Science
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Supplementary Materials for

A market for 30x30 in the ocean

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The PDF file includes:

Materials and Methods

Data description

This work relies on multiple sources of spatial and tabular data to establish the potential benefits and costs of conservation. We use species distribution models, spatially explicit catch data, ex-vessel price of catch, location of existing marine protected areas, political boundaries, and marine ecoregions to construct conservation supply curves and simulate trade outcomes. We provide a detailed description of the data and how we incorporate each of them in our work. When necessary, data sets were reprojected or rasterized to conform to a 0.5 x 0.5 degree raster with standard WGS84 ellipsoid and datum.

Gridded data sets

Habitat Suitability Index

We use species distribution models (SDM) from AquaMaps (10). These provide the probability (between 0 and 1) of a species occurring on any given ocean grid cell along a 0.5 x 0.5 degree grid. This probability of occurrence is modeled from the abiotic characteristics of the grid cell, such as temperature, dissolved oxygen, salinity, and depth (10). Importantly, these abiotic factors are unaffected by the protection status of the grid cell or the protection status of adjacent grid cells. The entire data set contains information for 33,518 species.

We implement two filters to these data. First, we remove 9,819 species for which SDMs were built using less than 10 records. These species are considered data-poor or with extremely restricted distribution. Our supplementary text shows that excluding these species has little effect on the Habitat Suitability Index we will calculate next. Then, we retain only cells for which the probability of occurrence of a given species is equal to or greater than 0.5 (i.e.$p_{ij} \geq 0.5$). These data are then used to compute the Habitat Suitability Index (HSI). Let p_{ij} be the probability of occurrence of species j in grid cell i, and S_i be the number of all species that may reside in grid cell i. The HSI of a cell is the average probability of occurrence for all species that inhabit it:

$$HSI_i = \frac{1}{S_i}\sum_{j=1}^{S_i} p_{ij}$$

In the extreme, all species in the grid cell i have a probability of 1.0, then $HSI_i = 1$. Thus, HSI_i is bounded between 0.5 and 1.

Fisheries revenues

Our cost layer is built by combining annual ex-vessel prices with spatially-explicit data on capture fisheries. We corroborate and update taxonomy across data sets using taxonomic data from FishBase (16) and SeaLifeBase (17) accessed via rfishbase 3.1.9 (18). The tabular dataset on ex-vessel prices from (12) contains 97,293 distinct records of taxa-specific annual ex-vessel prices. We remove records identified as ``freshwater``, records occurring outside the 2005-2015 period, records with no ex-vessel price reported, and records not relevant to the marine environment, leaving us with 17,419 records. We calculate the median annual price for each species, genus, family, order, and ISCAAP code (Acronym for the ``International Standard Statistical Classification for Aquatic Animals and Plants", which categorizes species into 50 groups based on taxonomic, ecological and economic characteristics (19)).

We use taxa-level reconstructions of annual catch by industrial and non-industrial fisheries for marine cells along a 0.5 x 0.5 degree grid from (11). We keep records between 2005 and 2015 and combine industrial and non-industrial reconstructed catch at the taxa-level. We then combine these data with the corresponding taxa-specific price data described above. Price data are not available for all species included in the reconstructed catch data set. We therefore perform a series of hierarchical matching steps based on taxonomy. We first attempt to match at the species-level, then by genus, then family and order, and finally class. The remaining groups are matched on the basis of ISCAAP groups.

Combining catch and price data allows us to calculate the cell- and species-specific annual fisheries revenue as the product of catch of species *j* at time *t* and grid cell *i* (c_{jti}) and unit prices of species *j* at time *t* (P_{jt}). We then calculate median historical revenue of each cell to produce a spatially-explicit measure of fisheries revenue *R* for patch *i*:

$$R_i = \text{median}\left(\sum_{j=1}^{J} P_{jt} c_{jti}\right)$$

The resulting gridded data are shown in in Fig S2.

Vector data sets

To construct national conservation supply curves, we must be able to assign jurisdiction to each grid cell described above. And to simulate bubble policies (more details below), we must also assign each grid cell to a hemisphere, realm, province, and ecoregion.

Exclusive Economic Zones - We assign national jurisdiction based on V11 of the "Maritime Boundaries and Exclusive Economic Zones" produced by the Flanders Marine Institute (20). We define "nation" as the nation state indicated by the standard 3-letter code of the territory for each polygon in the data set. When territory data were missing for a polygon, we used sovereign attribute instead. We also excluded polygons of overlapping claims (N = 30 polygons) and joint regimes (N = 20 polygons). We also remove the polygon around Antarctica.

Biogeographic regionalization - We used Spalding's biogeographic regionalization, which divides the world into a hierarchical system of 12 realms, 62 provinces, and 232 ecoregions (14). Not all of these intersect with national boundaries, so we performed a spatial intersection between the EEZ and Biogeographic region polygons and excluded biogeographic regions that occur outside of national boundaries considered (n = 13 Ecoregions). Similarly, we remove nations with Exclusive Economic Zones that do not overlap marine Ecoregions (Azerbaijan, Turkmenistan, and Kazakhstan in the Caspian Sea).

Existing Marine Protected Areas - Finally, we attempt to account for areas that have already been protected to deal with the issue of non-additionality. We use Marine Protected Area (MPA) boundaries from MPAatlas as of December 23, 2022 (mpaatlas.org) and retain only strongly-protected areas as defined by IUCN protected area management categories, which classify areas based on their management objectives. We retain polygons belonging to categories Ia (Strict nature reserve), Ib (Wilderness area), and II (National park). While they have slight differences in their objectives, these are the three most stringent categories and seek to conserve a "particular natural feature" or "whole ecosystem and ecosystem processes" (21). The resulting data set contains 2,866 spatial features attributed to 97 nations. All vector data were rasterized onto a 0.5 x 0.5 degree; partially protected cells are assumed to not be protected and cells with less than

50% covered by any EEZ were excluded from the analysis due to the working resolution (8 grid cells).

Building conservation supply curves

We divide the ocean's surface into individual units using a standard 0.5x0.5 degree grid (about 55 x 55 km at the equator); a resolution for which data are readily available, balances computational feasibility with the scale of interventions, and is comparable to that used in other global marine conservation studies (e.g. 7, 9, 22). We then use this grid to compute the costs and benefits for each grid cell occurring within nations' Exclusive Economic Zones as described below.

We define conservation benefits in line with Aichi target 11 in the Convention on Biological Diversity, which measures progress in marine conservation with area-based metrics (e.g. km^2 protected) but incorporates the principle of protecting areas of particular importance for biodiversity. For example, the indicator for tracking progress is described as "*Trends in representative coverage of protected areas including sites of particular importance for biodiversity"* (2). If the area of grid cell *i* is α_i (in km^2), our measure of conservation benefit produced by protecting that cell is given by $Q_i = \alpha_i HSI_i$ (HSI-weighted area). We can colloquially think of Q_i as the "conservation benefit" of protecting suitable habitat in grid cell *i*. This formulation captures how suitable a grid cell is based on abiotic characteristics that are not affected by protection status of the grid cell or any adjacent grid cells. It also implies that conservation benefits of grid cells are independent of protection status of other grid cells. We calculate Q_i for all grid cells that occur within the Exclusive Economic Zone of the coastal nations identified above (See Fig S3). We later perform additional analysis where the unit of conservation is simply km^2 (Figure S18, Table S1).

We also need a measure of the cost of conservation. In principle we would like to reflect the opposition a nation may face when protecting pixel *i* vs. pixel *j*. Because this opposition most frequently comes from the fishing sector (7, 23, 24), we would like a measure of the opportunity cost of closing any given pixel to fishing, although we note that mining and energy are other relevant sectors. Candidate measures are catch, fishery revenue or fishery profit in pixel *i*. The former two are likely more appropriate in settings where concerns over food security, raw landings, and fishing income prevail and have been used elsewhere in the literature (9). The latter measure nets out fishing cost so may better reflect opportunity cost in industrial settings. We further note that if fishing cost is a constant fraction of revenue, then the two measures imply the same percentage reduction in conservation costs from adoption of a market (25). Thus, we use fishing revenue in pixel *i* as a measure of the opportunity cost of closing pixel *i* to fishing. We create a spatially explicit data set of median fisheries revenue (between 2000 and 2015) by combining high-resolution spatio-temporal data on fisheries catch (11) and ex-vessel prices (12) at the same level of aggregation as our derivation of Q_i above (Figure S2).

We combine the spatial layers of conservation benefits and costs to build conservation supply curves. We first calculate the per-unit cost of conservation benefit for each grid cell by taking the ratio of benefits to costs (Figure S4), and then rank all grid cells within a nation in ascending order of marginal cost. The same process is done for the bubble policies described in the next section. We account for MPAs that are already in place and adjust the conservation supply curves by excluding grid cells that occur within strongly protected areas as described earlier. The conservation benefit produced by those MPAs is taken into account, but they are excluded from the market. This implies that nations that have already met their conservation target by protecting *in situ* are not required to protect any additional units, but are allowed to produce additional conservation by selling conservation credits to other nations. Our supplementary materials also include two robustness checks: one assuming no MPAs have been implemented at all, and one where the cost of protecting the habitat inside them is exactly 0. The resulting national conservation supply curves are the first contribution of our paper, and are shown in Figure S5-S8 (ecoregion supply curves not shown due to space).

Inducing habitat representation

A single global market could inadvertently agglomerate conservation of one habitat and fail to protect others. To meet the principle of "habitat representation" (2), we can impose additional constraints on market trading. In other environmental markets, this has been achieved by delineating spatially distinct regions, or ``bubbles'', as they are referred to in air quality markets (13). Three rules dictate trade under a bubble policy: 1) a nation holds rights (and conservation obligations) to a bubble if their Exclusive Economic Zone spatially intersects it; 2) nations only participate in markets in which they hold rights; and 3) trade is allowed only within bubbles, never between them. We examine the consequences of four alternative bubble policies (Figure S9) that divide the oceans on the basis of geographic hemispheres (4 bubbles) or biogeographic regions (14), thus dividing the world into ecologically coherent bubbles defined by realms (12 bubbles), provinces (60 bubbles), and ecoregions (219 bubbles).

