Strategic approaches to restoring ecosystems can triple conservation gains and halve costs

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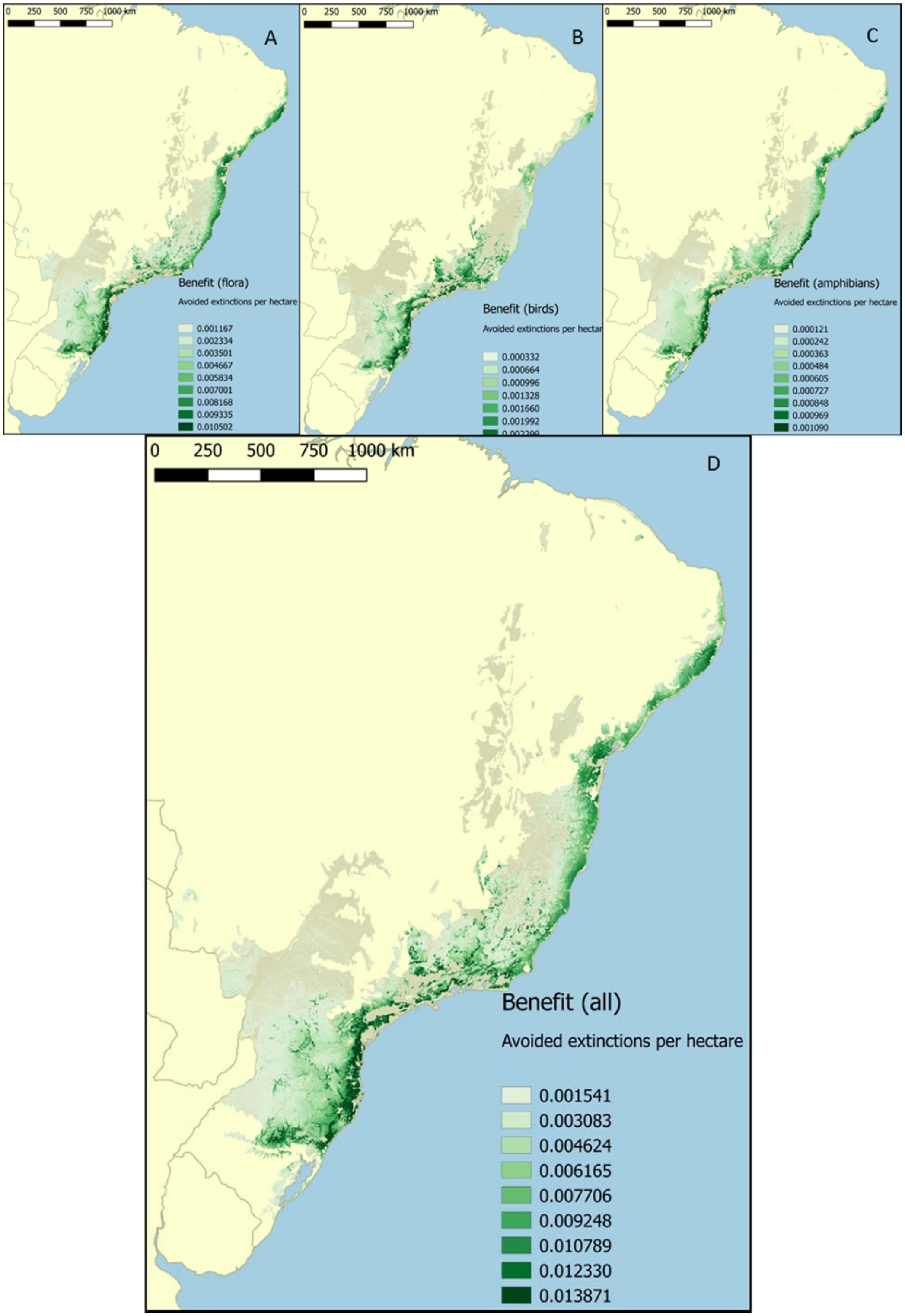
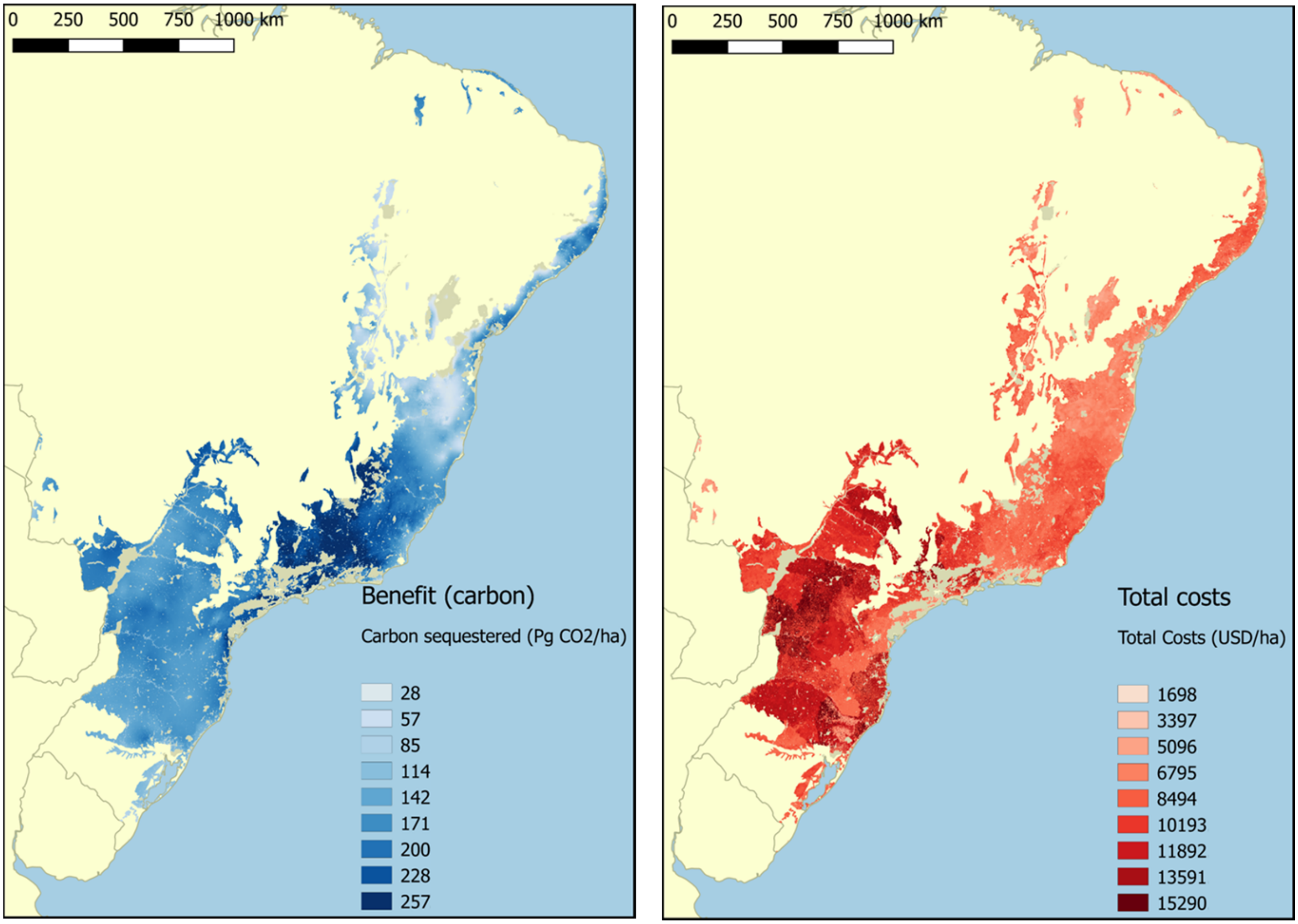
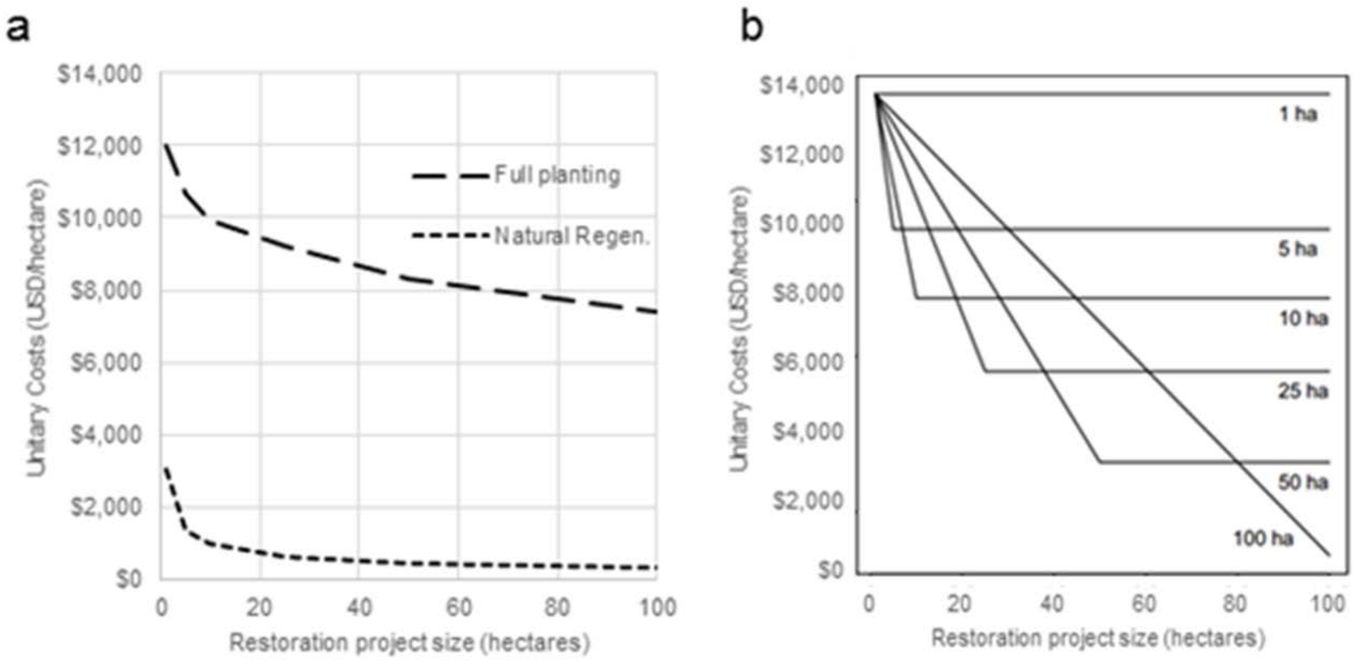
Extended Data



