S1. Appendix. Material used in the survey.

Text. Ecosystem benefits and services survey questionnaire

A. The "card game": benefits and services in the region of interest

[Show a satellite view of the region and discuss location of main landmarks with interviewee to ensure common understanding of the spatial environment.]

1. How does your household benefit from the lagoon? (e.g. fishing, recreation, traditional medicine…) [Open-ended question, then probe with "benefit cards" showing/explaining each use/service if necessary ("what about this?")]
2. How important are the following benefits for your household? Please rank these benefits from the one that is the most important to your household to the one that is the least important [Use "benefit cards" for ranking]

B. The "drawing game" and the "tokens game": mapping places of importance for specific benefits and services for the community

Fishing benefit:

3. Where do you (or main fisher in the household) usually go fishing? What gear do you use in these fishing zones? What do you catch most often in these fishing zones? [Ask interviewee to draw fishing zones, and annotate map with gear and main species caught in each fishing zone]
4. How important is each of these fishing zones for your household? [Give a fixed number of tokens and ask to distribute the tokens between fishing zones. Report number of tokens on the map next to corresponding fishing zone]
5. Which one of these fishing zones is your favourite? [Report favourite fishing zone on map.] Why is it your favourite?

Other benefits:
[Show "benefit cards" one by one, by order of decreasing importance as per Q2. Ask Q6 and Q7 and perform mapping exercise for each card at a time.]

6. Can you show me on the map the places that are accessed for this benefit by your household? [Ask interviewee to draw boundaries of these places. One colour per benefit category. Report legend on paper questionnaire.]
7. How important is each of these places for your household? [Give a fixed number of tokens for each benefit of interest, and ask to distribute the tokens within all places corresponding to the benefit of interest. Report number of tokens on the map next to corresponding place]

Table. 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.
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.