Estimating the gains from trade

We define the gains from trade as the ratio of the costs avoided due to trade to the total costs under uniform conservation obligations:

$$G_t = \frac{TC_t^{bau} - TC_t^{mkt}}{TC_t^{bau}}$$

Where the sub-index t indicates a given conservation target (t is between 10% and 100%), the hyperindices indicate the business-as-usual (*bau*) approach of uniform conservation requirements and the market-based approach (*mkt*). Further detail on how to calculate TC_t^{bau} and TC_t^{mkt} is provided below.

Our analysis uses a 0.5x0.5 degree grid so it is possible that conserving the entirety of the n^{th} pixel would result in more conservation than otherwise required, or that avoiding conservation of said pixel would preclude the nation form meeting its target. For example, how should a small nation with only two identical pixels attain a 10% conservation target? We can allow fractional protection of the n^{th} pixel. In this case, protecting 20% of one of the two identical pixels would attain the conservation target. The fraction f of the n^{th} pixel that must be protected is given by:

$$f_i = 1 - \left[\frac{B - \left(\frac{tB}{p}\right)}{b_i}\right]$$

Where B are the total benefits attained by conserving all pixels leading up to and including pixel i, t is the conservation target, p is the fraction of total conservation benefits attained up to and including pixel i, and b_i is the conservation benefit of protecting pixel i entirely (So $\mathrm{B} - \frac{\mathrm{tB}}{\mathrm{p}}$ denotes the excess conservation benefit that would be produced if the entirety of n^{th} cell were protected). We assume that pixel characteristics are homogeneous within the pixel, so costs, benefits, and area protected of the pixel are adjusted accordingly. All other pixels leading up to the n^{th} are entirely protected.

Calculating TC_t^{bau} - For a given conservation target t and bubble policy, the total cost to each nation is simply the sum of the cost of protecting all grid cells required to meet the conservation target, accounting for fractional pixels as outlined above. Then, the total cost of imposing uniform conservation targets is simply the sum of the costs to each individual nation. Our supplementary text provides a graphical depiction of this in Figure S1.

Calculating TC_t^{mkt} - Under uniform conservation mandates, every nation must conserve up to t. This is no longer true under a market, and we must therefore identify how much conservation each nation produces within its waters. To do this, we start by horizontally summing across national conservation supply curves (within each bubble), and then find the marginal cost of protecting the t^{th} unit in this aggregate supply curve, which is known as the market clearing price. We then return to the nation-bubble specific conservation supply curves and find the point at which each supply curve intersects the market clearing price. The corresponding value of t is then the amount of *in situ* conservation produced by each nation, call this t_{mkt}. Like before, the total costs to each nation are the sum of all grid cells that are between 0 (or however much conservation has already been produced) and t_{mkt}. The total cost of meeting conservation targets under trade is simply the sum of the costs to each individual nation. Additionally, we can calculate the nation-specific gains from trade as the difference between their costs under each policy, as shown in Figure S1.

All data and code are available on GitHub at: github.com/jcvdav/transferable_conservation

Supplementary Text

Leveraging heterogeneity to reduce costs

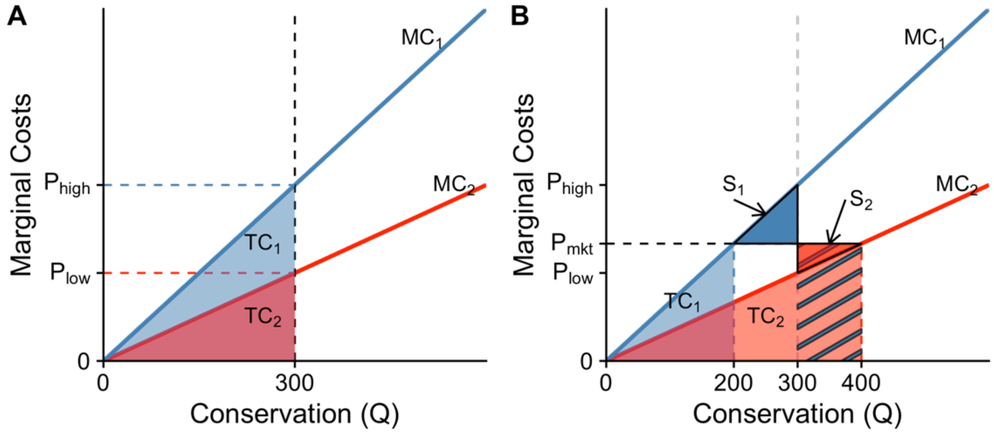

Fig. S1.

Stylized conservation supply curves and conservation outcomes under uniform conservation obligations (A) and trade-enabled conservation (B). Both scenarios produce the same amount of conservation. In panel B), the solid triangles labeled S_1 and S_2 indicate the savings to each nations under a market. The hashed area shows the transfer between nations.

The figure above shows the marginal cost of providing conservation in two nations that each initially produce 300 units of conservation (for example, this might be 300 km^2 of marine protection). Each curve indicates the change in total cost that arises from producing one additional unit of conservation (i.e. the marginal cost). While the first few units of conservation are similarly cheap for both nations, each additional unit of conservation is more expensive to provide in Nation 1 (blue) than in Nation 2 (red). The 300th unit of conservation in 1 costs P_{high}, but only costs P_{low} in Nation 2. Together, the two nations produce 600 units of conservation at an aggregate cost of uniform conservation $TC_{uni} = TC_1 + TC_2$ (where TC_1 is the blue shaded area under MC_1 and TC_2 is the red shaded area under MC_2, between 0 and 300). The fact that MC_1 (300) $\neq MC_2$(300) guarantees that there is a more cost-effective way to attain the same level of conservation.

These marginal cost curves can be interpreted as the nations' conservation supply curves (26) and indicate the amount of conservation a nation is willing to produce for a given price. Panel B shows the conservation outcome when both nations engage in trade. For a price P_{mkt}, Nation 1 would conserve 200 units in its waters, and then pay Nation 2 to conserve an extra 100 units in its name (shown in red-blue hashed area). Nation 2 now conserves 400 units of its marine territory. As in the case of uniform conservation obligations, this outcome also produces 600 units of conservation. However, Nation 1 avoids the high costs of conserving at prices between P_{mkt} and P_{high}, and Nation 2 is paid to protect in the name of Nation 1. The market gains for this transaction are $S_1 + S_2$.

As shown here, the main allure of trade is that it can lower the costs of conservation to all nations. Buyers of conservation credits benefit from trade because it lowers their cost of compliance, and sellers benefit from trade because the selling price more-than-offsets the cost of their additional conservation (because $P_{mkt} > P_{low}$, for all units below 400). Allowing trade in this way will always reduce costs to all parties if costs and benefits are not perfectly correlated and if the ratio of costs to benefits is heterogeneously distributed between nations.

Robustness checks

Robustness check 1: Use full set of species from AquaMaps - In our main text calculations we calculated HSI_i after removing species with less than ten records. Here, we include the entire AquaMaps data and re-compute the HSI_i. We find that removing these species has little effect on the resulting Habitat Suitability Index (Figure S17A-B) or it's spatial distribution (Figure 17C), even when most species filtered are found in the tropics. At the most extreme, removing species with less than ten records excludes 50% of species (21 pixels with 1 instead of 2 species; Figure S17D).

Robustness check 2: A different unit of conservation - Our analysis assumes that all nations have agreed upon a clearly defined unit with which to measure conservation benefits: the extent of an area weighted by its habitat suitability index. However, despite of much opposition by the scientific community (27, 28), most conservation agreements use area-based targets, where progress in conservation is measured by the extent (typically in km^2) of marine habitat covered by MPAs and other area-based conservation measures. We now repeat our calculations using km^2 as a measure of progress in conservation (although we restrict habitat to pixels with $HSI_i \geq 0.5$). For example, for a 30% target, nations are required to protect 30% of suitable marine habitat regardless of its *HSI*. We find that when an area-based target is used (shown as *ABT*), the gains from trade are still large and follow our main findings. Under an area-based target and a 30% goal, between 36.9 and 98.7 of costs can be avoided (See ABT under Gains from Trade in Table S1). Note that when an area-based target is used, the total amount of conservation benefit is not held constant. Using an area-based target but quantifying the benefits based on HSI-weighted area, we find that these ranges between -0.09% and 0.75% of what would be achieved using the HSI-based measure. Figure S18 then shows that the general conclusions hold across different conservation targets and bubble policies when we define conservation benefits using area-based targets.

Robustness check 3: Other ways of accounting for existing MPAs - Under BAU, our main-text calculation assumed that when a conservation-minded nation had already met or exceeded its target its costs of attaining the set target are zero. This follows the strict interpretation that “each nation must protect X%”. For some targets and bubble policies considered in our analysis, it is possible that the amount of conservation benefit produced under BAU exceeds the target (and the conservation benefit produced under a market). This is due to the strict interpretation of uniform conservation requirements under BAU, where all nations must meet the target even if some nations exceed the target. We believe this is the agreed-upon interpretation of unilateral requirements: every nation is required to protect X%, even if some nations produce a surplus of conservation benefits in their waters. How much of the gains from trade are attributable to the surplus conservation that may result from this interpretation? In the following sections we 1) quantify the cost of this interpretation, and 2) perform two robustness checks that relax this assumption. In all cases, we show that the vast majority of the gains from trade arise thanks to the allocative efficiency of the market, and not due to the resulting surplus conservation.

The first step is to quantify the additional amount of conservation, if any, produced in a BAU scenario relative to a market. These calculations are shown in Figure S19A, which shows the surplus of conservation benefits produced under BAU, relative to the total conservation benefits produced under a market. The maximum relative surplus (less than 4% relative to the market scenario) is observed for a 10% conservation target because many nations have already protected *more* than 10%, but other nations still need to attain this target (Note that this is only a surplus of 4% of a 10% target). The surplus quickly decreases as the global target increases to values well-above what any nation has already conserved. Importantly, note that for our headline 30% target, the surplus conservation is only present in the ecoregion bubble policy (at a 0.086% surplus relative to market) because this is the only bubble policy in which some bubbles have exceeded the 30% target (The Torres Strait Northern Great Barrier Reef at 43.9% and Revillagigedos at 33.4%). For a 30% target, there is no surplus conservation for Global, Hemishpere, Realm, and Province bubble policies. Our main text results remain unchanged.