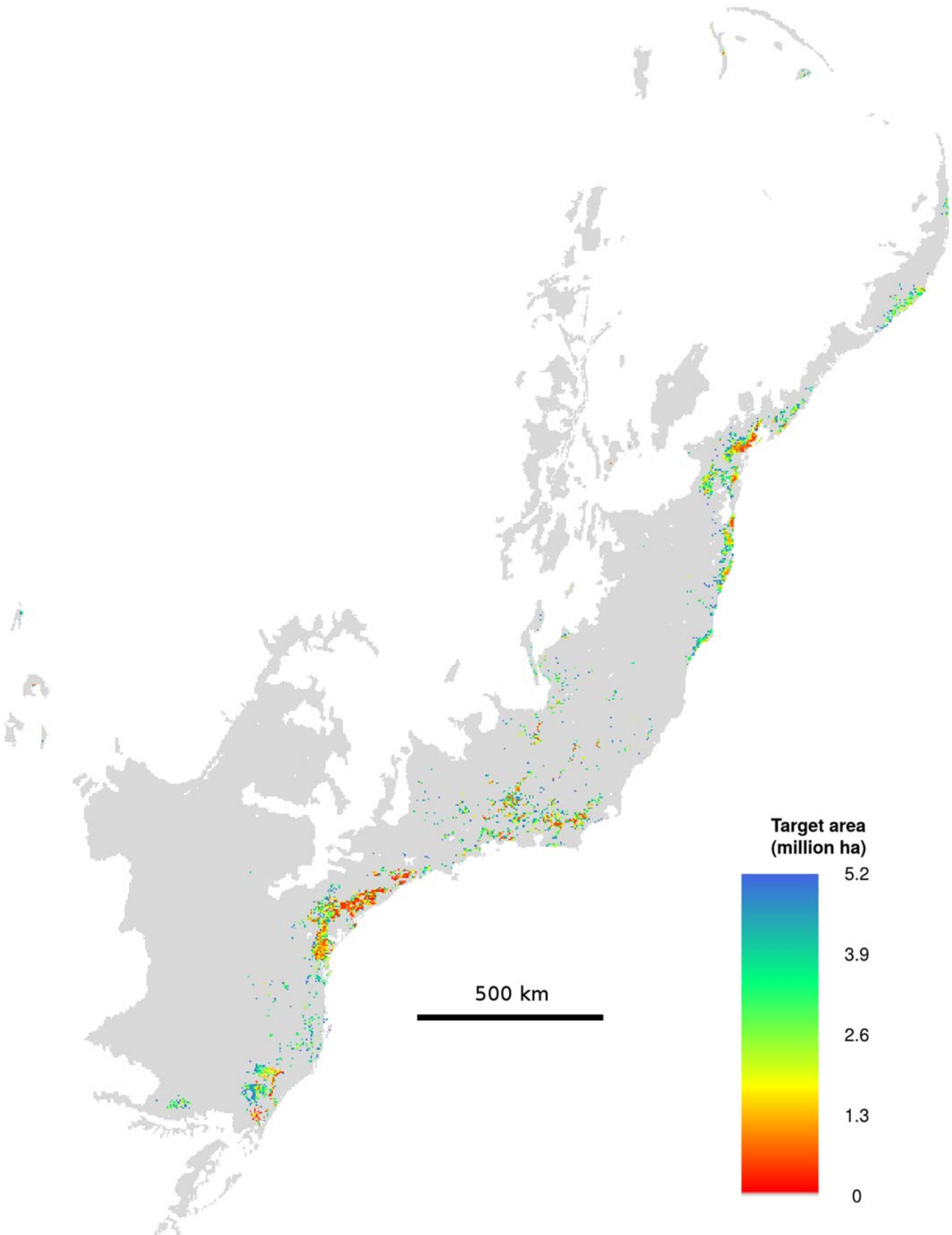
Extended Data Figure 1 – Biodiversity Conservation benefits surfaces for amphibians, birds, plants and all species combined. The benefits for biodiversity conservation was measured in terms of avoided extinctions per hectare, and the maps show these benefits for woody plants (a), birds (b), amphibians (c) and for all species combined (d). Importantly, these benefits are shown here for the starting situation, as when we allocate the first areas (1/20th of our target) we dynamically adjust these surfaces to reflect increased habitat (and consequently reduced extinction probabilities) for species whose ranges fall within the selected areas.