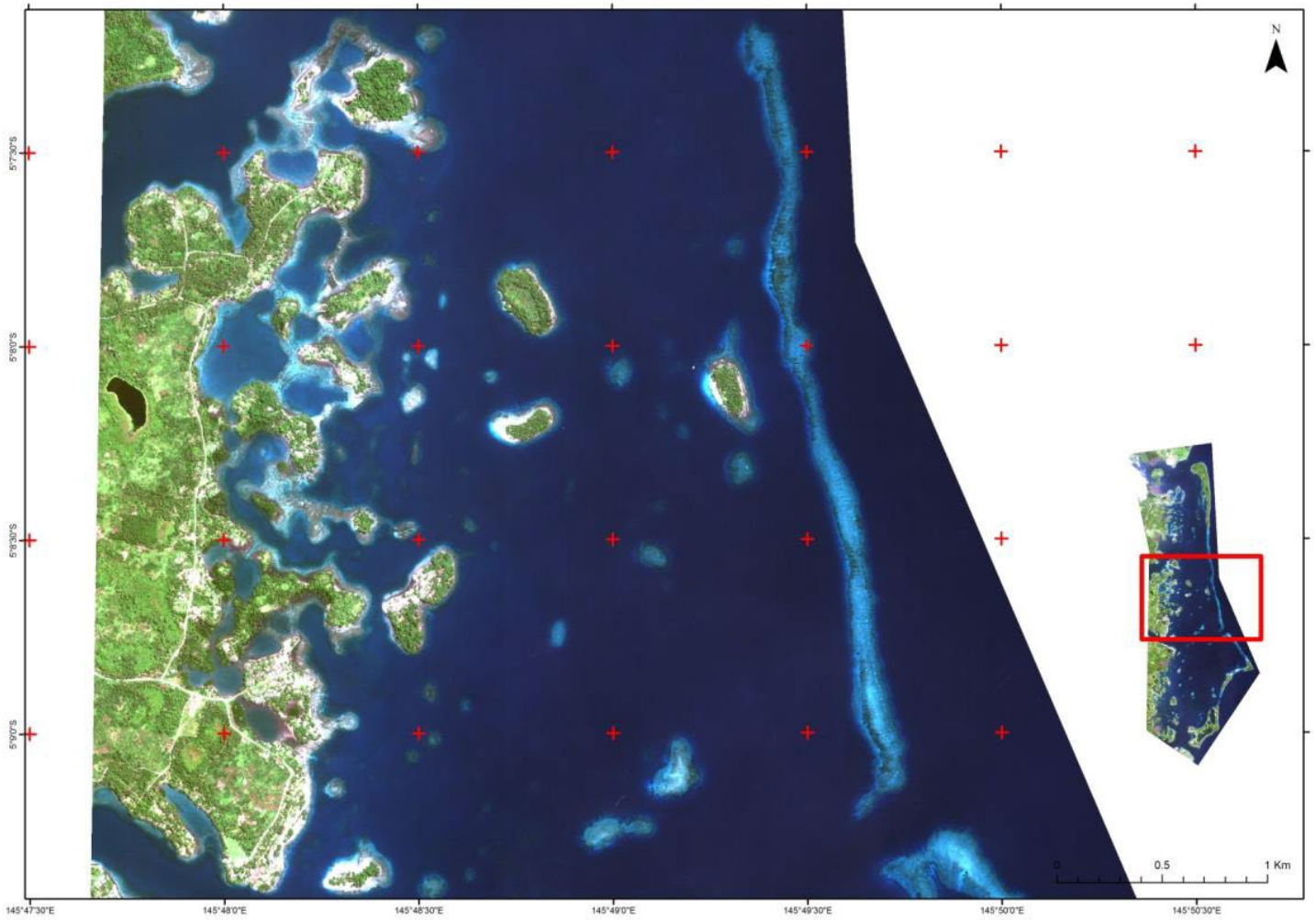

Fig. Example of satellite image used during the survey. Each image like the one below was printed on an A3 sheet. Worldview image reprinted under a CC BY license with permission from DigitalGlobe, Inc. © 2010.

S2 Appendix. Details on methods.

