

Supplementary Information 1: Details on data collection methods (step D1).

1. Fieldwork period and study participants

Fieldwork was conducted over a 20-day period from 14 November to 3 December 2012 in all villages, hamlets, and islands that make up the Riwo community. After a preliminary community meeting to explain the project, refine data collection methods, and obtain approval from the chief and residents, four preliminary focus groups were held prior to household interviews to explore the range of perceived benefits derived from the Madang Lagoon. Groups represented gender and occupational roles: male fishers, male non-fishers, female fishers, and female non-fishers.

Interviews were conducted with 52 heads of households, representing approximately 17% of Riwo households [49]. Opportunistic sampling was used to include participants across all parts of the community. Although the head of household was the primary respondent, other household members were often present and contributed to discussion.

2. Focus group procedure

2.1. Identification of benefits

Each focus group began with open-ended questions about why community members visit the lagoon and what they obtain from these visits. Participants described activities, experiences, and values associated with specific places. Discussions continued until no new benefits were identified.

2.2. Use of picture cards

Following open discussion, picture cards illustrating potential benefits were introduced to refine the list. Cards were prepared prior to the focus groups, adapted from the “landscape values” typology in Brown and Reed [35] and tailored to the Madang Lagoon context. Only cards considered relevant by participants were retained; others were removed. A description of the picture cards is presented in S1 Appendix Table 1.

2.3. Facilitation and documentation

All focus groups were facilitated in English by the lead author. At least one bilingual community member (English/Tok Pisin or English/Bel) was present in each group to translate and clarify concepts and minimise language bias. Notes were recorded on paper, and discussions were audio-recorded with participants’ consent.

3. Household survey protocol

3.1. Materials

Several high-resolution satellite images (A3 laminated print; imagery year 2010; multispectral spatial resolution ~2 m) covering relevant parts of the Madang Lagoon and adjacent coastline

were used. A sample image is reproduced with permission on p6. Mapping was done with coloured felt tip markers and A3 sheets of tracing paper laid over the satellite images. Benefit cards selected by the focus groups were used in the survey, where prompting was deemed necessary. A full list of the benefits used is on p7. Tokens consisted of shells or small stones.

3.2. Introduction

Each household interview followed a three-part, game-based survey designed to identify important benefits, map the areas used to access them, and quantify the relative importance of each place. The protocol involved three elicitation components: a **Card game**, a **Drawing game**, and a **Token game**.

Before beginning, the interviewer showed a satellite map of the region and confirmed that the interviewee recognised key landmarks to ensure a common spatial understanding. This step was also useful to engage the participant and start the conversation about how they use the lagoon.

3.3. Card game: identifying and ranking benefits

Identifying lagoon benefits

Interviewees were asked: *“How does your household benefit from the lagoon?”* (e.g., fishing, recreation, traditional medicine).

This was open-ended and without using prompt cards. If needed, the interviewer used “benefit cards” illustrating each benefit category to prompt additional benefits (e.g., *“What about this one?”*).

Ranking benefits by importance

Interviewees were then asked to rank the benefits: *“How important are the following benefits for your household? Please rank these from most to least important.”*

Ranking was performed using the benefit cards, which participants physically ordered by importance.

3.4. Drawing game: mapping places used to access benefits

Preparation

The satellite images covering relevant parts of the Madang Lagoon and adjacent coastline were chosen by participants, based on their knowledge of the area. Points of known latitude and longitude were pre-marked on the tracing sheets for each household to enable accurate georeferencing of all mapped features during digitisation. Each benefit was assigned a unique colour marker.

Protocol

Fishing benefit prompts were different to other benefits because this information was also used in separate fishing-focused analyses. For all non-fishing benefits identified in the Card game, the interviewer repeated the mapping steps below. Benefit cards were presented one at a time, in order of decreasing importance according to the interviewee’s ranking. The protocols followed are detailed in **Supplementary Table S1**.

Supplementary Table S1. Protocols followed for participatory mapping of important areas of the Madang Lagoon where Riwo people derive ecosystem benefits.

Fishing benefits	Other benefits
Mapping fishing areas Participants were asked: <i>“Where do you (or the main fisher in the household) usually go fishing?”</i> For each fishing zone, they were also asked about: • fishing gear used • main species caught Participants drew each fishing zone on the map. Gear types and species were annotated directly on the map.	Mapping areas used for each benefit For each benefit category, participants were asked: <i>“Can you show me on the map the places that your household uses to access this benefit?”</i> Participants drew place boundaries on the map. A different colour was used for each benefit category. A legend was created on the paper questionnaire.
Identifying favourite fishing area Participants were asked: <i>“Which of these fishing zones is your favourite, and why?”</i> The favourite zone and the reasons given were recorded.	NA

3.5. Token game: assigning relative importance or areas

Protocol

For each benefit category, participants received a fixed number of tokens and were asked to distribute them among the mapped places according to their relative importance. Token counts were recorded next to each place.

Token allocation rule

The number of tokens given to a household for each benefit was proportional to the number of polygons they drew, ensuring respondents could meaningfully differentiate relative importance.

For each benefit and each household:

1. Count the number of polygons drawn.
2. Multiply by two.
3. Round the resulting number up to the nearest multiple of five.