But what are the costs of this surplus? It is not possible to identify which pixels in each country would not have been protected due to the interpretation of BAU requirements. We quantify the costs of all surplus based on the market clearing price (highest marginal cost attained under a market) as a lower bound, and the median marginal cost of all units across all nations in each bubble as an upper bound. The results are shown in Figure S19B, which shows that up to 5% of the gains from trade arise due to surplus conservation for a 10% target. These costs are negligible or 0 when looking at the 30% target referenced in our main text. Another alternative is to relax our interpretation of the BAU uniform conservation requirements and re-estimate the gains from trade, which is done below.

Alternative 1: A world with no MPAs - We now assume that no MPAs have been implemented, so we don't remove pixels that are currently placed within an MPA from the conservation supply curves. We then proceed as outlined above and build new conservation supply curves, simulate the conservation outcomes under BAU and trade, and calculate the gains from trade. The results are shown in Figure S20. In this world without MPAs the total benefits under BAU and MKT are always identical: there is no conservation surplus under any bubble policy or any target. For the main estimates of our 30% scenario, we find that allowing trade in a world with no MPAs would still yield large gains from trade. Under a 30% target, a Global market would avoid 98.5% of the costs, compared with 98.6% in our main text. The Hemisphere bubble policy would see gains of 97.4% instead of 97.5% from the main text. When segmenting the market into Realms, Provinces, and Ecoregions the gains are similar to the ones in the main text: 97.3% (down from 97.5%), 76.2% (from 76.7%) and 36.3% (from 37.2%), respectively. This scenario implicitly assumes that MPAs have not been implemented, or that the global network of MPAs has been dissolved or downgraded. Because the marginal costs of habitat within MPAs are now determined by historical fishing revenue, it is possible that some currently protected pixels are no longer protected in our simulations. The next alternative addresses this.

Alternative 2: The marginal cost of conserving habitat within MPA boundaries is 0 - We now assume that the costs of conserving habitat within MPAs is 0. This means that, as nations work toward a target, they will always begin by protecting pixels within MPAs. In this case, conservation supply curves are built in the same way as before, but the conservation benefit is used to break ties between pixels with equal marginal costs (because all grid cells within MPAs have equal marginal costs). As before, this alternative ignores any conservation benefits that nations have already produced, but allows nations to construct conserve in a way that aligns with the current state of the world (because, regardless of target, habitat within MPAs will always be the cheapest to protect under market and BAU). In this case there is no surplus of conservation, but any habitat that exceeds a conservation target is not protected (so, some areas that are currently protected would not be in this simulation). The results for this exercise are shown in Figure S21. As before, the gains from trade are large across all targets and bubble policies implemented, and the total benefits are identical between BAU and MKT for all targets. For the relevant case of 30%, we find that the gains from trade in the Global, Hemisphere, Realm and Province bubble policies are the same as in the main text. For the Ecoregion bubble policy (where to ecoregions had exceeded the target) the gains from trade are 37.237%, which are similar to what we report in our main text (37.236%).

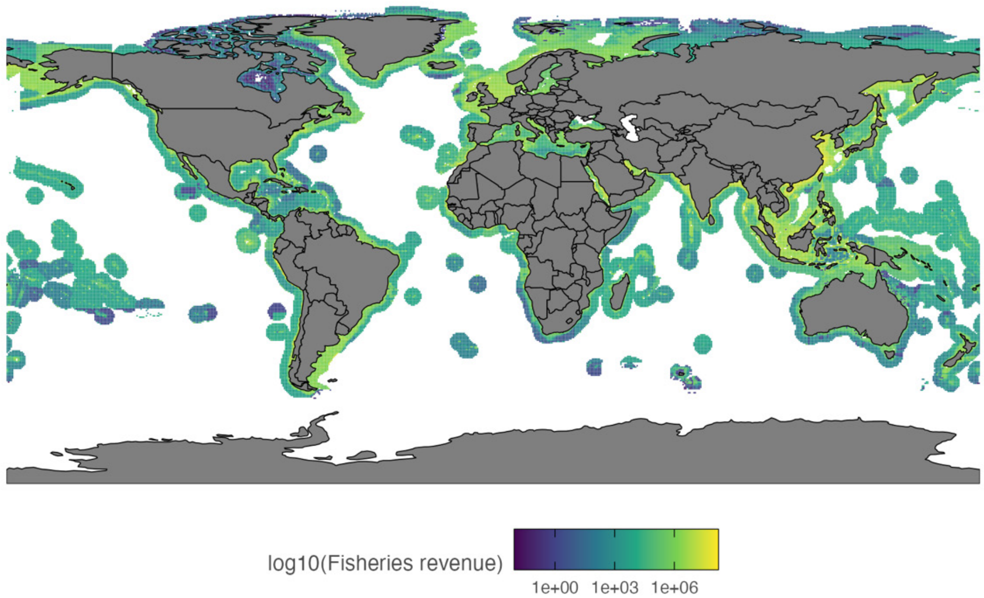

Fig. S2.
Map of median fisheries revenue (M USD; 2005 - 2015). Note that color scale has been log10-transformed for visualization.

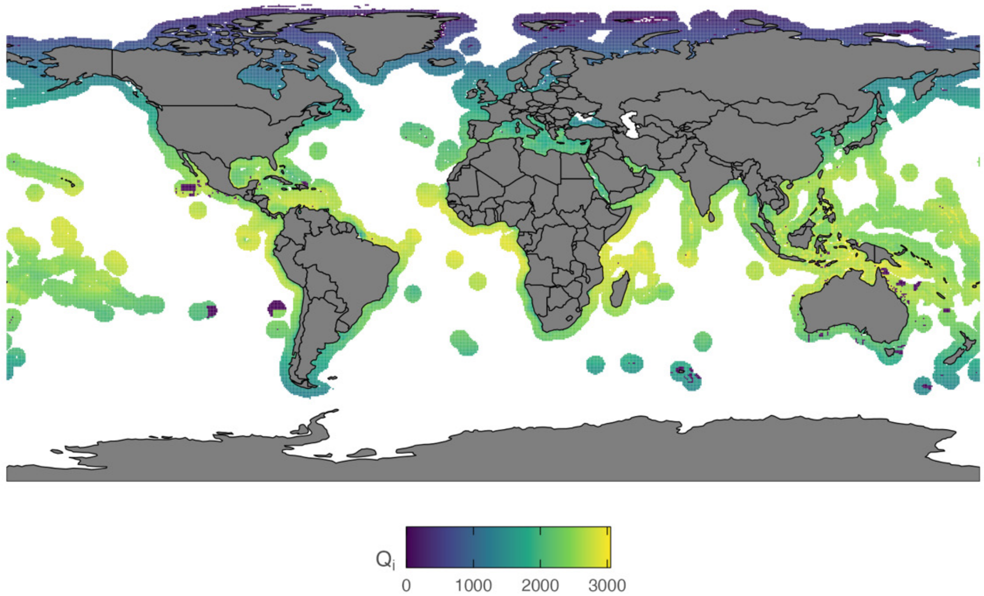

Fig. S3.

Map of conservation benefit ($Q_i = HSI_i \times \alpha_i$) that each grid cell can produce when protected. HSI is the habitat suitability index and alpha is the area of each grid cell.

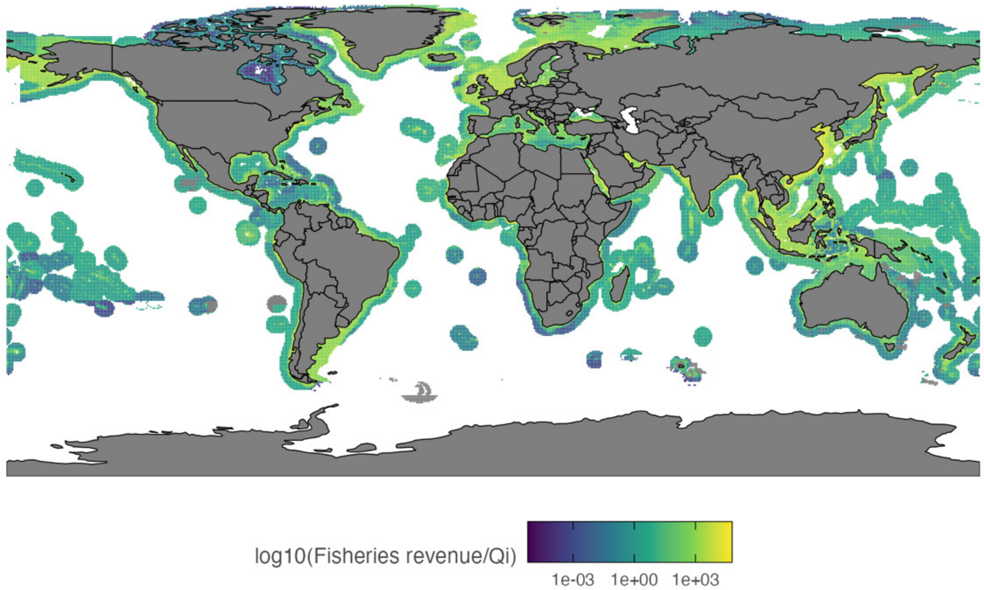

Fig. S4.
Map of marginal cost of conservation for every grid cell that occurs within national boundaries. Note that the color bar has been log-10 transformed to aid in visualization.