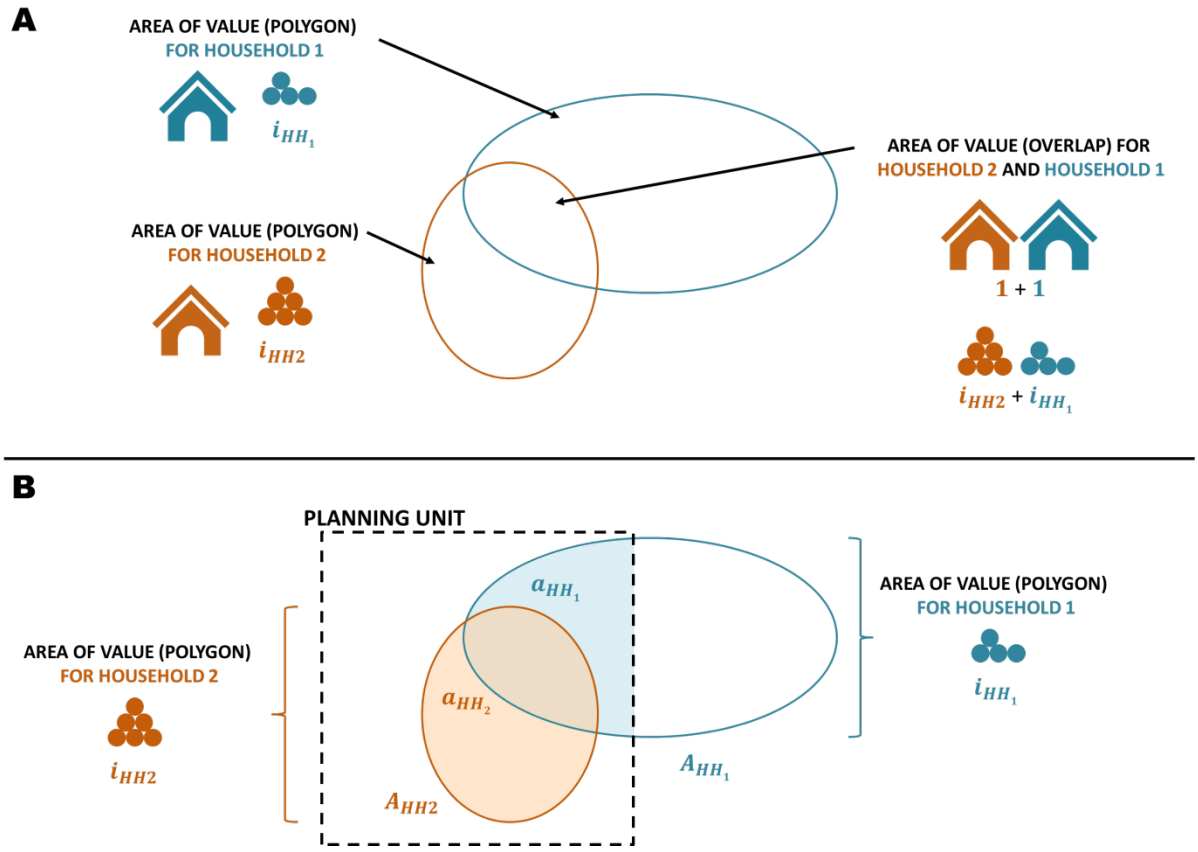

Fig 1. Schematic representation of the variables used to derive spatial datasets for each benefit of interest (e.g. fishing, recreation, aesthetics), showing the importance of areas (A) and places (planning units) (B). In both panels, the same two polygons are presented, each delineated by a different 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 $\boldsymbol{i_{HH1}}$ and $\boldsymbol{i_{HH2}}$ based on the number of tokens), and its total area (respectively $\boldsymbol{A_{HH1}}$ and $\boldsymbol{A_{HH2}}$). 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 $\boldsymbol{i_{HH_n}}$,), depending on the method chosen. In (B), the importance of a place (or planning unit) is calculated as described in **Table 1** and **Table 2**. One place is represented, covering partially area $\boldsymbol{a_{HH1}}$ of the polygon delineated by household 1 and entirely the polygon delineated by household 2 ($\boldsymbol{a_{HH2}} = \boldsymbol{A_{HH2}}$).

Table 1. Cost variables, based on indicators of the importance of each area/planning unit for a single benefit or combination of benefits. Cost $\boldsymbol{x}$ was calculated for all areas/planning units in the planning region from variables associated with delineated polygons (see **Table 2** for a description of variables). All indicators were normalised as percentage of maximum to standardise units and allow direct comparisons ($0 \leq \boldsymbol{x} \leq 100$).

Calculated for	Type	Indicator	Formula	Description
An area (raw data) **Figure 1.A**	Single benefit	HOUSEHOLDS	$x_1 = n$	Number of households who visited the area for the benefit of interest.
		TOKENS	$x_2 = \sum_{n=0}^{N} i_{HH_n} . w_{HH_n}$ with $w_{hh_n} = \frac{a_{HH_n}}{A_{HH_n}}$	Importance of an area for the benefit of interest. Sum of the number of tokens associated with polygons for each household $\boldsymbol{n}$ within the area $\boldsymbol{i_{hh_n}}$, weighted by the proportion of the area of each polygon intersecting the area $\boldsymbol{w_{hh_n}}$.
	Multiple benefits	COMB BENEF	$x_3 = b$	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	$x_5 = \sum_{b=0}^{B} j_b . x_2$	Importance of an area for a combination of benefits of interest. Sum of all calculated $\boldsymbol{x_2}$ (TOKENS) for all benefits of interest, weighted by the relative importance $\boldsymbol{j_b}$ of each benefit.
A place (planning unit) **Figure 1.B**	Single benefit	TOKENS	$x_6 = \sum_{n=0}^{N} i_{HH_n} . w_{HH_n}$ with $w_{hh_n} = \frac{a_{HH_n}}{A_{HH_n}}$	Importance of a place for the benefit of interest. Sum of the number of tokens associated with polygons for each household $\boldsymbol{n}$ within the place $\boldsymbol{i_{hh_n}}$, weighted by the proportion of the area of each polygon intersecting the place $\boldsymbol{w_{hh_n}}$.
	Multiple benefits	COMB TOKENS	$x_7 = \sum_{b=0}^{B} j_b . x_6$	Importance of a place for a combination of benefits of interest. Sum of all calculated $\boldsymbol{x_6}$ (TOKENS) for all benefits of interest, weighted by the relative importance $\boldsymbol{j_b}$ of each benefit.
	Reference	UNIFORM	$x_8 = 100$	Uniform importance (each planning unit, including trimmed ones had the same cost).

