

## Supplementary Materials for

### **Participation, not penalties: Community involvement and equitable governance contribute to more effective multiuse protected areas**

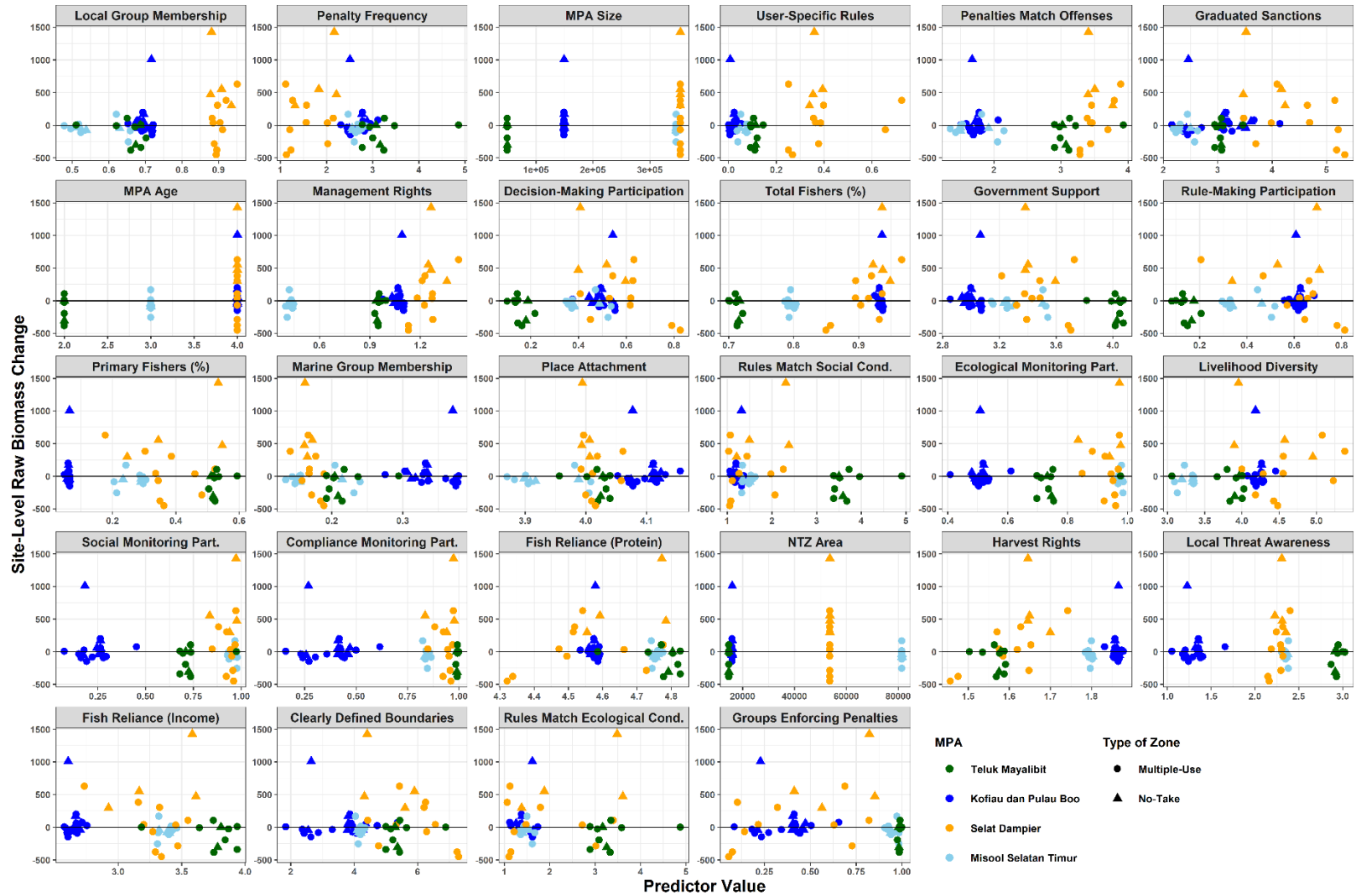
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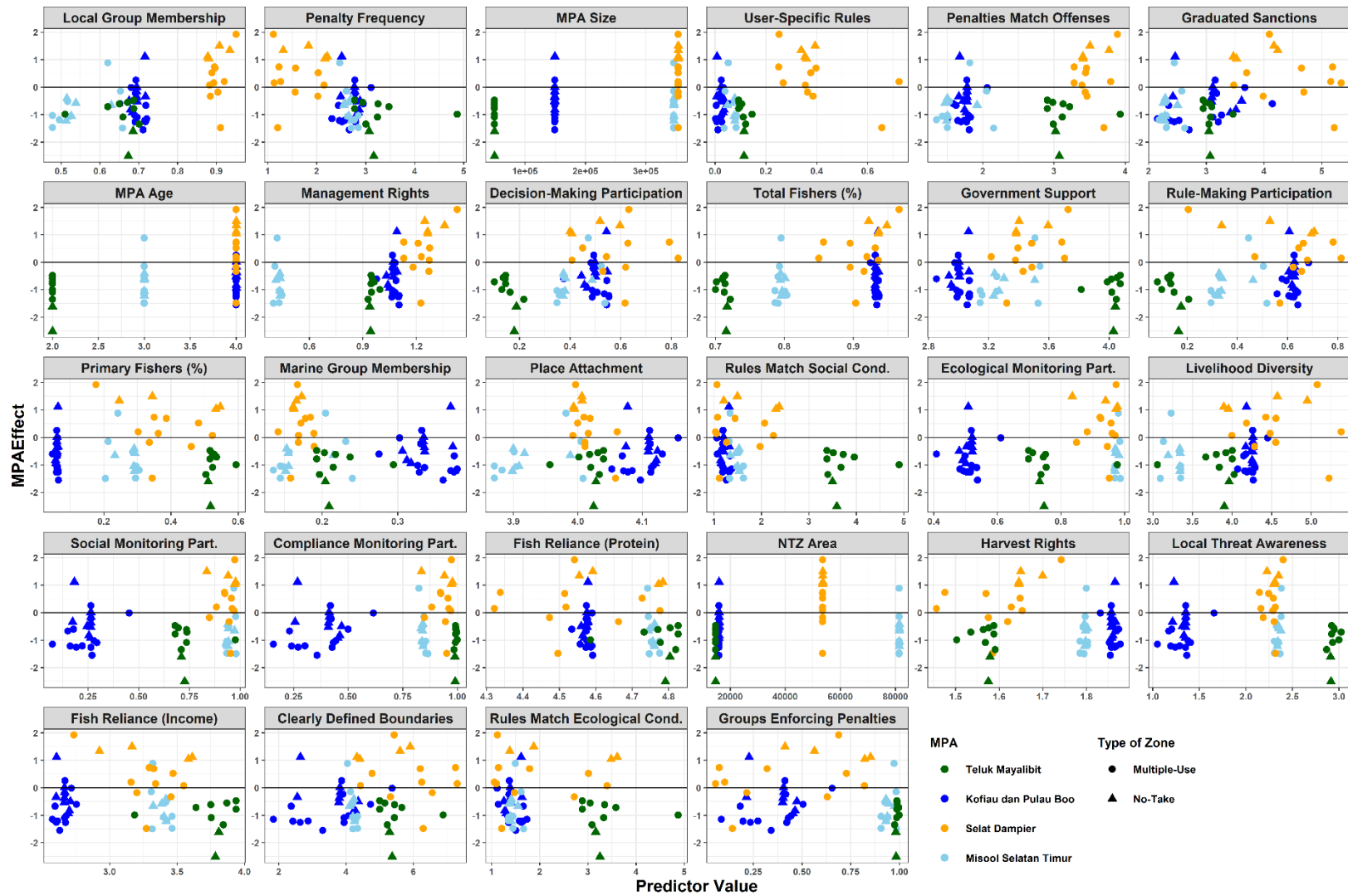
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#### **This PDF file includes:**