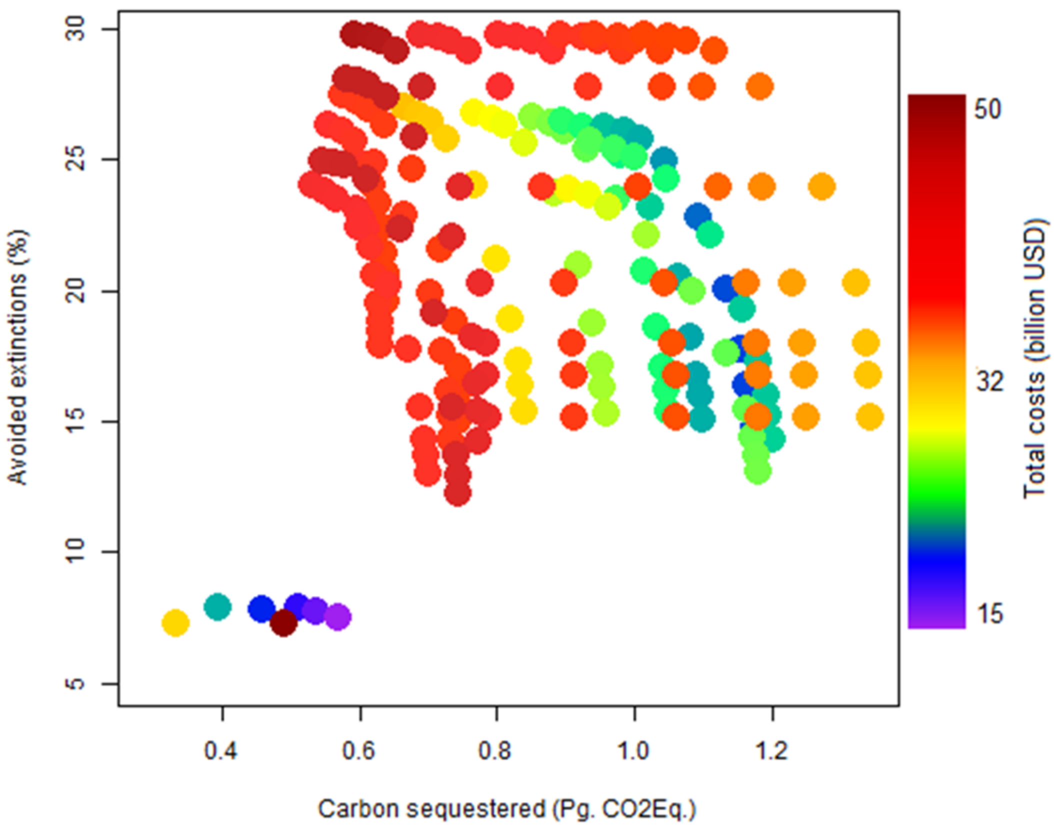
Extended Data Figure 2 – Climate-change mitigation benefits and total costs surfaces. (a) - Benefits were measured in terms of carbon dioxide equivalent (CO_2Eq.) sequestered as an area is restored. Estimates are conservative as they only cover the first 20 years after restoration; **(b)** Costs are measured in (USD/hectare) and combine direct restoration costs (including implementation and maintenance) and opportunity costs, which are the foregone agricultural profits incurred when an agricultural land is converted back into a native ecosystem. The latter is a good proxy for conflict with agricultural production.



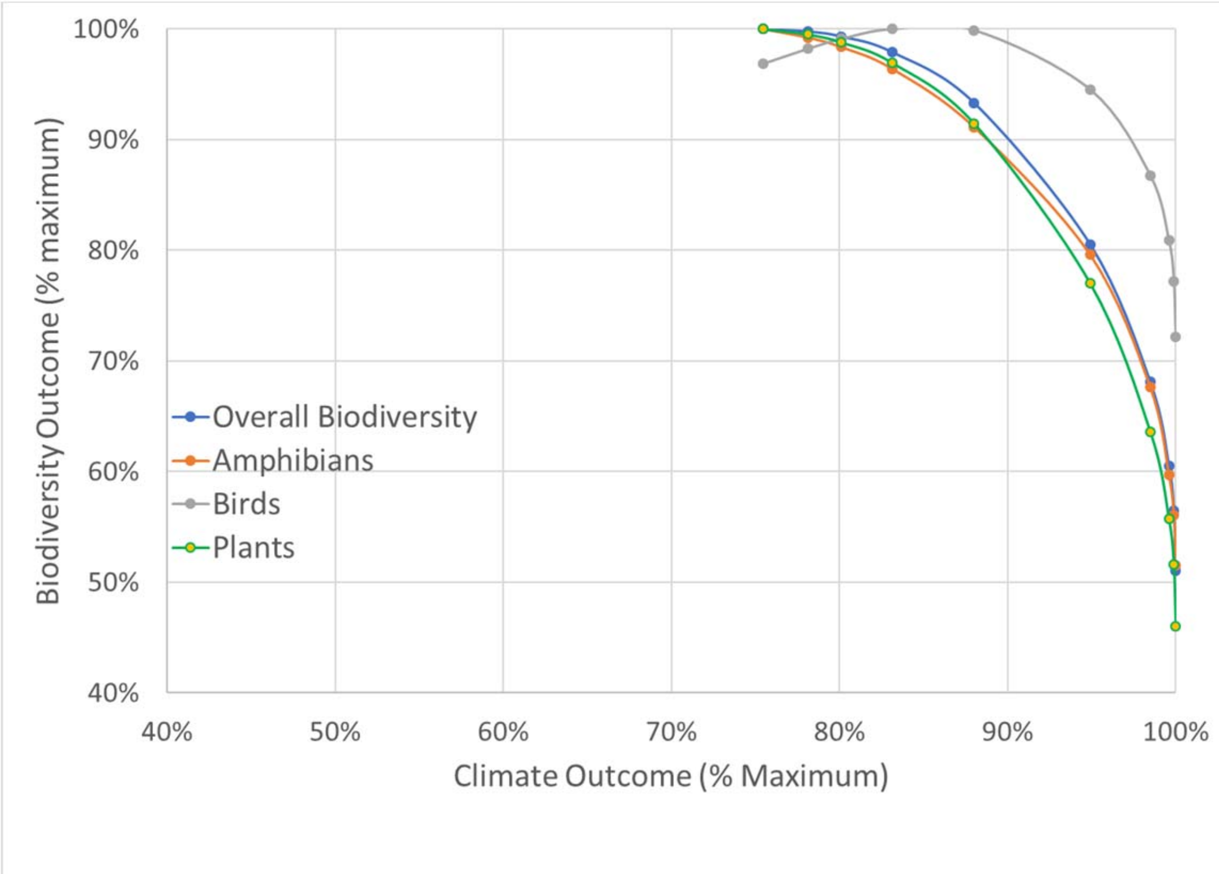
Extended Data Figure 3 – Economies of scale of restoration. (a) Data collected for the implementation costs of full planting methods from Atlantic rainforest companies. We explicitly requested firms for estimates for restoration projects of 1, 5, 10, 25, 50 and 100 hectares. Natural regeneration costs were estimated based on fencing costs. **(b)** Six scenarios of economies of scale in restoration costs, as included in our algorithm. At one extreme forest is assumed to be restored in 1 ha blocks and there is no economy of scale. At the other extreme, there is a continuous increase in economies of scale up to the maximum of 100 ha of restored forest. The intermediate scenarios represent economies of scale that increase up to a given block size, after which there are no further improvements in efficiency.