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

Text. Methods: 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 **Figure 2**) 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 **Figure 2**) indicated that HOUSEHOLDS gave higher values than TOKENS. Pixels close to 0 (shown in yellow in **Figure 2**) indicated no notable difference between the two indices.

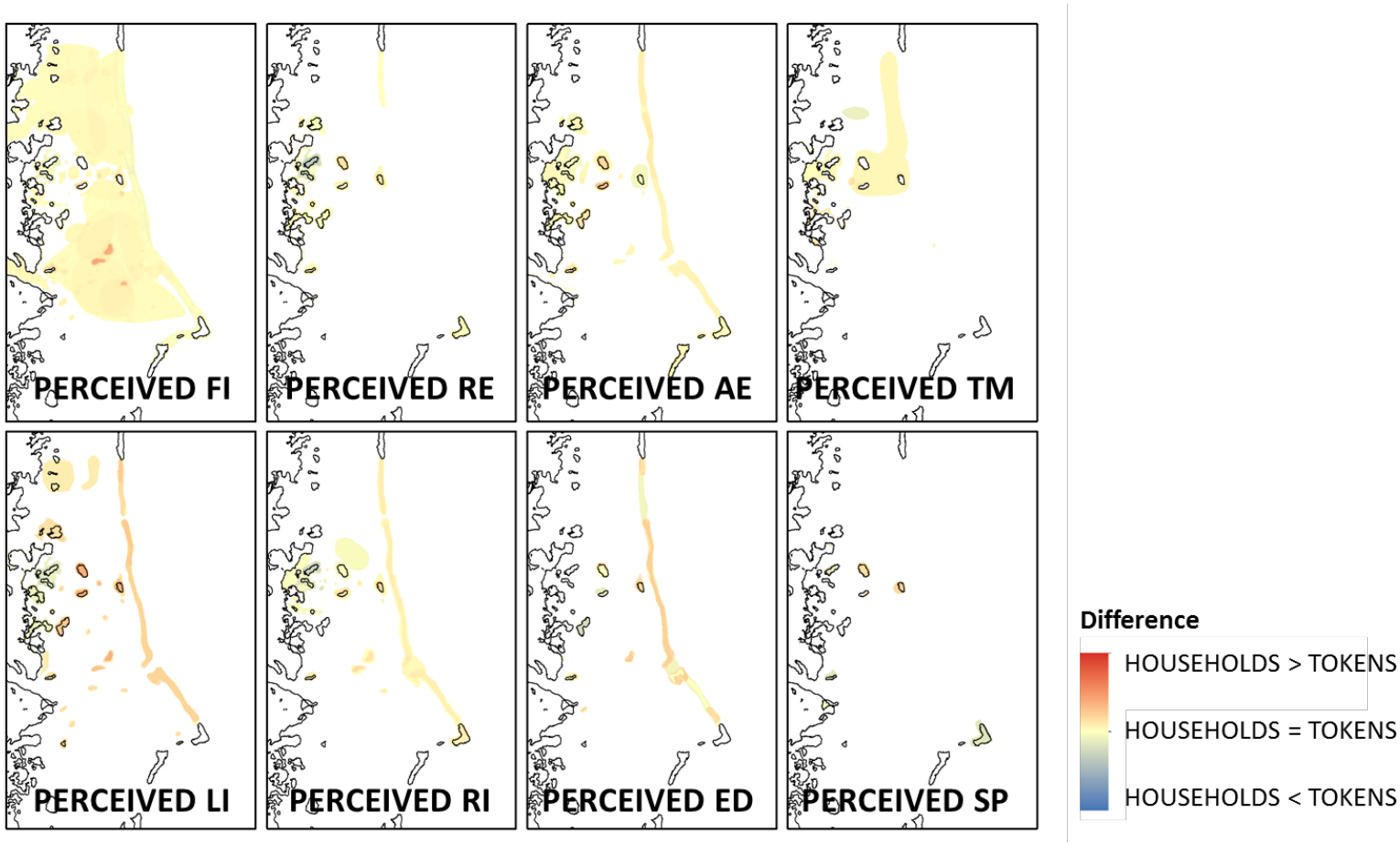

Fig 2. Map of the importance of areas as measured by the number of tokens (TOKENS) and the number of households (HOUSEHOLDS) for individual benefits. Benefits of interest included fishing (FI); recreation (RE); aesthetics (AE); traditional medicine (TM); collecting material to make lime for betel nut 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.