Example:

- 3 polygons $\rightarrow 3 \times 2 = 6 \rightarrow$ rounded to 10 tokens
- 7 polygons $\rightarrow 7 \times 2 = 14 \rightarrow$ rounded to 15 tokens

3.6. Survey duration and outputs

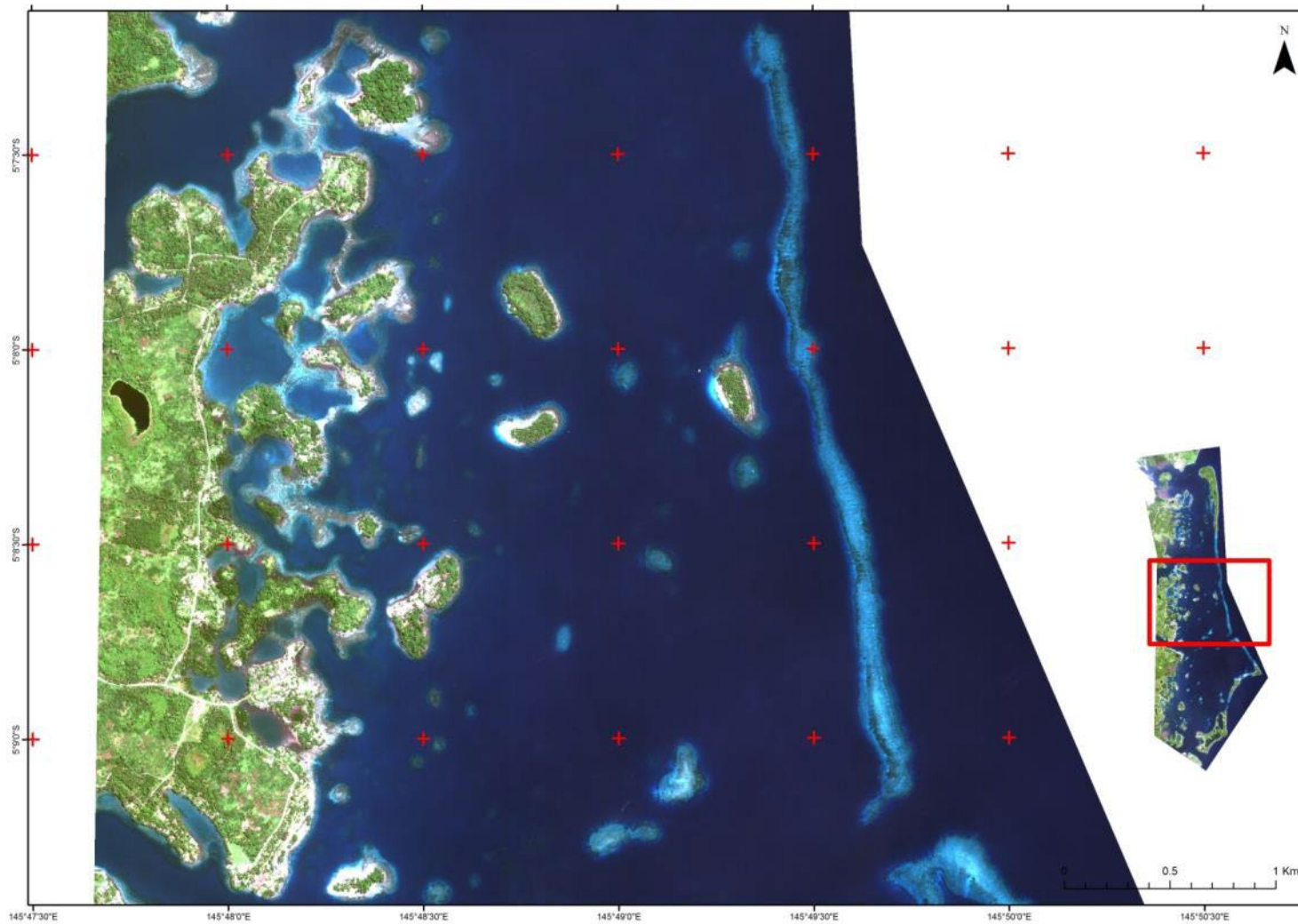
Each interview lasted approximately one hour. One tracing paper map (or a set where large amounts of information were mapped) was produced per household, with each benefit represented in a unique colour. At the end of each interview, respondents reviewed the map and confirmed its accuracy.

3.7. Data processing

All maps and audio files were digitised and archived.

Due to the remoteness and limited access to power in the Riwo village, the interviewer transferred mapped polygons to digital format after the fieldwork period.

To ensure comparability across households, raw token counts were converted to a 0–100 scale for each benefit. The sum of standardised scores for each benefit and household equalled 100.



Supplementary Figure S1. Example of satellite image used during the survey. Each image like the one below was printed on an A3 sheet. Worldview image reprinted under a CC BY license with permission from DigitalGlobe, Inc. © 2010. The final map layout was produced by the authors using ArcGIS Desktop version 10.0 (ESRI, Redlands, CA, USA; <https://www.esri.com>).

Supplementary Table S2. Description of benefit cards used in the survey. Each of the 10 cards, showing only photographs, was printed on an A5 sheet. Photographs were obtained from the Internet and chosen to be as culturally relevant as possible. Due to copyrights on original photographs, we replaced them with descriptions here.