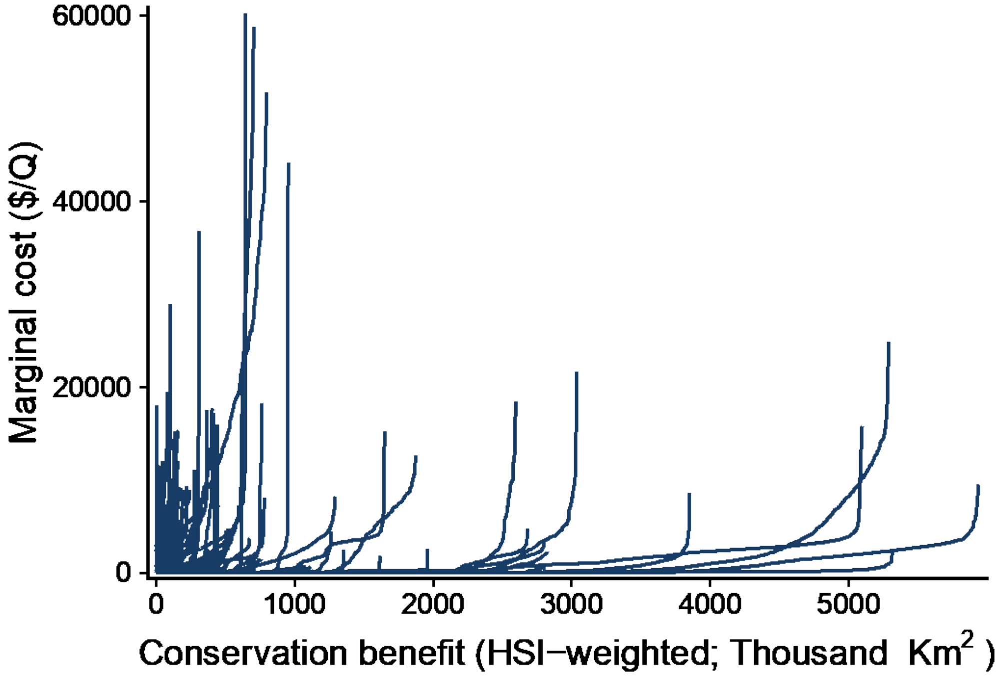

Fig. S5.

National conservation supply curves for coastal nations. The x-axis shows the total conservation benefit, the y-axis shows the marginal costs of attaining them, and each line represents a coastal nation. Note the variation in the relationship between conservation benefits and marginal costs of conserving across nations. Q is the conservation benefit. HSI is the abbreviation for the Habitat Suitability Index.

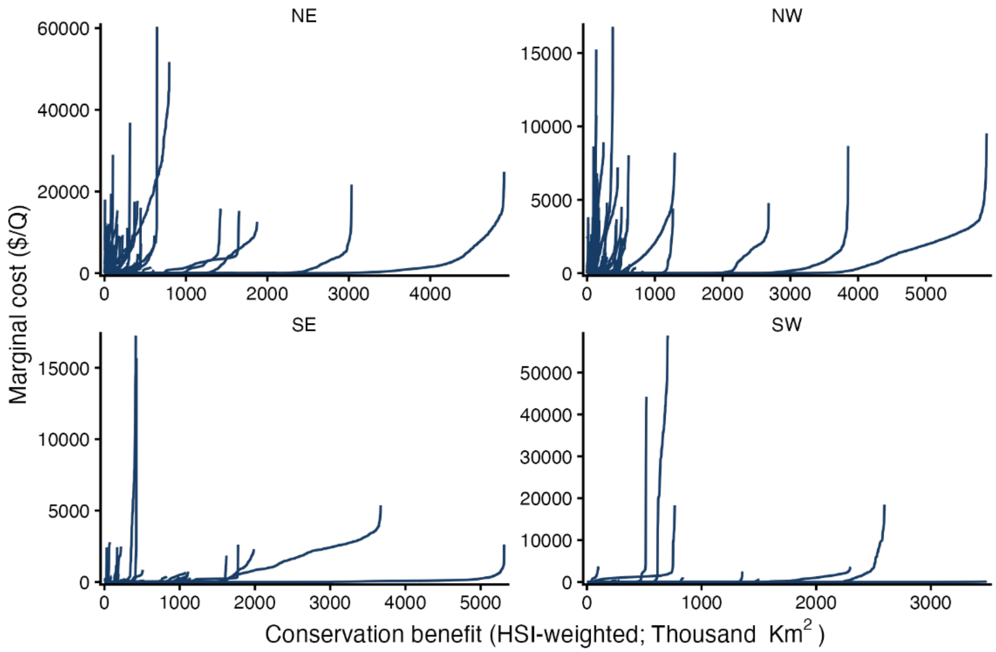

Fig. S6.

Conservation supply curves for nations across four Hemispheres (NE: North east, NW: North west, SE: South east, SW: South west). Q is the conservation benefit. HSI is the abbreviation for the Habitat Suitability Index

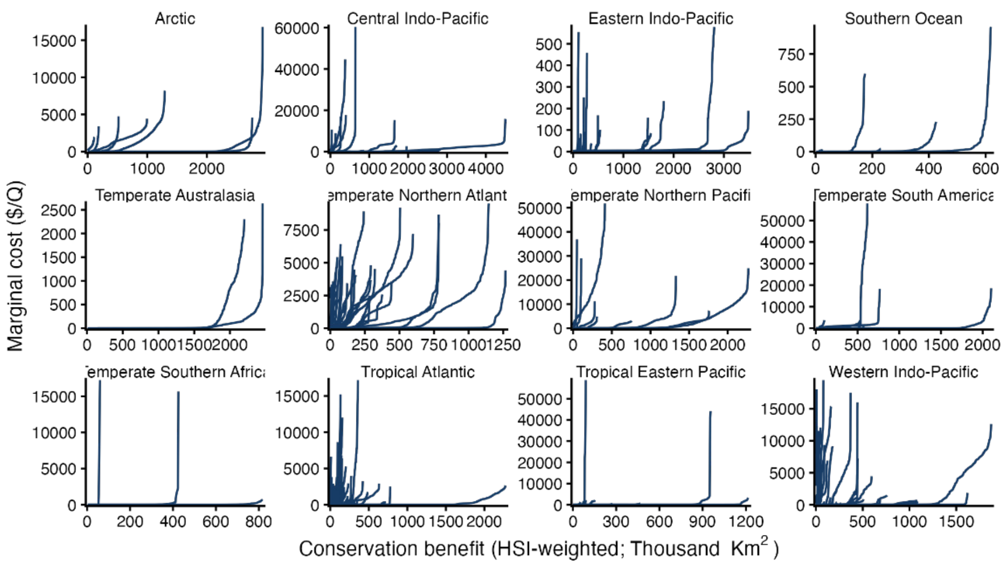

Fig. S7.

Conservation supply curves for nations across 12 biogeographic Realms. Q is the conservation benefit. HSI is the abbreviation for the Habitat Suitability Index.

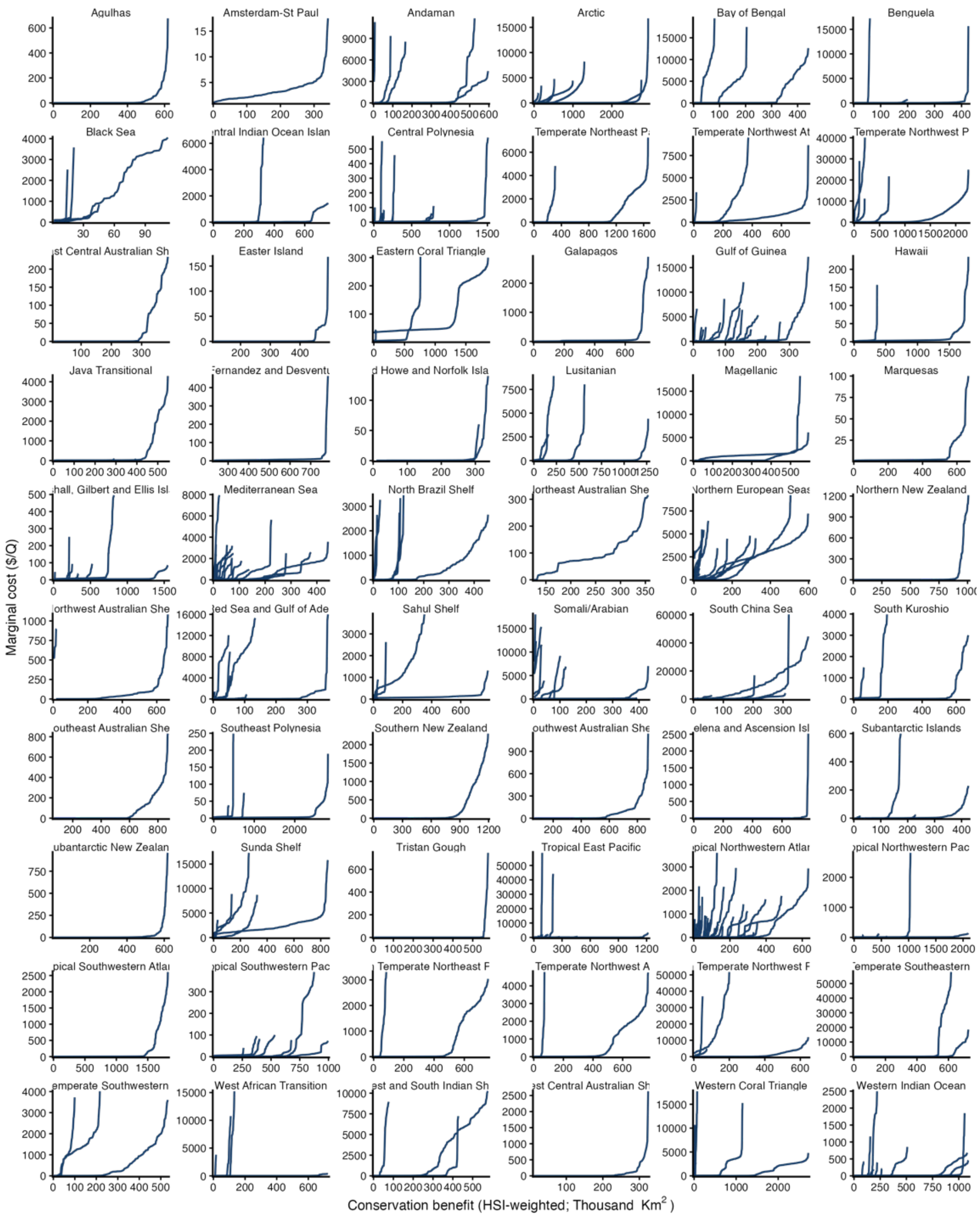

Fig. S8.

Conservation supply curves for nations across 60 biogeographic provinces. HSI is the abbreviation for the Habitat Suitability Index.