S3 Appendix. Details on geomorphic habitat data.

Table. 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
	lagoon-exposed fringing	enclosed lagoon or basin	36.9	70.5
		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
	outer barrier reef complex	deep terrace	11.5	11.8
		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

S4 Appendix. Details on results.

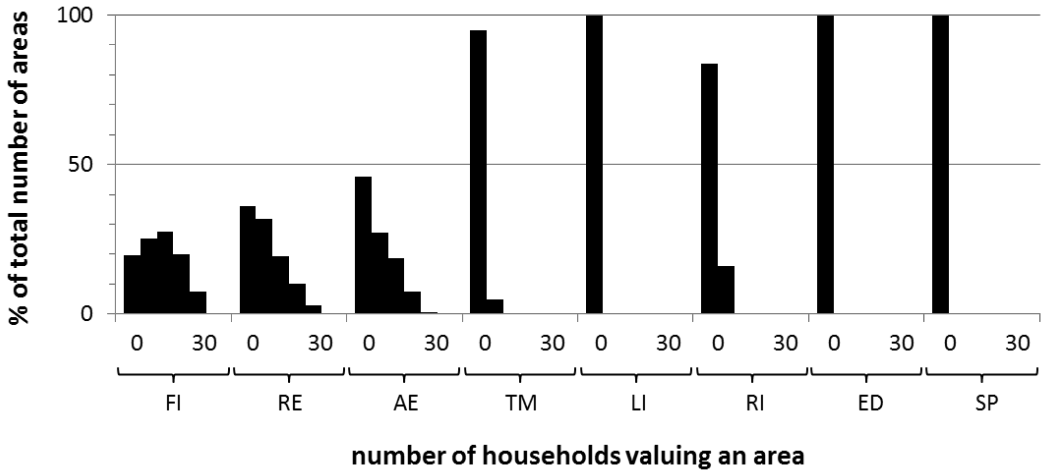

Fig 1. Frequency of areas in each "number of households" class for different ecosystem benefits. Benefits of interest included fishing (FI); recreation (RE); aesthetics (AE); traditional medicine (TM); collecting material to make lime for betel nut chewing (LI); perceived biological richness (RI); education and knowledge sharing (ED); spiritual value (SP). Benefits for which areas were valued by many households (higher classes on the x axis) reflect more consensus among households, whereas benefits for which areas were mostly valued by fewer households (lower classes on the x axis) reflect less consensus. Details on data are found in Table 1.

Table 1. Frequency of areas in each "number of households" class for different ecosystem benefits.

	Proportion of all areas valued for a given benefit							
Number of households valuing an area	**FI**	**RE**	**AE**	**TH**	**LI**	**RI**	**ED**	**SP**
0-5	19.6	36.1	46.1	95.0	99.8	83.9	100.0	100.0
5-10	25.4	31.7	27.2	5.0	0.2	15.9	0.0	0.0
10-15	27.4	19.1	18.7	0.0	0.0	0.2	0.0	0.0
15-20	19.9	10.2	7.3	0.0	0.0	0.0	0.0	0.0
20-25	7.4	2.9	0.6	0.0	0.0	0.0	0.0	0.0
25-30	0.3	0.0	0.0	0.0	0.0	0.0	0.0	0.0

