation in the data (R^2 = 0.46; Vincent, Kaczan, et al., in prep.), which is reasonable performance given the wide range of countries, years and restoration contexts represented by these reports. A strength of this model is that it is based on empirical evidence in contrast to alternative approaches to estimating establishment costs that are based on expert opinion. The model indicates that establishment costs are positively associated with per-capita GDP, that reforestation is more expensive than afforestation (this appears to arise as a result of the increased difficulty and expense of accessing and preparing partially forested sites compared to marginal agricultural lands), and that there are scales of economy associated with the total area of forest restored.

Establishment costs were estimated spatially using gridded GDP estimates for 2011 (Kummu *et al.*, 2018) and a model of the potential for natural regeneration (Beyer et al., in prep.). The latter was used to determine the value of the binary active/natural regeneration variable for each cell. All of the other binary variables were set to 0, and we use the mean restoration area among all projects (9604 ha) to estimate establishment costs. Establishment costs were transformed from 2011 to 2017 US$ using annual inflation rates (2012-2017: 1.019, 1.037, 1.056, 1.067, 1.078, 1.099, respectively).

Opportunity costs were based on estimates of annual land rent (a measure of net income generated by land) for cropland and pastureland (2017 USD values) at a resolution of approximately 10km (Vincent & Yi, in prep.). As an initial step, gross annual revenue was determined separately for cropland and pastureland using existing gridded data sources (cropland: MapSPAM, www.mapspam.info; pastureland, Gridded Livestock of the World, https://dataverse.harvard.edu/dataverse/glw), augmented by national data from FAOSTAT (http://www.fao.org/faostat/en/#data/QC; http://www.fao.org/faostat/en/#data/QL). In the final step, detailed farm budget data from large-scale household surveys conducted by the World Bank and FAO in several dozen developing countries were used to convert gross annual revenue to annual land rent. The cropland opportunity cost layer took precedence over the pastureland

opportunity cost in areas where the two overlap. Establishment costs are short-term but opportunity costs are ongoing. We therefore calculate the total cost of restoration in each cell as the establishment cost plus the in perpetuity opportunity cost (the opportunity cost divided by a discount rate of 5%).

Limitations of this analysis

The difficulties of defining the areas available for restoration are described above. This analysis makes several other assumptions and judgments that are likely to influence the analysis.

The analysis assumes that the climate mitigation and biodiversity conservation benefits arising from active and natural regeneration do not differ. However, active regeneration may sometimes be associated with planting non-native tree species that have commercial value (e.g. eucalypts for timber production, or species with food-production value). For example, Brazil's Forest Code allows up to 50% of non-native species to be used in forest restoration. Depending on how these species are planted and maintained they may still have substantial value for carbon sequestration, but they are likely to have diminished value for biodiversity conservation. The link between the proportion of non-native species planted and the value to biodiversity conservation has not been well established, but it could mean that this analysis has overestimated the extinction-reduction benefits arising from active regeneration.

This analysis also ignores any variation in the temporal rates at which benefits arise spatially, or as a function of the regeneration method. There may be substantial differences in these rates as a result of differences in seedling establishment and survival, competition, succession, and growth rates. Accounting for some of these effects and their implications for the rates at which benefits are achieved is a goal for the future refinement of the WePlan Forests decision support platform.

This analysis enforces no assumptions about the maximum level of forest cover that might be permitted in an area, which typically results in a substantial spatial concentration of fully-restored forested areas (see solution maps). Large, contiguous blocks of forest may provide additional benefits to biodiversity (e.g. reduction in edge effects, reduced accessibility to people) but may have detrimental impacts on local communities. It would be straightforward to limit the maximum area of forest cover at

a planning unit or jurisdictional level if nations wish to identify forest restoration solutions that are more aligned with the land sharing perspective than the land sparing perspective.

This analysis focuses on the benefits and costs at the societal level, and does not account for land tenure and livelihoods at local levels. A major challenge for policy is to identify ways of funding forest restoration and compensating affected landowners such that there is no net negative impact. Ideally, both society and individuals achieve net benefits from forest restoration (so called win-win solutions).

All of these assumptions could be addressed within the WePlan – Forests framework through collaboration with individual nations.

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About us

International Institute for Sustainability Australia (IIS-AU)

The International Institute for Sustainability Australia is a not-for-profit organisation based in Canberra, Australia, and is the first sister-organisation of the International Institute for Sustainability in Rio de Janeiro, Brazil. IIS-AU develops evidence-based approaches for systematic spatial planning to support the design and implementation of environmental policy, and to develop science and technology for environmental decision-making, with a focus on forest ecosystem restoration.

International Institute for Sustainability Rio (IIS-Rio)

The International Institute for Sustainability (Rio) is an independent think-and-do-tank focused on understanding the relationship between human society and the environment. Their work promotes sustainable land use, in particular biodiversity conservation, ecosystem service provisioning, sustainable soil management, climate change mitigation and adaptation, and the socioeconomic development of actors involved in these processes.

Convention on Biological Diversity (CBD) Secretariat

The Convention on Biological Diversity is a multilateral treaty established in 1993 with the objectives of conservation of biological diversity, sustainable use of its components and the fair and equitable sharing of the benefits arising from the use of genetic resources. The convention promotes international cooperation and defines global goals for conservation to achieve its objectives. The secretariat is responsible for assisting Parties in implementing the programmes and reaching the targets.

Forest Ecosystem Restoration Initiative (FERI)

The Forest Ecosystem Restoration Initiative (FERI) supports developing countries Party to the CBD in the development and operationalization of national targets and plans for ecosystem conservation and restoration. FERI is supported by the Korea Forest Service of the Republic of Korea and implemented by the Secretariat of the Convention on Biological Diversity (CBD).

Korea Forest Service of the Republic of Korea

The Korea Forest Service is an independent agency specializing in forestry that is overseen by the South Korean Ministry for Food, Agriculture, Forestry and Fisheries. It is responsible for maintaining forest lands in South Korea and for the establishment and implementation of forest policies and laws