Benefit	Description of images used
Fishing (FI)	- A local fisher fishing on a traditional outrigger canoe. - Close up on the hands of a Madang fisher holding a yellowfin tuna. - Local people selling and buying fish at the Madang markets. - Local fisher in the water, holding a spear gun. A fishing motorboat can be seen in the background. - Close-up on dried shark fins and beche-de-mer for sale at a local market in Papua New Guinea. - Five, ten, twenty, fifty, and a hundred Kina notes, the Papua New Guinea currency.
Recreation (RE)	- Madang kids laughing and playing in the water. - Madang kids surfing on waves with plywood boards. - Locals bathing at a beach in the Madang Lagoon.
Aesthetic enjoyment (AE)	- Over-under photo showing mountains covered in green lush forest (over) and a healthy, diverse and colourful reef scape (under). - Sunrise in Madang showing orange and red lights and clouds above the sea. - View of Guzem Island in the Madang Lagoon from Jais Aben, showing clear waters, green palm trees, sandy beaches and blue skies with a few clouds. - Coastline landscape in the Madang Lagoon, showing palm trees and vegetation in the background, water, a local on a boat, and a bird swimming in the foreground.
Traditional medicine (TM)	- Herbal medicine next to modern drug tablets. - A local patient is being looked after by a local doctor, outside in a Madang village.
Collecting material to make lime for betel nut chewing (LI)	- Ingredients used to chew betel nut: a jar of lime powder (kambang); a bean-like green stick called mustard (daka) and green betel nuts (buai). - A motorboat to represent betel nut trade between villages. - Five, ten, twenty, fifty, and a hundred Kina notes, the Papua New Guinea currency.
Perceived biological richness (RI)	- A view from Pig Island, showing clear turquoise waters, a green mangrove tree, coral bommies in the water, blue skies with some clouds, and the mountains covered with rainforest in the background. - Underwater view of a colourful healthy shallow coral reef in Papua New Guinea, showing many species of fish, corals, sponges in clear water. - Underwater view of a colourful healthy deep coral reef, showing many species of fish, hard and soft corals, sponges, hydrozoans, ascidians in clear water. - Local kids along the coast in Madang.
Education and knowledge sharing (ED)	- Local knowledge sharing activity, showing children and adults in a hut discussing a poster with images of local fish, in Papua New Guinea. - A father and son fishing off a pontoon. - Students working at desks in a school in Papua New Guinea. - A woman discusses coral reef biodiversity with local community members.

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Benefit	Description of images used
Spiritual value (SP)	- A woman inspects a sign notifying people that they are in a Locally Managed Marine Area (LMMA) in Papua New Guinea. - A child in Madang province reads the Bible. - Traditional dancers from Madang. - Women clapping hands and singing during a religious service in Madang.
Wrecks (WR)	- A plane wreck similar to those found in the Madang Lagoon.
Tourism (TO)	- Aerial view of the Kalibobo Village (Madang Resort). - Foreign tourists travelling on a water taxi in Madang. - A Madang local scuba diving on the reefs in the Madang Lagoon. - A foreign tourist swimming in turquoise waters in the Madang Lagoon. - Five, ten, twenty, fifty, and a hundred Kina notes, the Papua New Guinea currency.

Supplementary Information 2. Details on data processing methods (step D2).

1. Data processing and calculation of cost layers.

1.1. Polygon processing

- Polygons from the drawing game were assigned to the corresponding household, identified benefit, and standardized token number (0–100).
- For each benefit, an “area” was defined as either a single polygon or the overlap of multiple polygons. Overlapping polygons generated multiple areas (e.g., two overlapping polygons produce three areas: non-overlapping parts of each polygon plus the intersection; Fig 1).

1.2. Single-benefit indicators

- **HOUSEHOLDS:** number of overlapping polygons per area (min 0, max 52).
- **TOKENS:** sum of tokens in polygons within the area, weighted by proportion of each polygon’s surface intersecting the area (min 0, max 52*100).
- Standardization: each indicator scaled from 0–100 within each benefit.

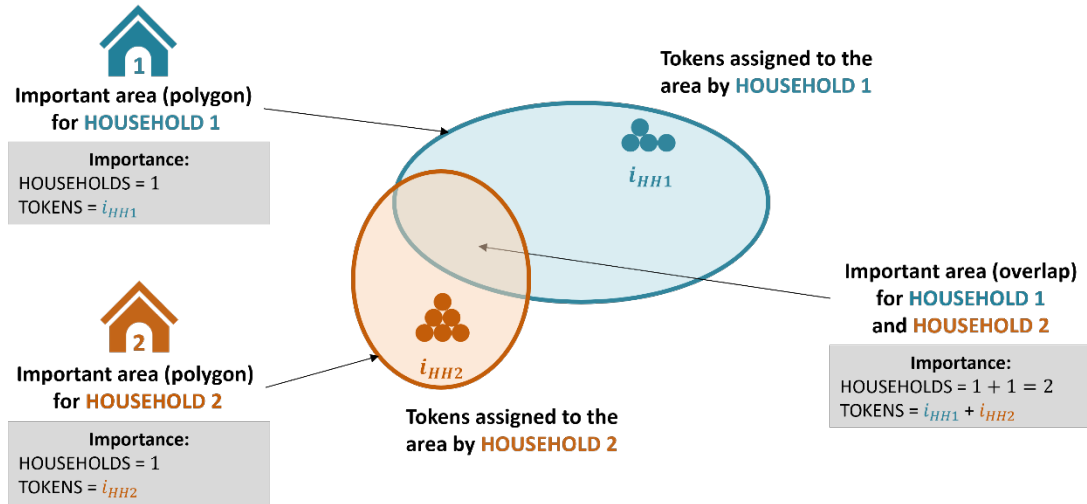
1.3. Combined-benefit indicators

- Polygons from all households and benefits were merged into single layers.
- **COMB BENEFITS** and **COMB HOUSEHOLDS:** polygons were dissolved by benefit or household, producing one multipart polygon per benefit or household. Overlapping polygons were then counted to generate indicators.
- **COMB TOKENS:** TOKENS in each benefit layer were weighted by the proportion of households for whom the benefit was relevant, then summed across all benefits.
- All three indicators were calculated for all benefits together and for extractive versus non-extractive subsets.