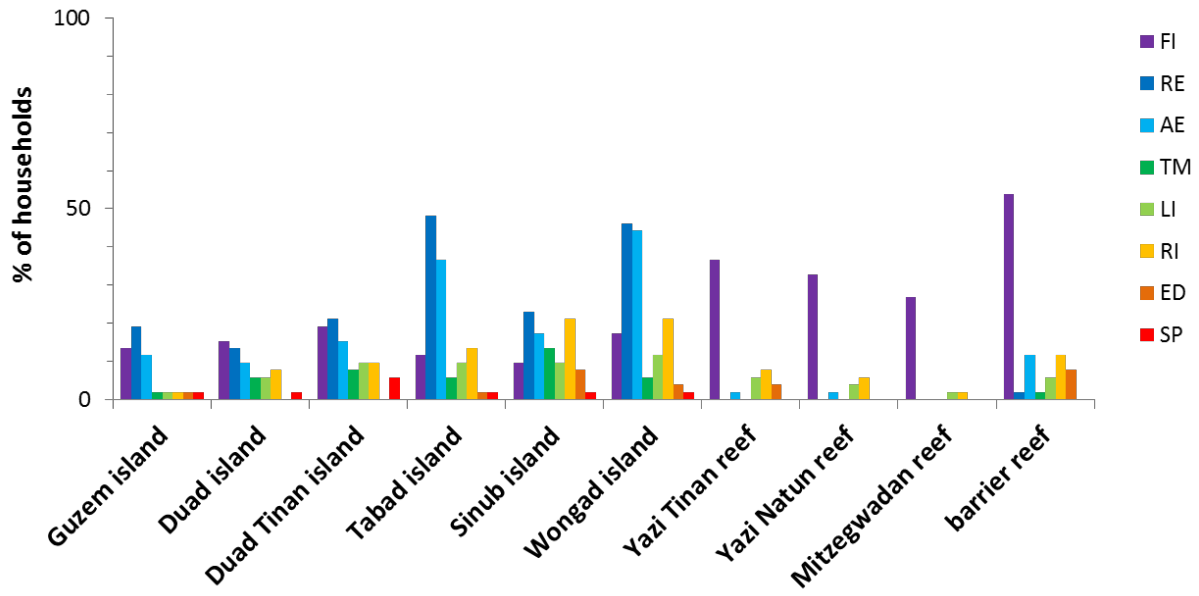

Fig. 2. Geomorphologic entities of importance for people of Riwo, according to the number of households valuing them for a range of ecosystem benefits. Islands and reefs were valued for fishing (FI), recreation (RE), aesthetics (AE), traditional medicine (TM), lime material (LI), perceived biological 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 Table 2.

Table 2. Geomorphologic entities of importance for people of Riwo, according to the number of households valuing them for a range of ecosystem benefits.

	Number of households for which the entity is important for a given benefit							
Geomorphic entities	**FI**	**RE**	**AE**	**TH**	**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