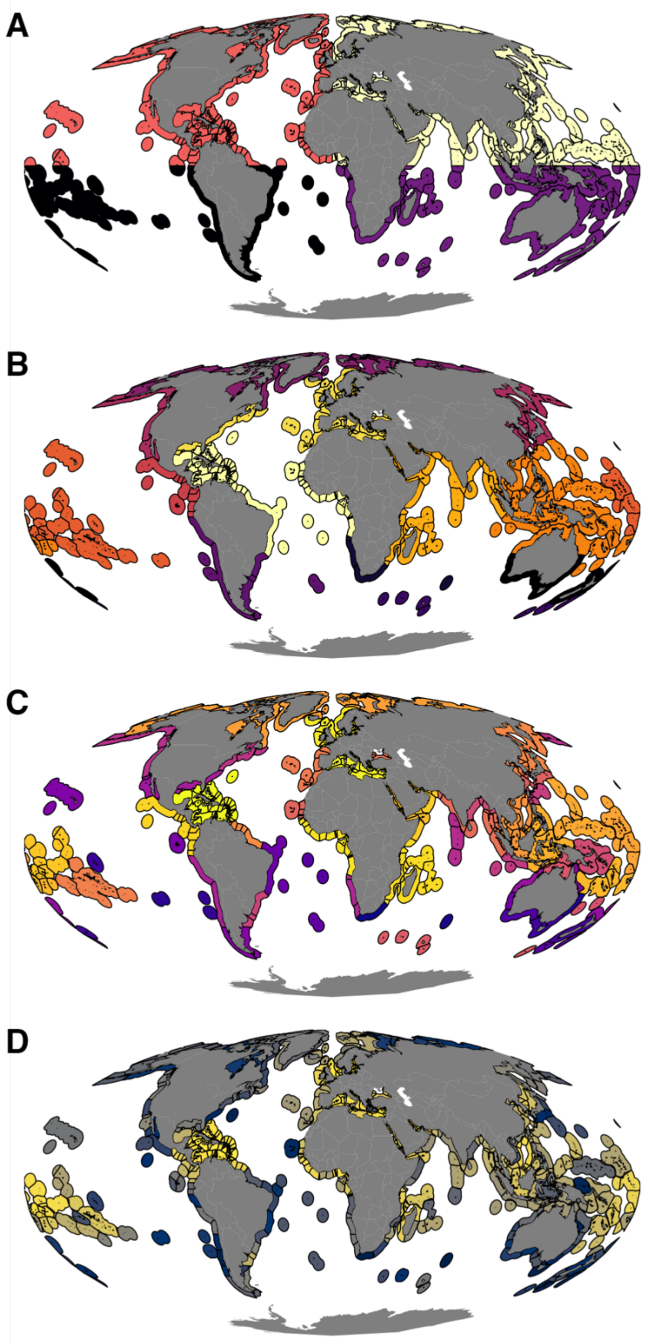

Fig. S9.

Spatial representation of the four bubble policies. Each subplot shows the exclusive economic zones (EEZs) of all coastal nations (lines) intersected with a bubble policy (colors). For example, panel A) shows EEZs in one of four colors, one for each intersection of Hemispheres and EEZs. Panel B) shows 12 colors, one for each biogeographic Realm, based on Spalding's biogeographic regionalization (14). Panel C) then shows 60 colors to indicate the sub-division of realms into 60 Provinces. Finally, panel D) shows the division of the world into 219 Ecoregions, and thus contains 219 colors.

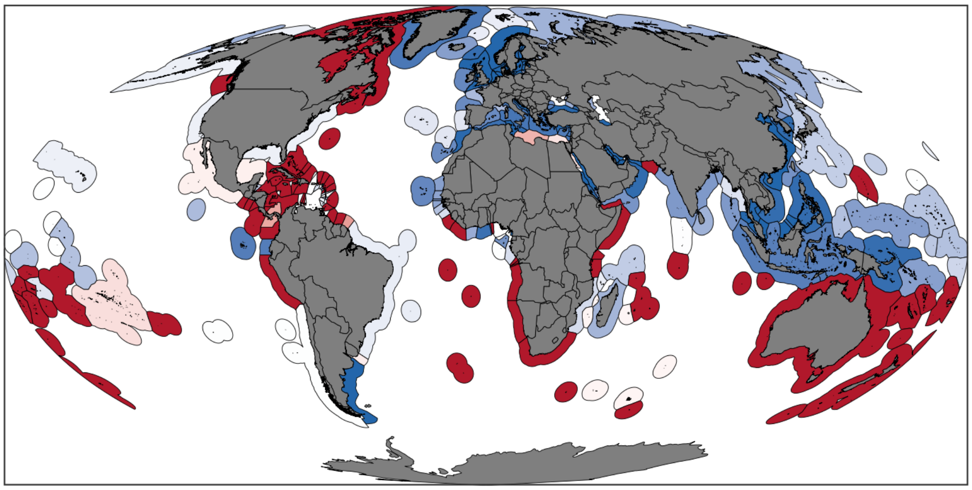

Fig. S10.
Outcome of trade under a global market for 30x30. The Exclusive Economic Zone of each nation is colored to indicate whether a nation avoids costs by buying (blue) or is paid for conserving in other nation's name (red), and the hue indicates the magnitude of the gains from trade relative to the total costs incurred by each nation under the business-as-usual scenario.

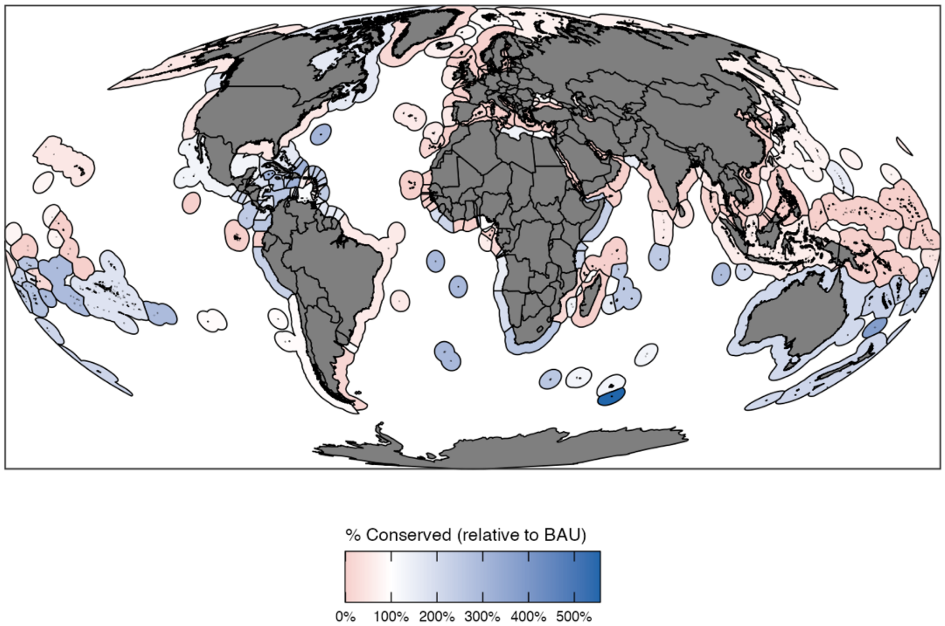

Fig. S11.
Change in within-nation conservation under a market relative to BAU, using a global bubble policy and a 30% target. Colors trending towards red are nations that conserve less area within its waters under a market and nations in blue are those who conserve more than they would have otherwise.

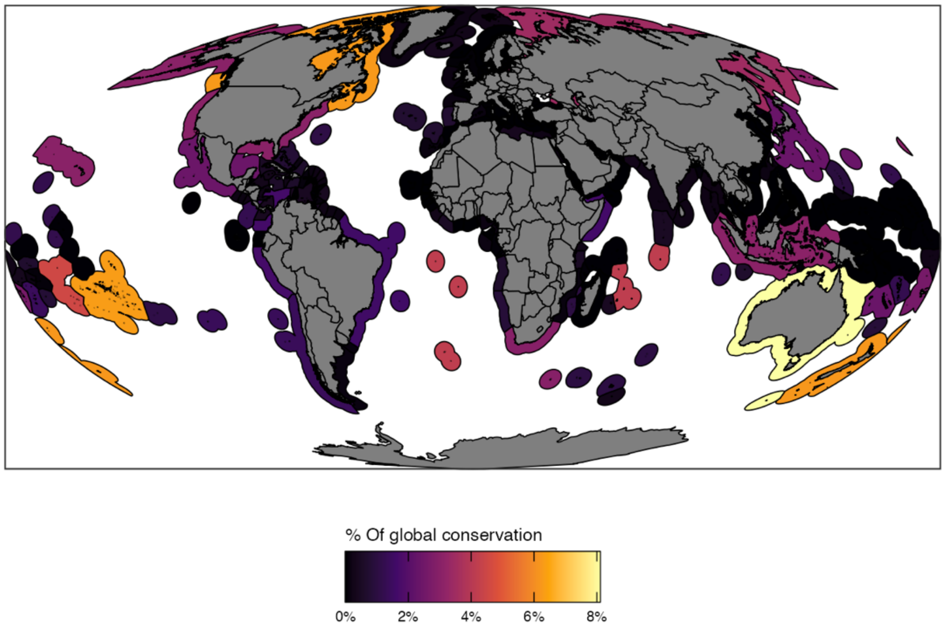

Fig. S12.
National contributions to global conservation under a global bubble policy and a 30% target. Colors indicate conservation produced within each nation relative to the aggregate amount of conservation in the world. Nations in black are the nations that don't conserve any habitat in their waters. Nations in pale yellow are the ones that produce the most conservation within their waters.