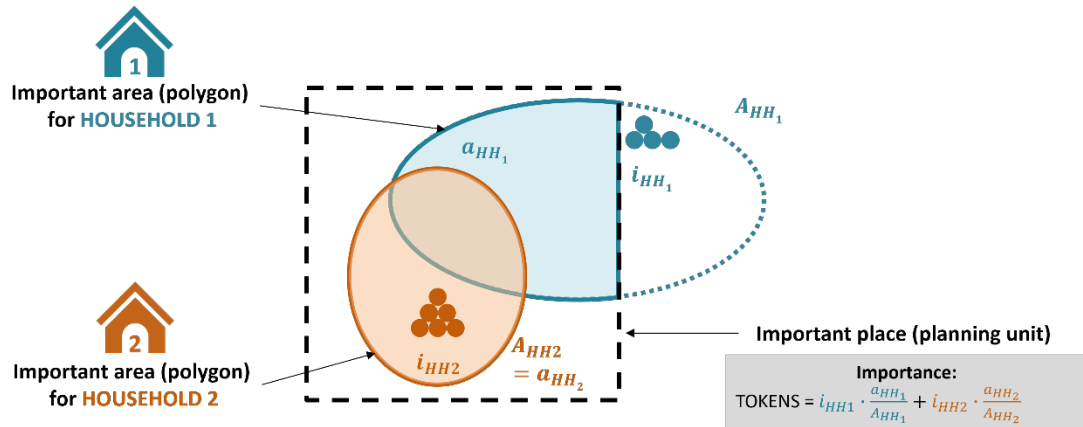
1.4. Cost calculations for each place (square planning unit)

- Single-benefit costs: TOKENS were computed for each place using the same methods as for area-level TOKENS (Tables 1 and 2).
- Combined-benefit costs: COMB TOKENS were computed for each place.
- Uniform cost: all places assigned 100.

A



B



Supplementary Figure S2. Schematic representation of the variables used to derive spatial datasets for each benefit of interest (e.g. fishing, recreation, aesthetics), showing the importance of areas (A) and places (square planning units) (B). In both panels, the same two polygons are presented, each delineated by a different head of household representing their household (1, in blue, and 2, in red). Each polygon is associated with its importance in regard to the benefit of interest (respectively i_{HH1} and i_{HH2} based on the number of tokens), and its total area (respectively A_{HH1} and A_{HH2}). In (A), the importance of each area is calculated as the number of households visiting the area (HOUSEHOLDS), or as the total number of tokens (TOKENS) associated with all overlapping polygons (sum of all i_{HH_n}), depending on the method chosen. In (B), the importance of a place (or planning unit) is calculated as described in **Supplementary Table S3** and **Supplementary Table S4**. One place is represented, covering partially area a_{HH1} of the polygon delineated by household 1 and entirely the polygon delineated by household 2 ($a_{HH2} = A_{HH2}$).

Supplementary Information 2. Details on data processing methods (step D2).

Supplementary Table S3. Cost variables, based on indicators of the importance of each area/planning unit for a single benefit or combination of benefits. Cost x was calculated for all areas/planning units in the planning region from variables associated with delineated polygons (see **Supplementary Table S4** for a description of variables). All indicators were normalised as percentage of maximum to standardise units and allow direct comparisons ($0 \leq x \leq 100$).

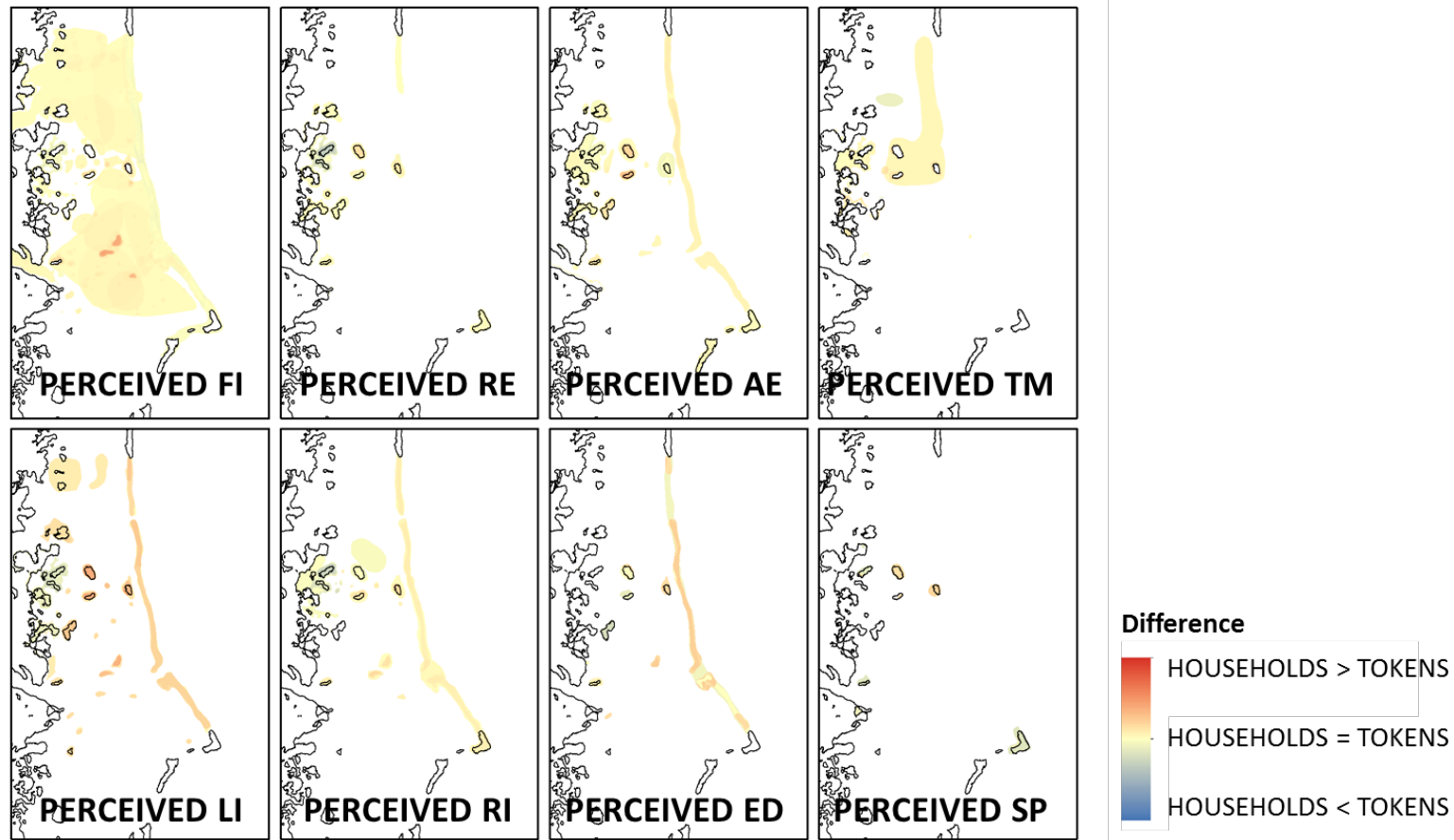
Calculated for	Type	Indicator	Formula	Description
An area (raw data)	Single benefit	HOUSEHOLDS	$x_1 = n$	Number of households who visited the area for the benefit of interest.
Supplementary Figure S2 (A)		TOKENS	$x_2 = \sum_{n=0}^N i_{HHn} \cdot w_{HHn}$ with $w_{hhn} = \frac{a_{HHn}}{A_{HHn}}$	Importance of an area for the benefit of interest. Sum of the number of tokens associated with polygons for each household n within the area i_{hhn} , weighted by the proportion of the area of each polygon intersecting the area w_{hhn} .
	Multiple benefits	COMB BENEFITS	$x_3 = b$	Importance of an area for a combination of benefits of interest. Number of unique perceived benefits assigned to the area.
		COMB HOUSEHOLDS	$x_4 = \sum_{b=0}^B n_b$	Importance of an area for a combination of benefits of interest. Number of unique households who visited the area, all benefits combined.
		COMB TOKENS	$x_5 = \sum_{b=0}^B j_b \cdot x_2$	Importance of an area for a combination of benefits of interest. Sum of all calculated x_2 (TOKENS) for all benefits of interest, weighted by the relative importance j_b of each benefit.
A place (planning unit) Supplementary Figure S2 (B)	Single benefit	TOKENS	$x_6 = \sum_{n=0}^N i_{HHn} \cdot w_{HHn}$ with $w_{hhn} = \frac{a_{HHn}}{A_{HHn}}$	Importance of a place for the benefit of interest. Sum of the number of tokens associated with polygons for each household n within the place i_{hhn} , weighted by the proportion of the area of each polygon intersecting the place w_{hhn} .
	Multiple benefits	COMB TOKENS	$x_7 = \sum_{b=0}^B j_b \cdot x_6$	Importance of a place for a combination of benefits of interest. Sum of all calculated x_6 (TOKENS) for all benefits of interest, weighted by the relative importance j_b of each benefit.
	Reference	UNIFORM	$x_8 = 100$	Uniform importance (each planning unit, including trimmed ones had the same cost).