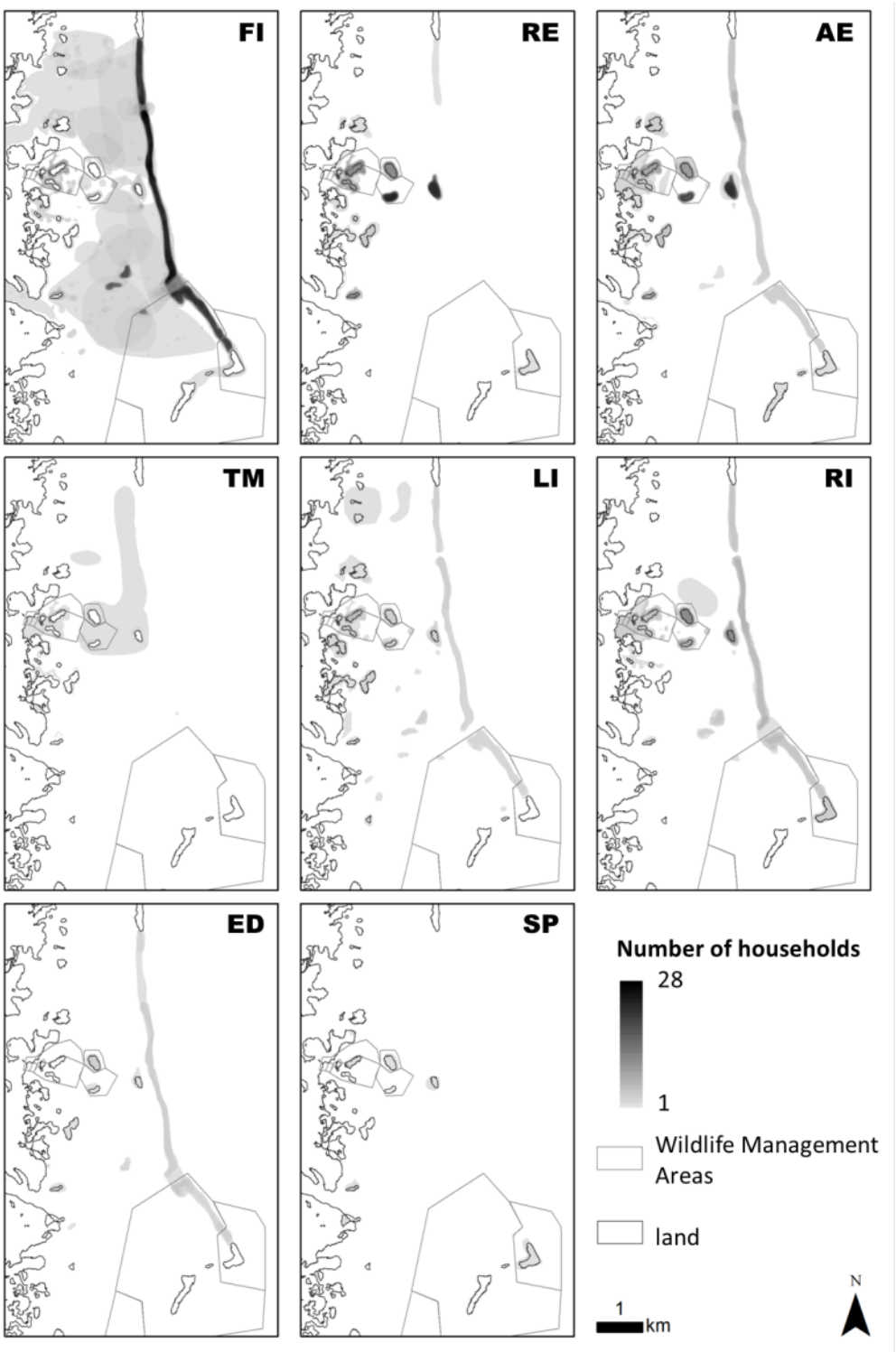

Fig 3. Number of households visiting and valuing different areas of the Madang Lagoon for the ecosystem benefits they provide. Types of benefits are: fishing (FI); recreation (RE); aesthetics (AE); traditional medicine (TM); collecting material to make lime for betel nut chewing (LI); perceived biological 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.