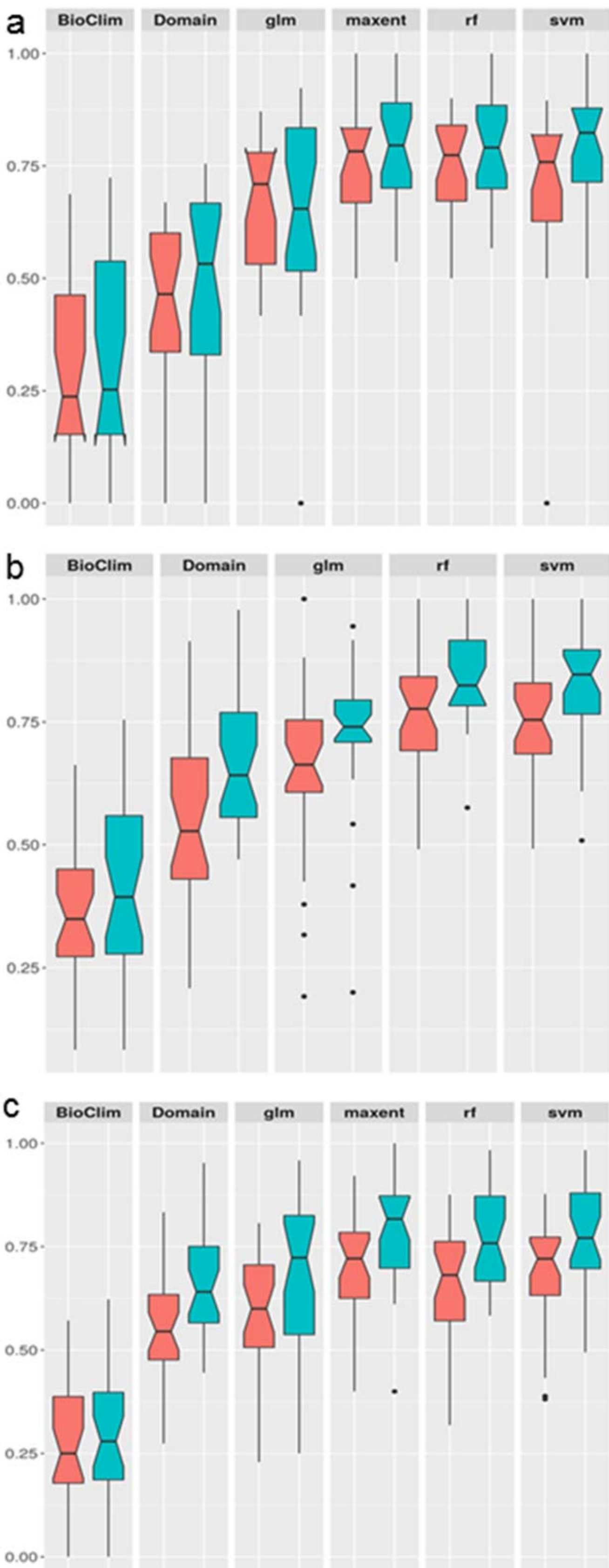
Extended Data Figure 4 – Cumulative priority areas for each 20-step increment in target areas. Our dynamic approach allocates the overall target (5.2 million hectares) in 20 steps, corresponding to approximately 260,000 hectares each. Areas in red are the top priorities selected in the first step, whereas areas in blue were added in the 20th step. These can be used for practical purposes such as prioritizing where to start the large-scale restoration effort from or in case land-owners decide to offset by financing conservation of existing fragments, consequently reducing the total offsets area dedicated to restoration.