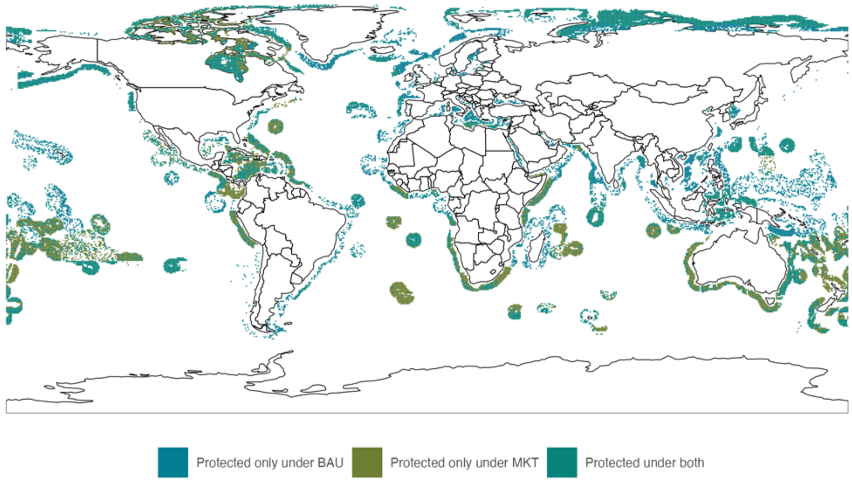

Fig. S13.
A market-based approach relocates some protection. Colors on the map indicate whether a grid cell is protected regardless of strategy (N = 9,996), protected only under uniform conservation requirements (N = 5,963), or protected only under a market (N = 5,526).

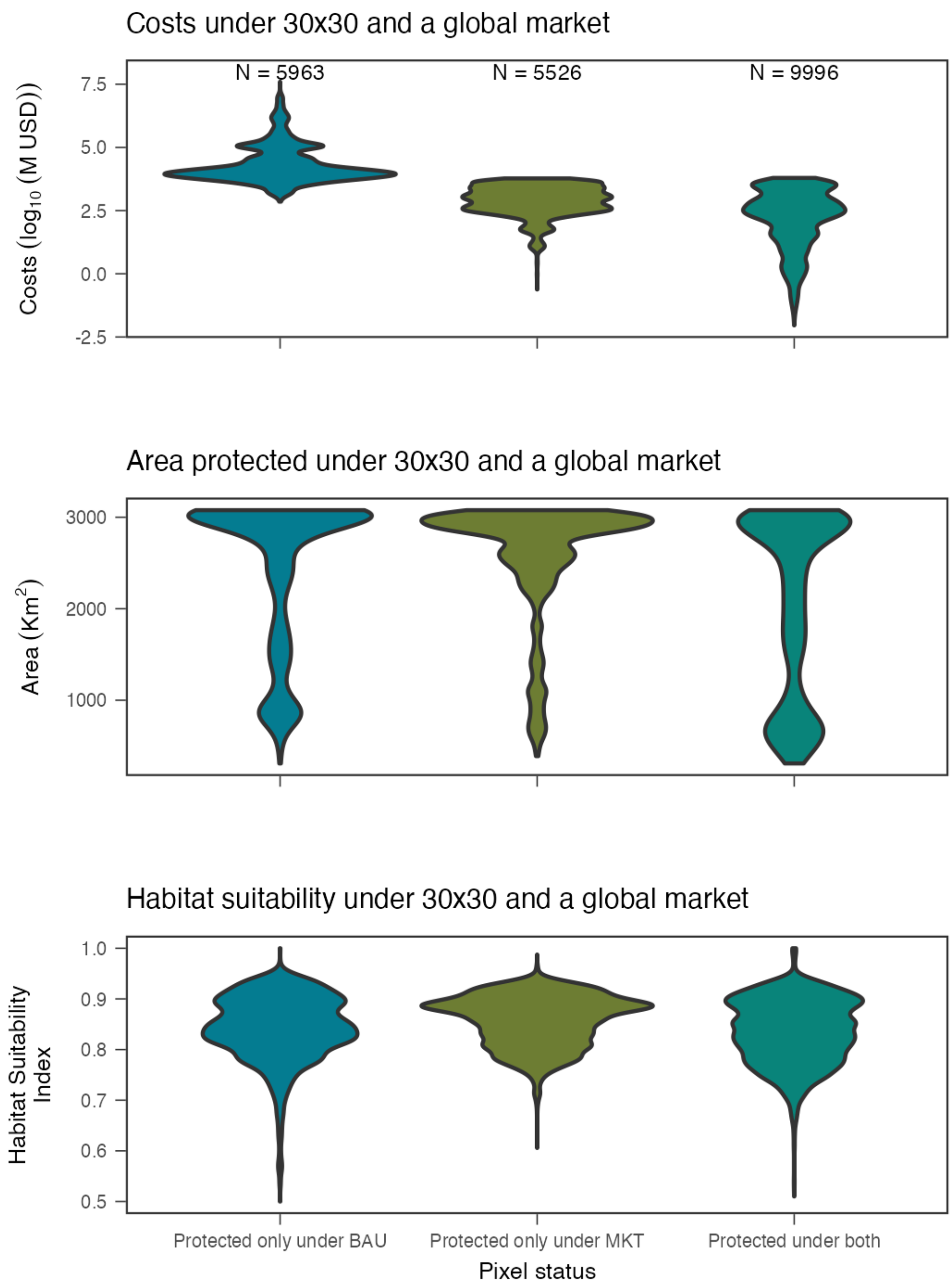

Fig. S14.

Allocative efficiency of a global market for marine conservation under a 30% protection target. Each panel shows a violin plot of the distribution of costs (top), area (middle), and habitat suitability index (bottom) across grid cells protected under uniform conservation (BAU), the market-based approach (MKT), or both scenarios. The numbers at the top indicate the number of grid cells protected only under uniform conservation requirements (N = 5,963, protected only under a market (N = 5,526), or protected regardless of strategy (N = 9,996).

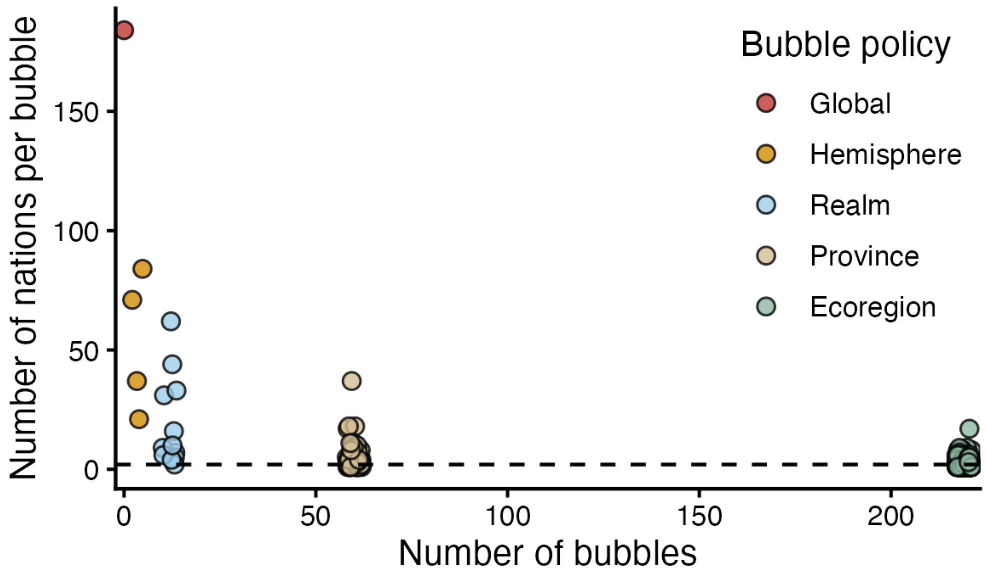

Fig. S15.

Segmenting the market limits the set of potential trading partners. The x-axis shows the number of bubbles created by each bubble policy (colors). The y-axis shows the number of nations within each bubble; one nation may be present in more than one bubble. Points are horizontally jittered by 2 units for visualization purposes. The horizontal dashed line intersects the y-axis at 2, the minimum number of nations required for trade.

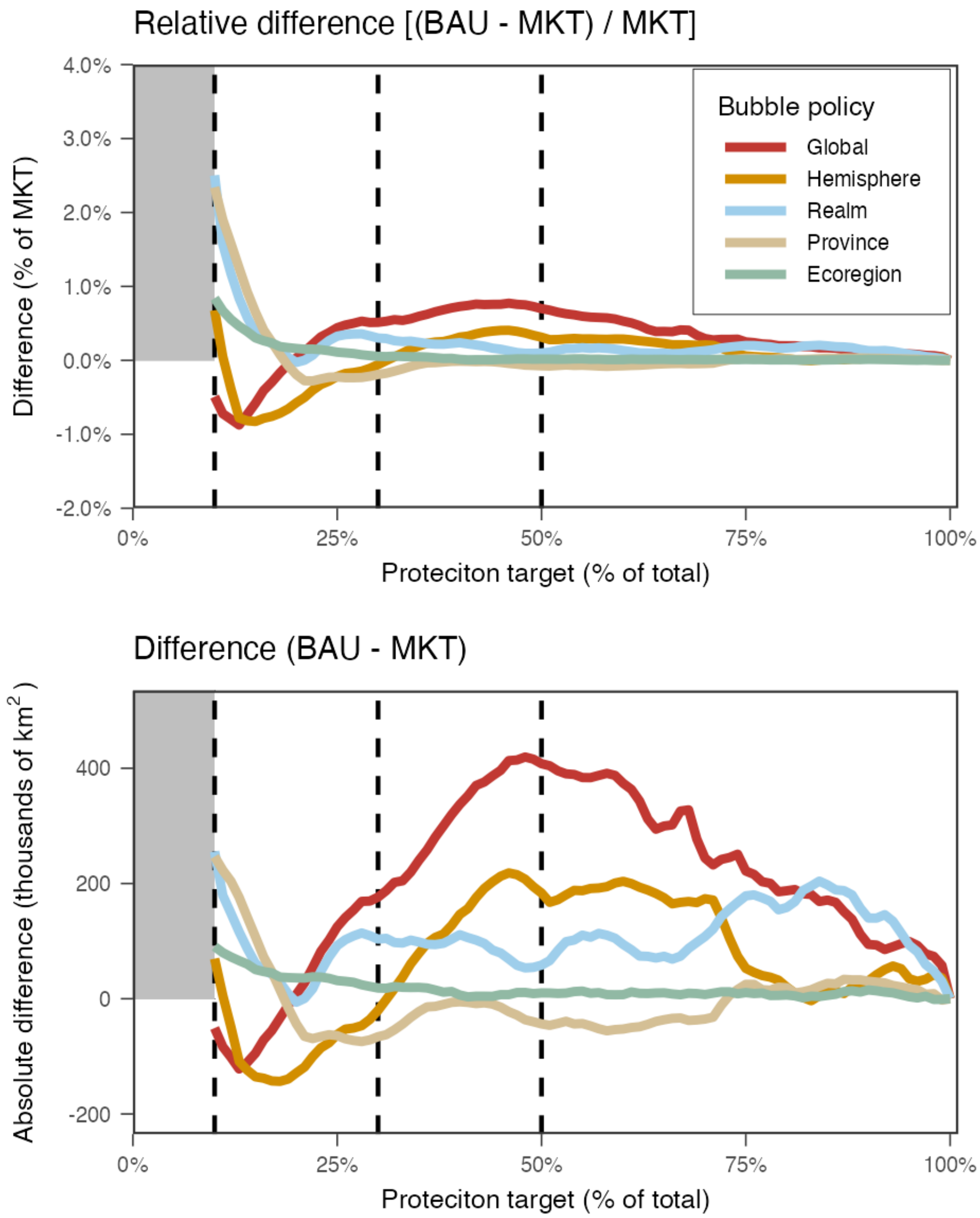

Fig. S16.
Differences in surface area (y-axis) needed to meet a given conservation target (x-axis) across four bubble policies. The top panel shows the relative differences, the bottom panel shows absolute differences.