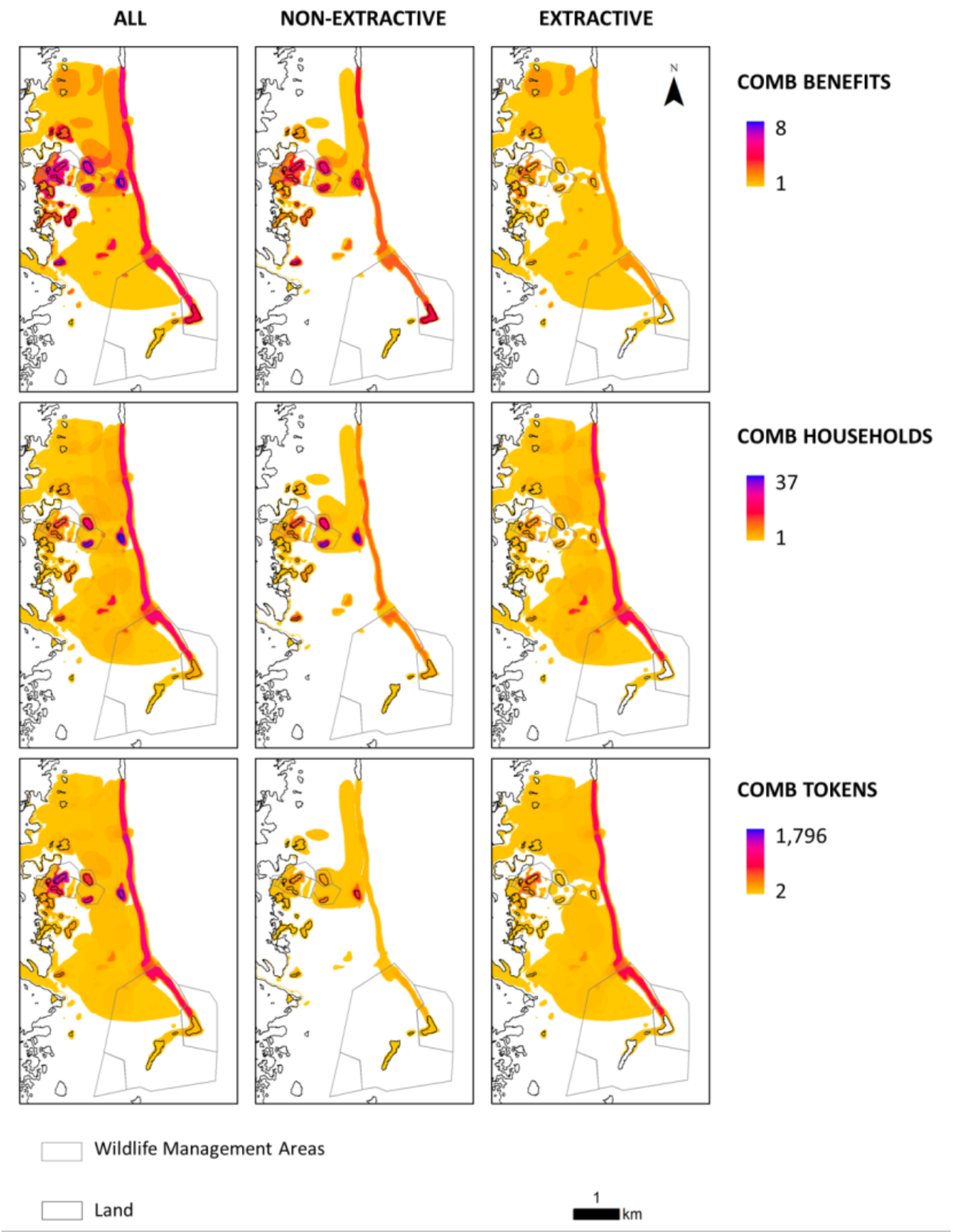

Fig 4. Importance of areas when combining benefits (raw data). All benefits combined (ALL), benefits related to non-extractive uses only (NON-EXTRACTIVE), and benefits related to extractive uses only (EXTRACTIVE). Three indicators were used: the number of benefits assigned to each area (theoretical minimum: 1 ≤ COMB BENEFITS ≤ theoretical maximum: 8), the number of households valuing each area (1 ≤ COMB HOUSEHOLDS ≤ 52) for any benefit, and the weighted sum of all tokens assigned to each area by all households (2 ≤ COMB TOKENS ≤ 1,796). See S2 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.

Table 3. 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 SOCIAL-ECOLOGICAL and ECOLOGICAL scenarios both aimed to minimise a cost representing the combination of all benefits. 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 cost (percentage of maximum possible cost for the benefit)									
Scenario	**FI**	**RE**	**AE**	**TR (all)**	**TR (ext)**	**TR (non-ext)**	**LI**	**BI**	**ED**	**SP**
FISHING	3	2	3	10	18	4	8	3	3	19
RECREATION	31	0	3	6	7	6	14	12	18	11
AESTHETICS	15	4	0	11	21	4	15	3	10	8
TRADITIONAL MEDICINE	27	4	6	0	1	0	13	9	15	17
TRADITIONAL MEDICINE (E)	33	33	35	35	0	61	21	41	41	34
TRADITIONAL MEDICINE (N-E)	27	3	6	7	15	0	15	11	19	15
LIME	16	4	7	5	1	8	1	5	11	31
BIOLOGICAL RICHNESS	17	7	8	16	16	16	20	1	23	9
EDUCATION	22	12	13	22	37	11	23	19	1	42
SPIRITUAL	35	10	14	26	43	14	35	19	24	0
UNIFORM	27	30	37	15	11	17	19	31	24	36
SOCIAL-ECOLOGICAL (ALL BENEFITS)	4	1	1	1	2	0	3	3	2	12
ECOLOGICAL (ALL BENEFITS)	4	1	2	1	2	0	2	3	3	15