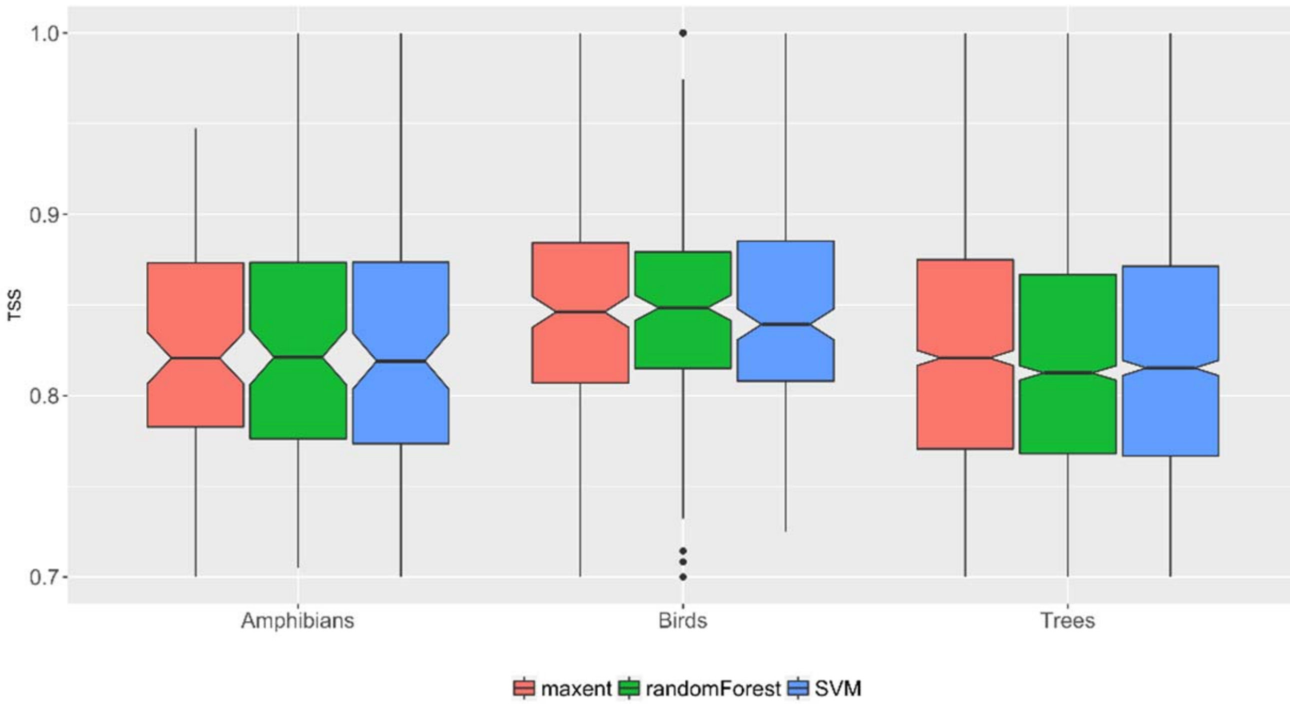
Extended Data Figure 5 – Outcomes for all scenarios modeled. Outcomes for all 362 scenarios modelled in terms of avoided extinctions (y-axis), climate change mitigation (x-axis) and total costs (colour legend). The cluster on the bottom-left corner corresponds to the baseline (yellow), random and minimum costs scenarios. Each of the concave strings of dots (as the ones shown in Figure 1) is formed by varying the weight between carbon and biodiversity, whereas the difference between the strings is generated by including costs into the optimization, by varying the maximum fraction of each cell that can be restored and by limiting the optimization by state borders.