Supplementary Table S4. List of variables used to calculate the importance of areas (raw data), and the costs of reserving each planning unit.

Variable name	Description
n	number of households “using” the place ($0 \leq n \leq N$)
N	total number of households surveyed
i_{HH_n}	importance (number of tokens) of the polygon used by household n for the benefit of interest
a_{HH_n}	area (m ²) of polygon used by household n within the place
A_{HH_n}	total area (m ²) of polygon used by household n
w_{HH_n}	proportion of the polygon used by household n within the place
b	number of perceived benefits provided by the place ($0 \leq b \leq B$)
B	total number of perceived benefits in the planning region
n_b	number of households “using” the place for the benefit of interest b ($0 \leq n_b \leq N$)
j_b	importance of benefit b for the community

2. Measuring the difference between TOKENS, and HOUSEHOLDS, two indicators measuring the importance of areas for each benefit.

For each benefit, we created two indicators (ranging from 0 to 100) by scaling the number of households and of tokens as a percentage of the maximum value assigned to an area (hereafter “HOUSEHOLDS” and “TOKENS”, respectively). TOKENS accounts for the relative importance of each of the areas identified by each household for a given benefit, while HOUSEHOLDS measures the number of households valuing each area for this benefit. To investigate differences between these two indicators, I created difference maps. For each benefit, we converted HOUSEHOLDS and TOKENS vector datasets (polygons) into raster format (pixels). Then we subtracted the HOUSEHOLDS raster from the TOKENS raster. The resulting difference raster contained pixels with values potentially ranging from -100 to 100. Negative values (shown in green or blue tones in **Supplementary Figure S3**) indicated that HOUSEHOLDS gave lower values than TOKENS to pixels for the benefit of interest, while positive ones (shown in orange or red tones in **Supplementary Figure S3**) indicated that HOUSEHOLDS gave higher values than TOKENS. Pixels close to 0 (shown in yellow in **Supplementary Figure S3**) indicated no notable difference between the two indices.