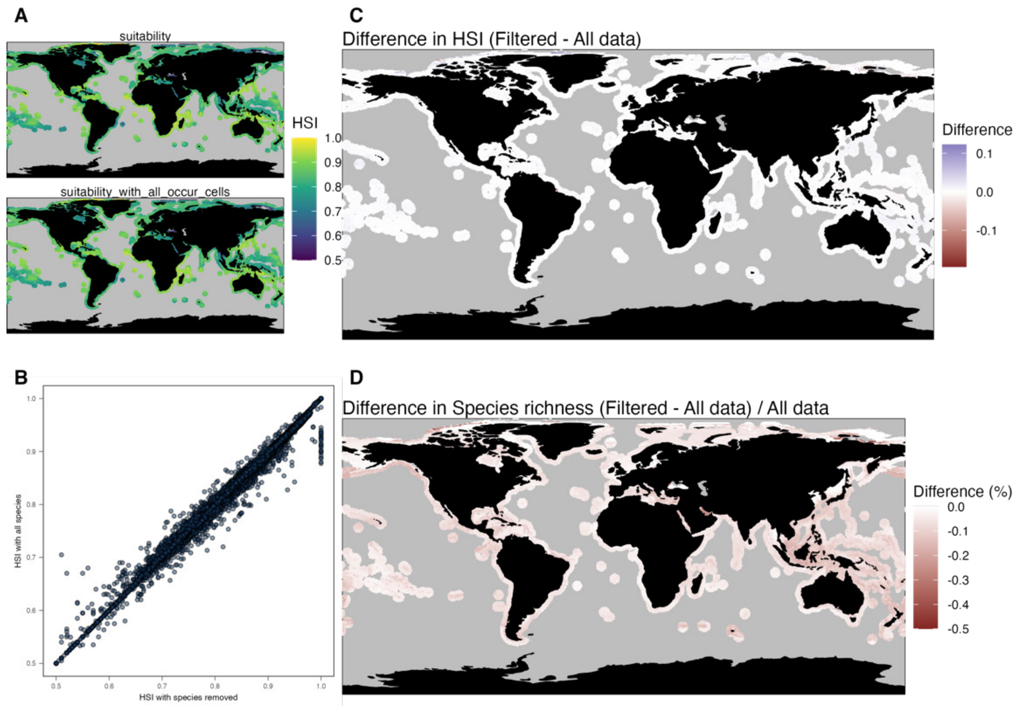

Fig. S17.

Comparison of HSI with and without removing species with less than 10 records. Panel A) shows a map of HSI with and without filtering species. Panel B) shows a pixel-wise scatterplot of the HSI that results from filtering species (x-axis) vs using the entire data set (y-axis). Panel C then shows a map of the difference in HSI (main text HSI minus HSI with all species). Finally, panel D shows the relative change in species richness.

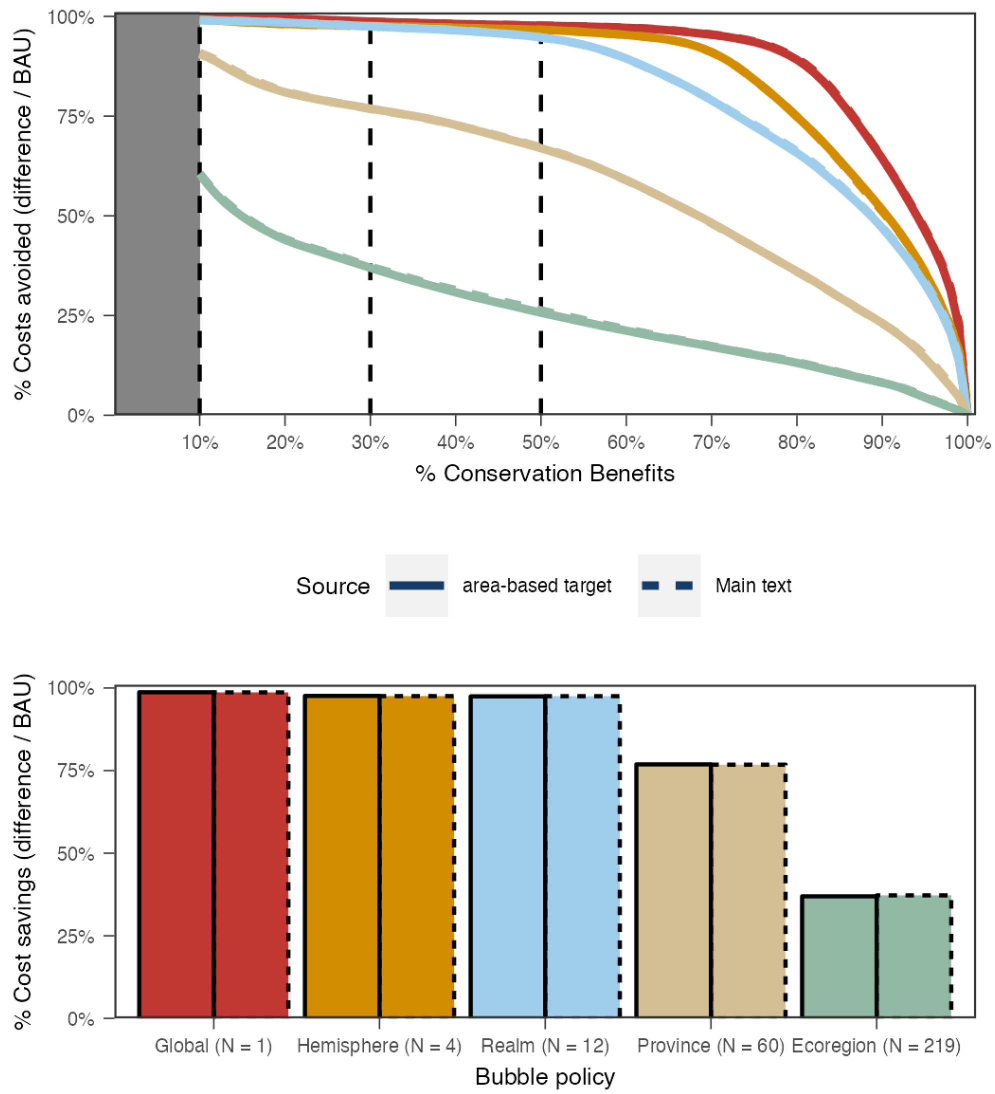

Fig. S18.

Gains from trade under area-based targets. Top panel shows gains from trade across bubble policies for multiple scenarios. Bottom panel shows gains from trade by bubble policy under 30x30.