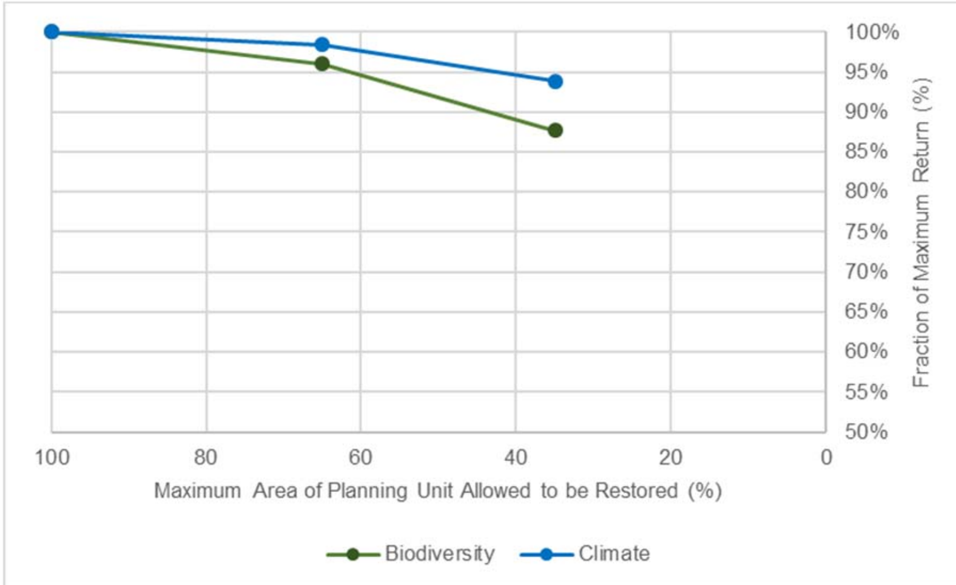
Extended Data Figure 6 - Trade-off curves between biodiversity conservation and climate change mitigation for individual taxa and overall biodiversity. Outcomes here are shown in comparison with the maximum attainable outcomes for each benefit (those achieve in scenarios "Maximum Biodiversity" and "Maximum Climate", from Fig. 1). Plants present the lowest synergies with climate change mitigation, with only 45% of the maximum avoided extinction for plants achieved in the "Maximum Climate" scenario. Birds, on the other hand, have 72% of their potential extinctions avoided in the "Maximum Climate" scenario. Birds congruence with carbon sequestration is high enough so that the best possible outcome for birds comes from an intermediate scenario with equal weights for biodiversity conservation and climate mitigation.



Extended Data Figure 7 – Preliminary ecological niche models' validation scores. Scores were measured using True Skill Statistics (TSS) values with (red) and without (blue) the buffer applied to generate the validation test points for birds (a), woody plants (b) and amphibians (c).



Extended Data Figure 8 – Final ecological niche models' validation scores - True Skill Statistics (TSS) for each algorithm used for the final ecological niche models used in the study, by biodiversity group.



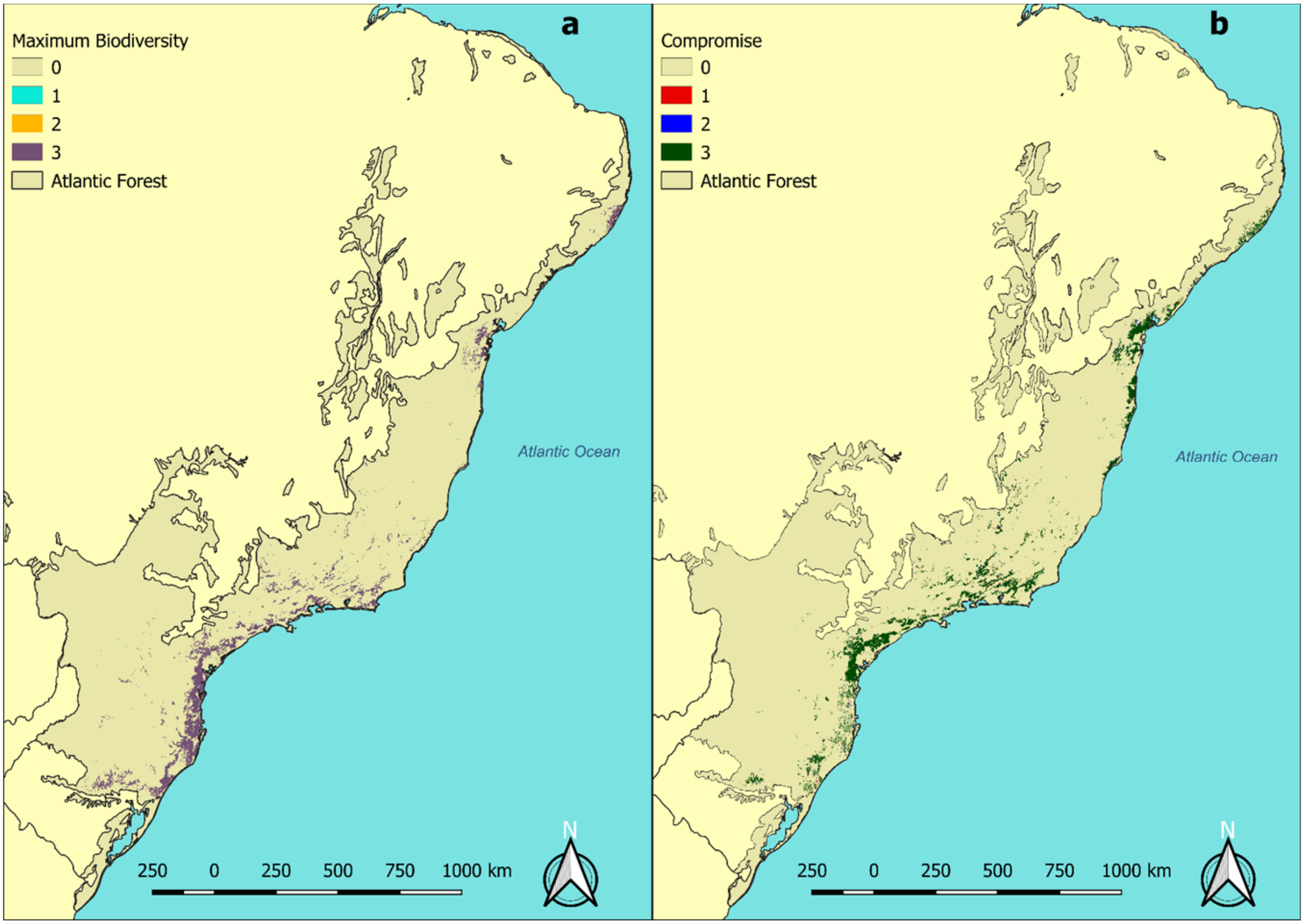
Extended Data Figure 9 - Impacts on outcomes of reducing the maximum fraction of the planning unit that can be restored. We simulated 3 options for the fraction of each planning unit that could be dedicated to restoration: 100%, 65% and 35%. Benefits for biodiversity, climate change mitigation and costs reduction are always higher when there is no restriction for allocation (100%). Reduction in outcomes are relatively small when moving from 100% to 65%, and higher when allowing only up to 35% of a given planning unit to be selected. Reductions are steeper for biodiversity conservation than for climate change mitigation.