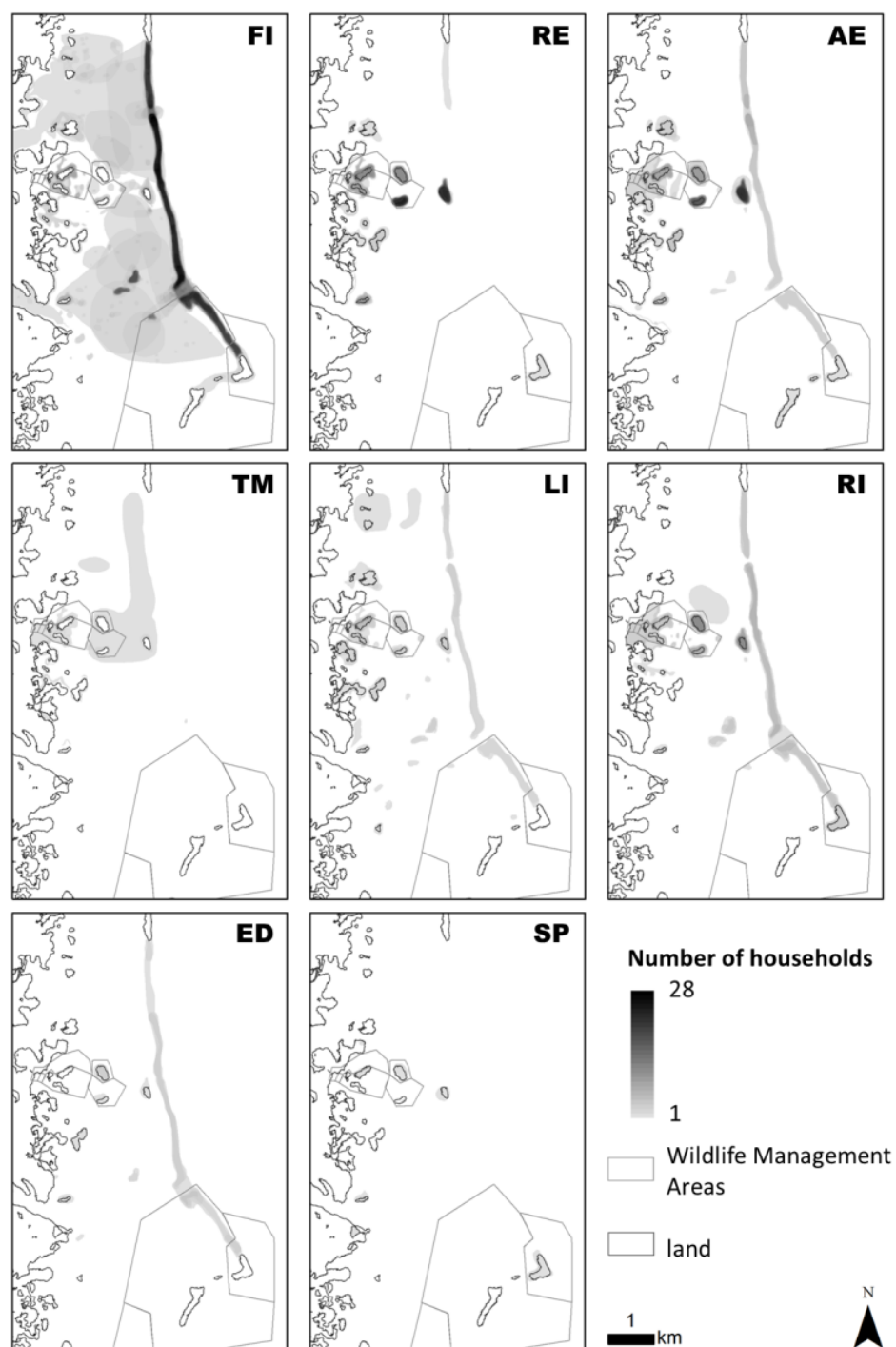
Supplementary Figure S3. Map of the importance of areas as measured by the number of tokens (TOKENS) and the number of households (HOUSEHOLDS) for individual benefits. Benefits of interest included fishing (FI); recreation (RE); aesthetics (AE); traditional medicine (TM); collecting material to make lime for betel nut chewing (LI); perceived biological richness (RI); education and knowledge sharing (ED); spiritual value (SP). Orange or red areas are more important according to HOUSEHOLDS than TOKENS. Green or blue areas are less important according to HOUSEHOLDS than TOKENS. Yellow areas are areas which importance is similar based on both indicators. Base maps and spatial layers were compiled and visualised using ArcGIS Desktop version 10.0 (ESRI, Redlands, CA, USA; <https://www.esri.com>), and final map layout was produced by the authors.

Supplementary Information 3. Details on geomorphic habitat data.

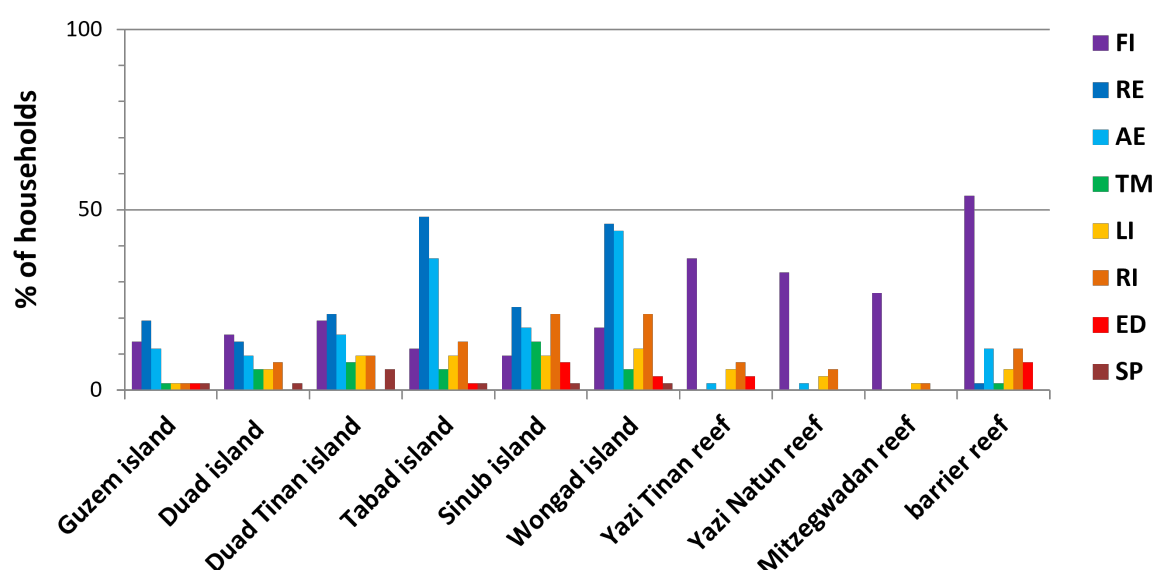
Supplementary Table S5. Geomorphic habitat types found in the Madang Lagoon and their corresponding extent within the planning region. For each habitat, the total extent occurring within the Madang Lagoon is also indicated. Six of the 28 geomorphic habitat types found in the Madang Lagoon do not occur in the planning region.