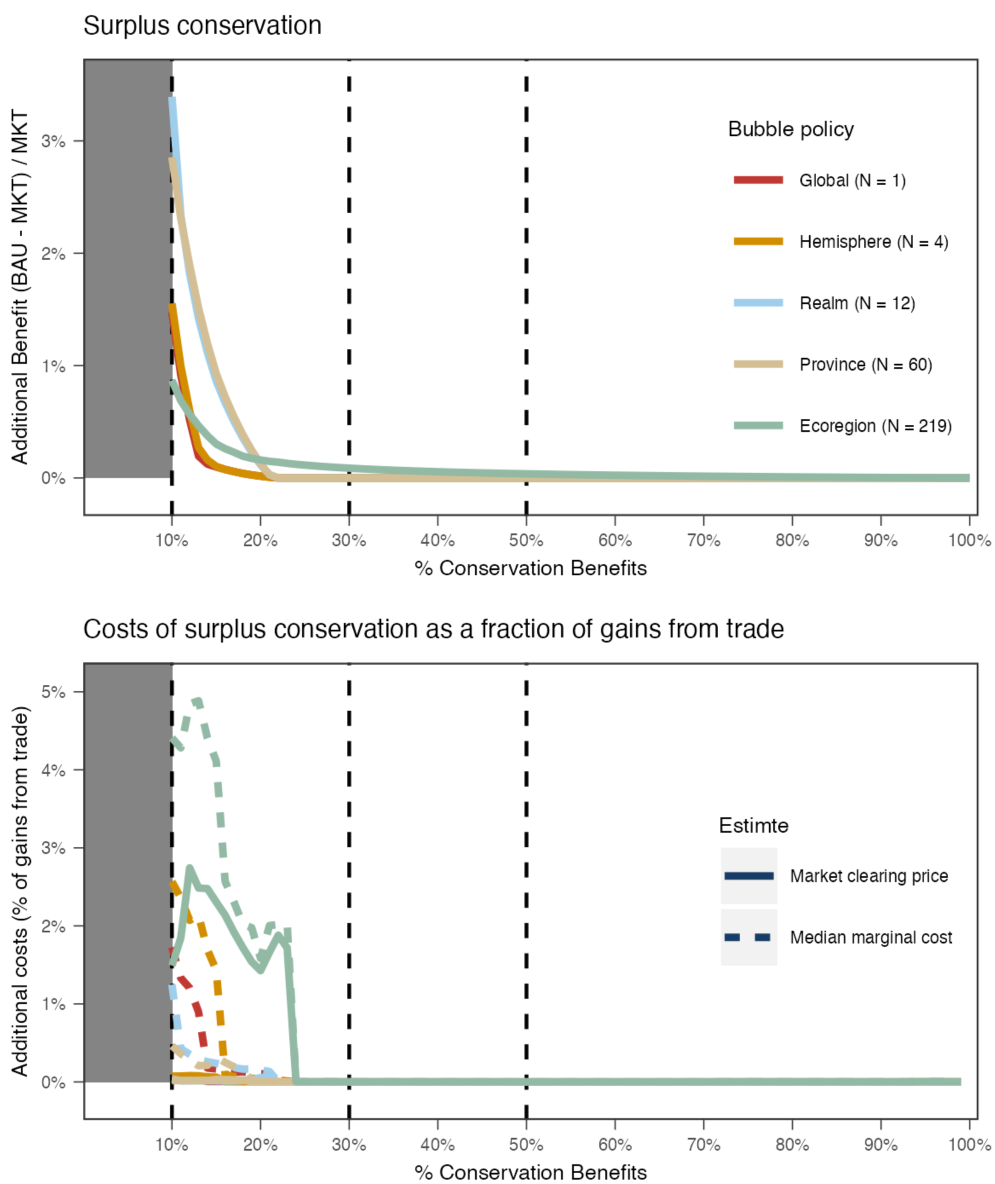

Fig. S19.
Surplus conservation benefit produced for some targets under BAU due to strict interpretation of uniform conservation mandates. In the top figure, the x-axis shows the target (% of global conservation benefits) and the y-axis shows the surplus of conservation benefit produced under BAU relative to the target (and what's achieved under a market). The bottom panel shows estimates of the costs of the surplus shown above, based on market clearing price in solid lines, and the median marginal cost of all units across all nations in the bubble in dashed lines.

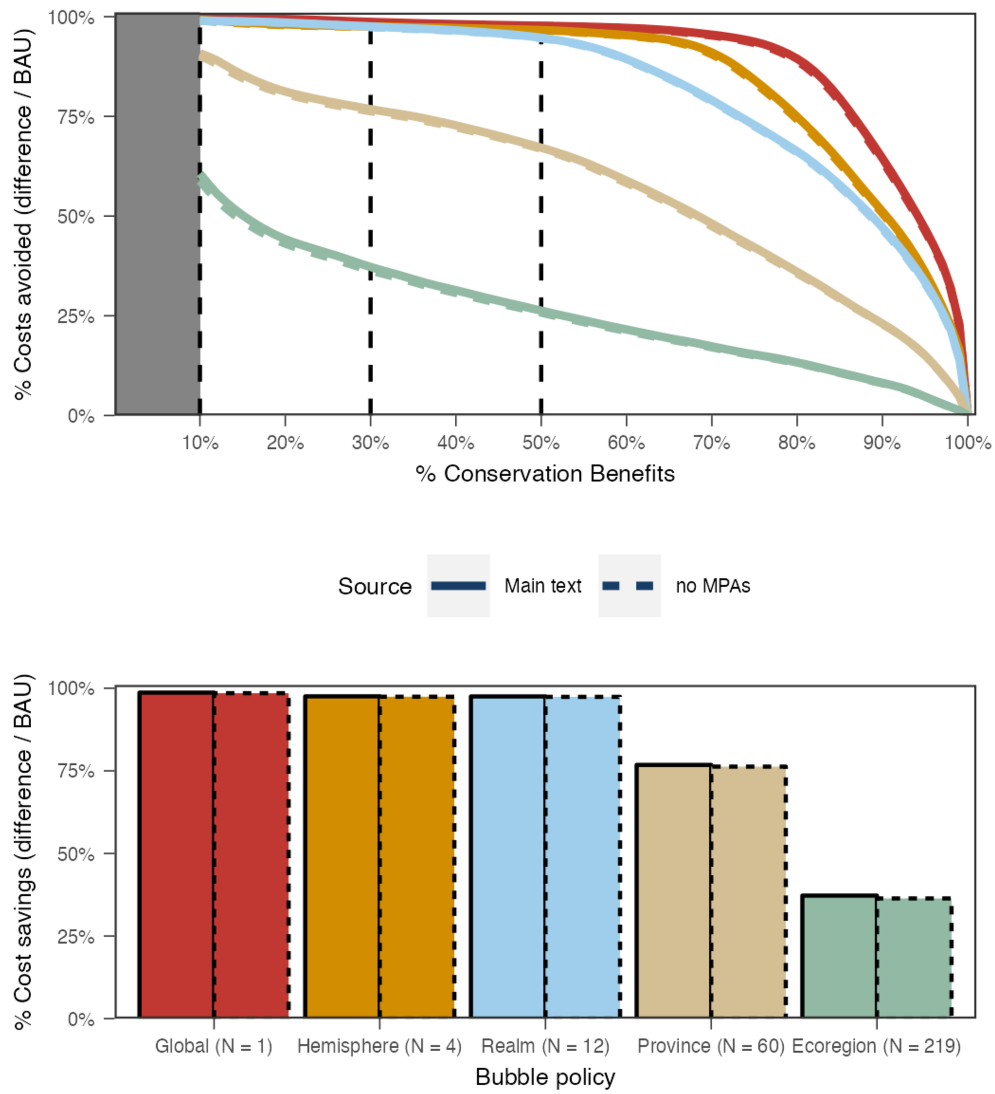

Fig. S20.

Gains from trade assuming there are no MPAs in the world. Top panel shows gains from trade across bubble policies for multiple scenarios. Bottom panel shows gains from trade by bubble policy under 30x30. On both panels, dashed lines indicate the scenario where supply curves assume there are no MPAs in the world. Solid lines represent our main-text results.

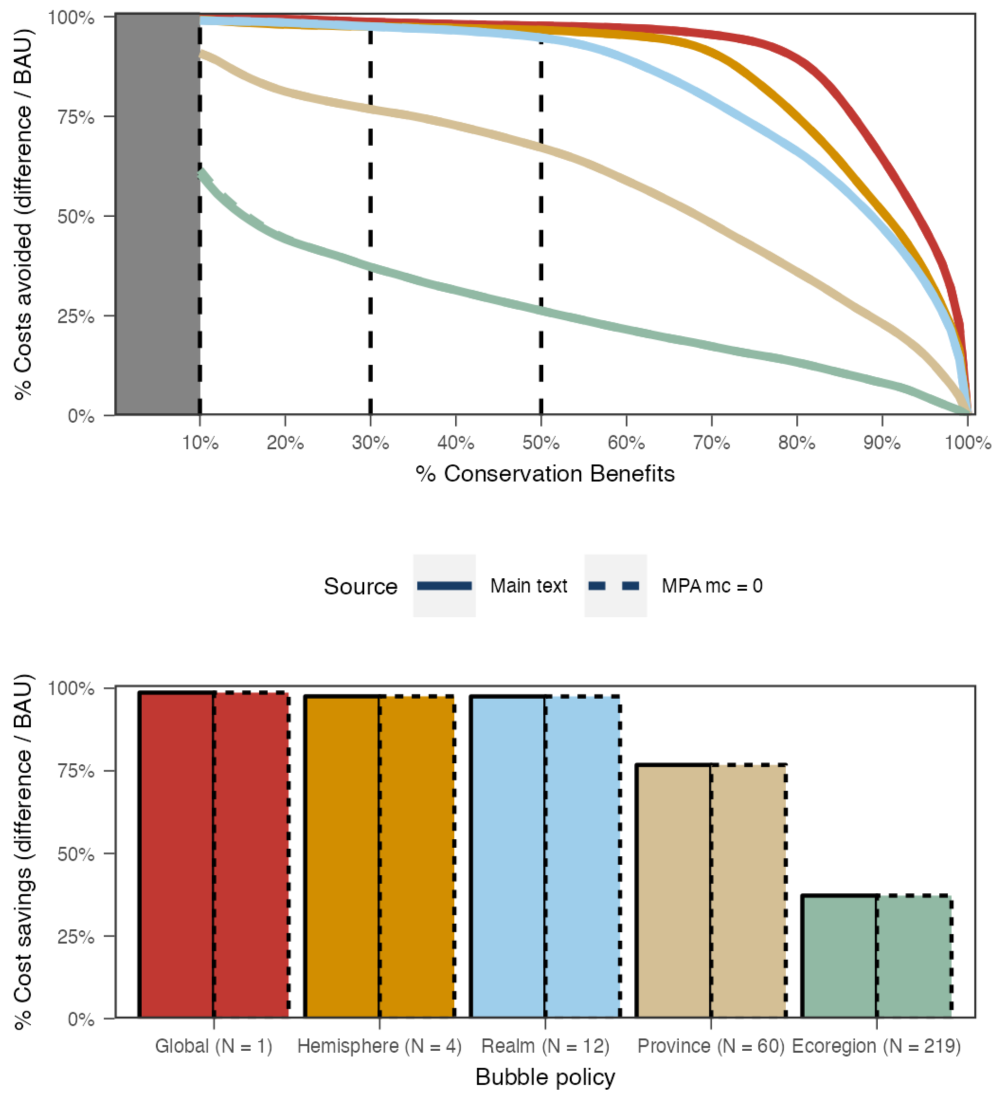

Fig. S21.

Gains from trade assuming the marginal costs of conserving MPAs is 0. Top panel shows gains from trade across bubble policies for multiple scenarios. Bottom panel shows gains from trade by bubble policy under 30x30. On both panels, dashed lines indicate the scenario where supply curves assume the marginal costs of conserving areas within MPAs is 0. Solid lines represent our main-text results.

Table S1.

Comparison of gains from trade for a 30-by-30 target using extent weighted by the habitat suitability index (labeled HSI) and using area-based targets (labeled ABT). The first column shows the bubble policy, the second and third columns show the relative gains from trade under each measure. The fourth column shows the change in total conservation benefits (HSI-weighted area), relative to benefits under area-based conservation and no trade.

Bubble policy	Gains from trade		
	HSI	ABT	Change in TB (%)
Global (N = 1)	98.681	98.712	0.750
Hemisphere (N = 4)	97.555	97.617	0.122
Realm (N = 12)	97.527	97.472	0.538
Province (N = 60)	76.795	76.884	-0.099
Ecoregion (N = 219)	37.237	36.950	-0.095

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