Scenario	Avoided Extinctions				Climate Mitigation (Pg CO2Eq)	Restoration Costs (bill. US$)	Opportunity costs (bill. US$)	Total costs (bill. US$)
	Total Biodiversity	Amphibians	Birds	Plants				
BAU	7.2%	7.4%	7.0%	7.2%	0.5 (0.4-0.6)	22.8	27.4	50.2
Maximum Biodiversity	29.7%	27.0%	31.5%	29.7%	1.0 (0.9-1.1)	24.6	10.3	34.9
Maximum Climate	15.2%	13.9%	23.5%	13.7%	1.3 (1.2-1.4)	16.3	13.1	29.4
Minimum Costs	7.5%	6.8%	6.7%	7.7%	0.6 (0.5-0.7)	5.9	9.2	15.2
Random	8.5%	8.6%	8.3%	8.6%	0.8 (0.7-0.9)	21.9	26.6	48.5
Compromise	25.8%	23.3%	27.1%	25.8%	1.0 (0.9-1.1)	12.0	9.8	21.7
Environment Only	29.5%	26.5%	32.2%	29.3%	1.1 (1.0-1.2)	24.4	10.2	34.6
Minimum Costs (Constrained by state boundaries)	15.9%	14.9%	15.4%	16.0%	0.4 (0.3-0.5)	8.0	23.6	31.6
Minimum Costs (within state or in priority areas for biodiversity anywhere)	16.6%	15.3%	17.0%	16.7%	0.4 (0.3-0.5)	8.8	23.5	32.2

Extended Data Table 1 - Results for selected scenarios. Extinctions estimates for the central estimate (z=0.25) are presented for total biodiversity and each of the taxon. Climate change mitigation presents the central estimate and, in brackets, lower and upper bound estimates.

Scenario	Avoided Extinctions											
	Total Biodiversity			Amphibians			Birds			Plants		
	z=0.15	z=0.25	z=0.35	z=0.15	z=0.25	z=0.35	z=0.15	z=0.25	z=0.35	z=0.15	z=0.25	z=0.35
BAU	7.7%	7.2%	6.8%	7.9%	7.4%	6.9%	7.5%	7.0%	6.6%	7.7%	7.2%	6.8%
Maximum Biodiversity	30.8%	29.7%	28.7%	28.0%	26.9%	25.8%	32.6%	31.5%	30.4%	30.8%	29.7%	28.6%
Maximum Climate	15.9%	15.2%	14.5%	14.6%	13.9%	13.2%	24.6%	23.5%	22.4%	14.3%	13.7%	13.1%
Minimum Costs	7.9%	7.5%	7.0%	7.2%	6.8%	6.4%	7.1%	6.7%	6.3%	8.2%	7.7%	7.2%
Random	9.0%	8.5%	8.0%	9.1%	8.6%	8.0%	8.8%	8.3%	7.8%	9.1%	8.6%	8.1%
Compromise	26.4%	25.8%	24.9%	23.9%	23.3%	22.4%	28.2%	27.1%	26.0%	26.3%	25.8%	24.9%
Environment Only	30.4%	29.5%	28.5%	27.3%	26.5%	25.5%	33.6%	32.2%	31.0%	30.1%	29.3%	28.4%
Minimum Costs (Constrained by state boundaries)	16.5%	15.9%	15.3%	15.5%	14.9%	14.3%	16.0%	15.4%	14.8%	16.5%	16.0%	15.4%
Minimum Costs (within state or in priority areas for biodiversity anywhere)	17.2%	16.6%	16.0%	15.9%	15.3%	14.7%	17.7%	17.0%	16.3%	17.3%	16.7%	16.1%

Extended Data Table 2 - Results for extinction risk sensitivity analyses for selected scenarios and species groups.



Extended Data Figure 10 – Sensitivity analysis of the impacts on priority areas distribution of varying the extinction risks estimate parameters. We used three different parameters for the extinction risk estimate formula (see Methods), varying the z exponent (z=0.20 ; z=0.25 ; z-0.35). The figures above shows the impact by colour-coding that were selected only by one of exponents, by two and areas that were selected by all three, for the Maximum Biodiversity scenario (**a**) and the Compromise scenario (**b**). It reveals a robust outcome, with 94% (**a**) and 98% (**b**) of the selected areas being chosen by all three variations.