Level 1	Level 2	Level 3	Extent in planning region (ha)	Total extent in Madang Lagoon (ha)
continental fringing	diffuse fringing	diffuse fringing	0.9	5.1
		enclosed lagoon or basin	36.9	70.5
	lagoon-exposed fringing	forereef	134.4	207.0
		reef flat	88.6	145.6
		river mouth	11.4	85.2
		shallow terrace	11.7	22.5
		shallow terrace with constructions	4.6	6.4
		subtidal reef flat	0.6	0.6
	ocean-exposed fringing	forereef	0	4.6
		reef flat	0	3.4
		shallow terrace	0	0.2
continental outer shelf barrier	ocean-exposed fringing	forereef	0	3.4
		deep terrace	11.5	11.8
	outer barrier reef complex	deep terrace with constructions	0	7.6
		enclosed basin	0	17.2
		forereef	79.4	158.8
		pass	17.3	92.5
		reef flat	11.5	33.9
		shallow terrace	8.6	11.0
		shallow terrace with constructions	0.2	1.4
		subtidal reef flat	61.1	70.0
continental patch complex	intra-lagoon patch reef complex	deep terrace with constructions	13.2	54.1
		enclosed basin	1.6	2.0
		forereef	78.6	129.5
		reef flat	24.4	52.6
		shallow terrace	9.1	11.8
		subtidal reef flat	27.6	39.6
shelf marginal structures	continental lagoon	deep lagoon	1,638.7	2,948.6
TOTAL			2,272.1	4,196.7

Supplementary Information 4. Details on results.



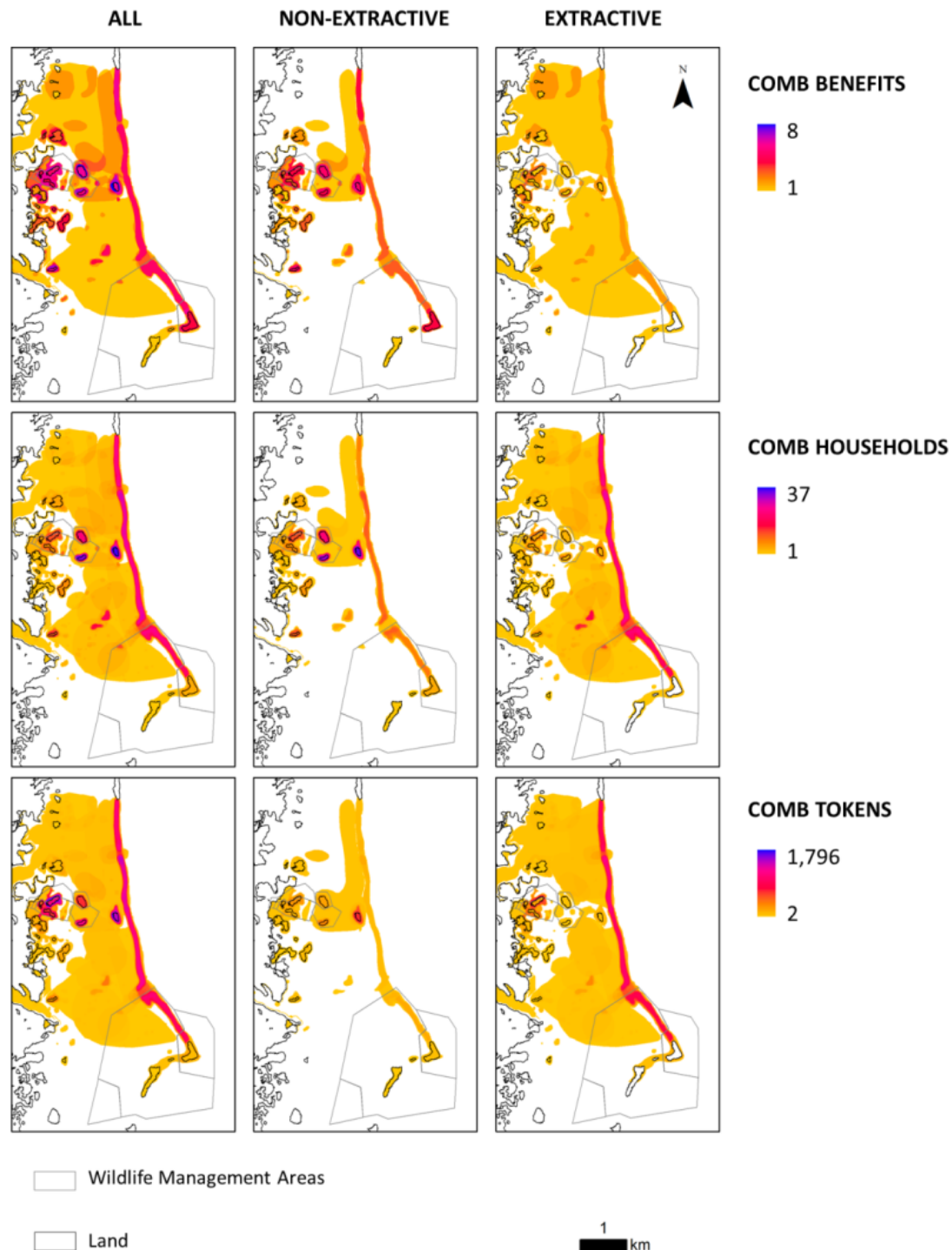
Supplementary Figure S4. Number of households visiting and valuing different areas of the Madang Lagoon for the ecosystem benefits they provide. Types of benefits are: fishing (FI); recreation (RE); aesthetics (AE); traditional medicine (TM); collecting material to make lime for betel nut chewing (LI); perceived biological richness (RI); education and knowledge sharing (ED); the spiritual value of places (SP). To enhance differences, the maximum possible value of the gradient was set to 28, the maximum number of households (out of 52) valuing a same area across all benefits. This value was measured for the fishing benefit. Base maps and spatial layers were compiled and visualised using ArcGIS Desktop version 10.0 (ESRI, Redlands, CA, USA; <https://www.esri.com>), and final map layout was produced by the authors.



Supplementary Figure S5. Geomorphologic entities of importance for people of Riwo, according to the number of households valuing them for a range of ecosystem benefits. Islands and reefs were valued for fishing (FI), recreation (RE), aesthetics (AE), traditional medicine (TM), lime material (LI), perceived biological richness (RI), education and knowledge sharing (ED), and spiritual value (SP). Bars show the maximum proportion of households valuing each area (i.e. single polygon or overlap between polygons) covering each of these geomorphologic entities. Details on data are found in **Supplementary Table S6**.

Supplementary Table S6. Geomorphologic entities of importance for people of Riwo, according to the number of households valuing them for a range of ecosystem benefits.

Geomorphic entities	Number of households for which the entity is important for a given benefit							
	FI	RE	AE	TM	LI	RI	ED	SP
Guzem island	13	19	12	2	2	2	2	2
Duad island	15	13	10	6	6	8	0	2
Duad Tinan island	19	21	15	8	10	10	0	6
Tabad island	12	48	37	6	10	13	2	2
Sinub island	10	23	17	13	10	21	8	2
Wongad island	17	46	44	6	12	21	4	2
Yazi Tinan reef	37	0	2	0	6	8	4	0
Yazi Natun reef	33	0	2	0	4	6	0	0
Mitzegwadan reef	27	0	0	0	2	2	0	0
barrier reef	54	2	12	2	6	12	8	0



Supplementary Figure S6. Importance of areas when combining benefits (raw data). All benefits combined (ALL), benefits related to non-extractive uses only (NON-EXTRACTIVE), and benefits related to extractive uses only (EXTRACTIVE). Three indicators were used: the number of benefits assigned to each area (theoretical minimum: $1 \leq \text{COMB BENEFITS} \leq$ theoretical maximum: 8), the number of households valuing each area ($1 \leq \text{COMB HOUSEHOLDS} \leq 52$) for any benefit, and the weighted sum of all tokens assigned to each area by all households ($2 \leq \text{COMB TOKENS} \leq 1,796$). See Supplementary Information 2 for equations to calculate each indicator. To enhance differences in the maps, the colour scale for each indicator was designed with colour gradients stretched from the minimum recorded value to the maximum recorded value. Base maps and spatial layers were compiled and visualised using ArcGIS Desktop version 10.0 (ESRI, Redlands, CA, USA; <https://www.esri.com>), and final map layout was produced by the authors.

Supplementary Table S7. Incidental costs from all scenarios. This table shows the data used to make figure 4 in the manuscript. All scenarios (far left column) had the objective of representing 20% of the extent of each habitat type in the planning region. (ext.) and (non-ext.) refer to “extractive” and “non-extractive” aspects of traditional medicine, respectively. (all) refers to both aspects of traditional medicine combined. For the UNIFORM scenario, a uniform cost layer was used, with all places in the planning region having a cost of 100. The ECOLOGICAL approach minimizes the total cost of the hypothetical reserve system to all benefits combined, treating socioeconomic considerations as a constraint. The SOCIAL-ECOLOGICAL approach treats socioeconomic costs as an objective: places with high aggregated benefits (above the third quartile), are locked out (grey areas), and reserves are selected only from locations of relatively low benefit. Each incidental cost for the best solution of each scenario, was calculated as the percentage of the maximum possible cost for the corresponding benefit (i.e. the total cost when all places were selected for reserves). Underlined costs indicate the cost for the benefit minimised in that scenario.

Scenario	Scenario cost (percentage of maximum possible cost for the benefit)									
	FI	RE	AE	TM	TM	TM	LI	RI	ED	SP
				(all)	(ext)	(non-ext)				
FISHING	<u>3</u>	2	3	10	18	4	8	3	3	19
RECREATION	31	<u>0</u>	3	6	7	6	14	12	18	11
AESTHETICS	15	4	<u>0</u>	11	21	4	15	3	10	8
TRADITIONAL MEDICINE	27	4	6	<u>0</u>	1	0	13	9	15	17
TRADITIONAL MEDICINE (ext.)	33	33	35	35	<u>0</u>	61	21	41	41	34
TRADITIONAL MEDICINE (non-ext.)	27	3	6	7	15	<u>0</u>	15	11	19	15
LIME	16	4	7	5	1	8	<u>1</u>	5	11	31
BIOLOGICAL RICHNESS	17	7	8	16	16	16	20	<u>1</u>	23	9
EDUCATION	22	12	13	22	37	11	23	19	<u>1</u>	42
SPIRITUALITY	35	10	14	26	43	14	35	19	24	<u>0</u>
UNIFORM	27	30	37	15	11	17	19	31	24	36
SOCIAL-ECOLOGICAL (all benefits combined)	4	1	1	1	2	0	3	3	2	12
ECOLOGICAL (all benefits combined)	4	1	2	1	2	0	2	3	3	15