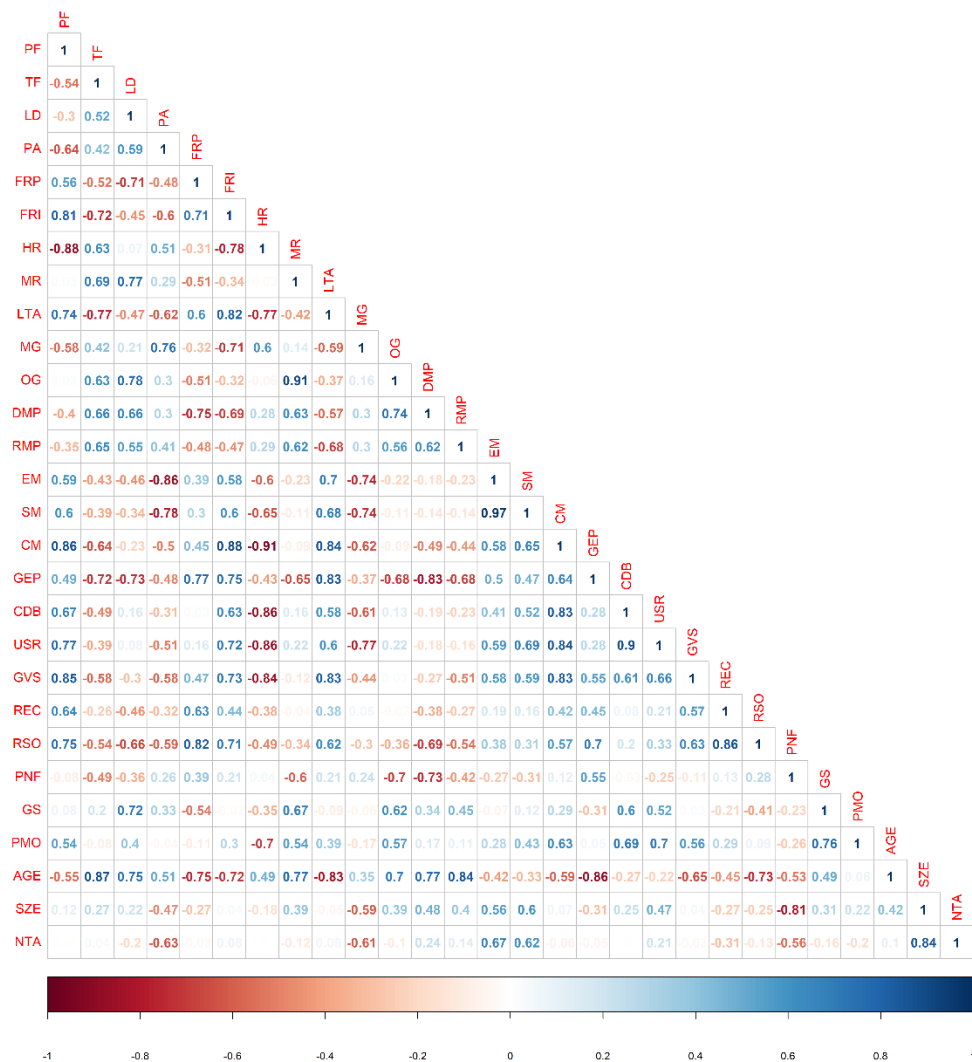
Figs. S1 to S7  
Tables S1 to S6



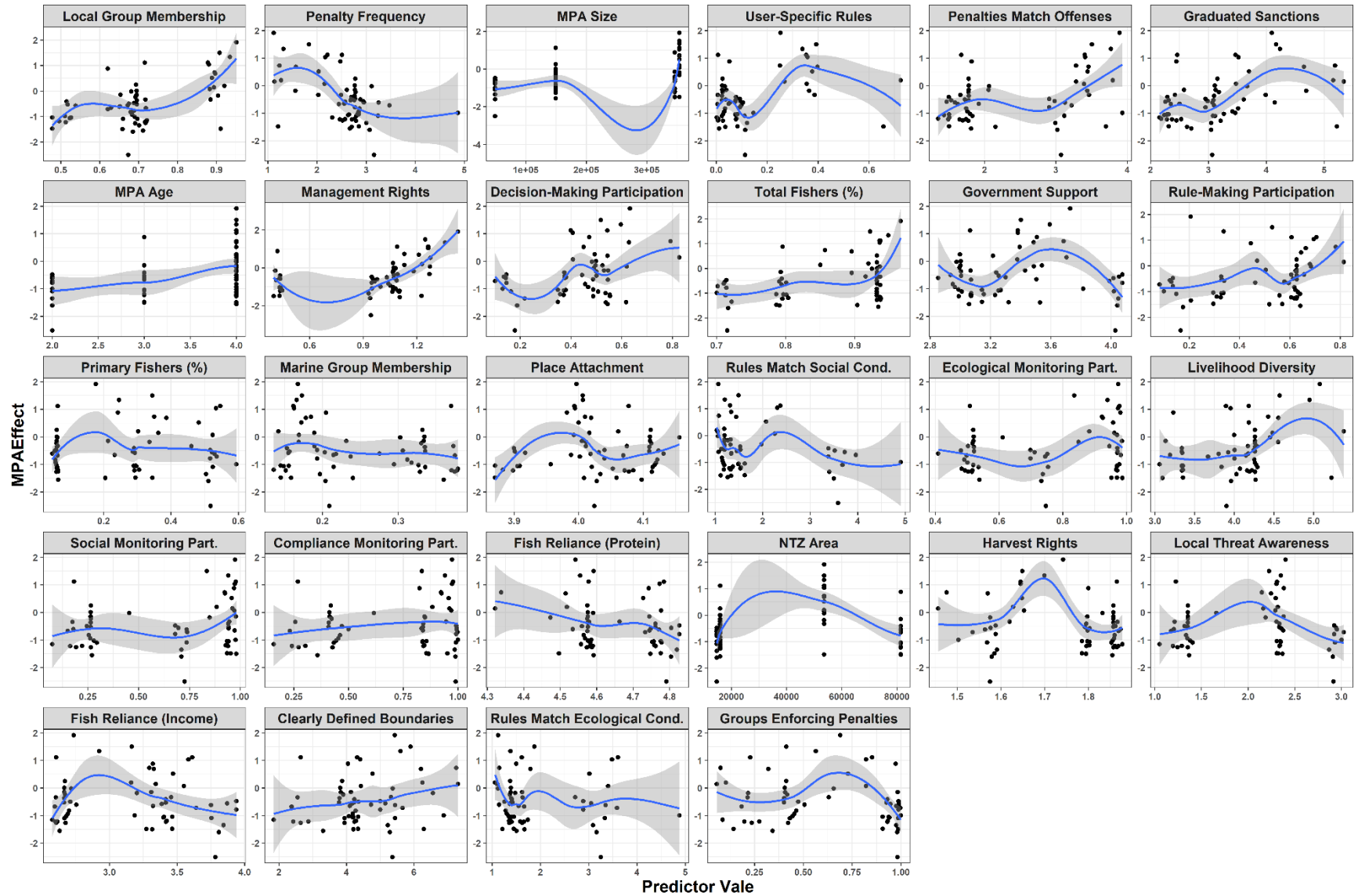
**Fig. S1. Raw fish biomass changes against predictor values by site.** Colors represent individual MPAs, while shapes represent the fishing restrictions at each site (circle: multiple-use zone; triangle: no-take zone).



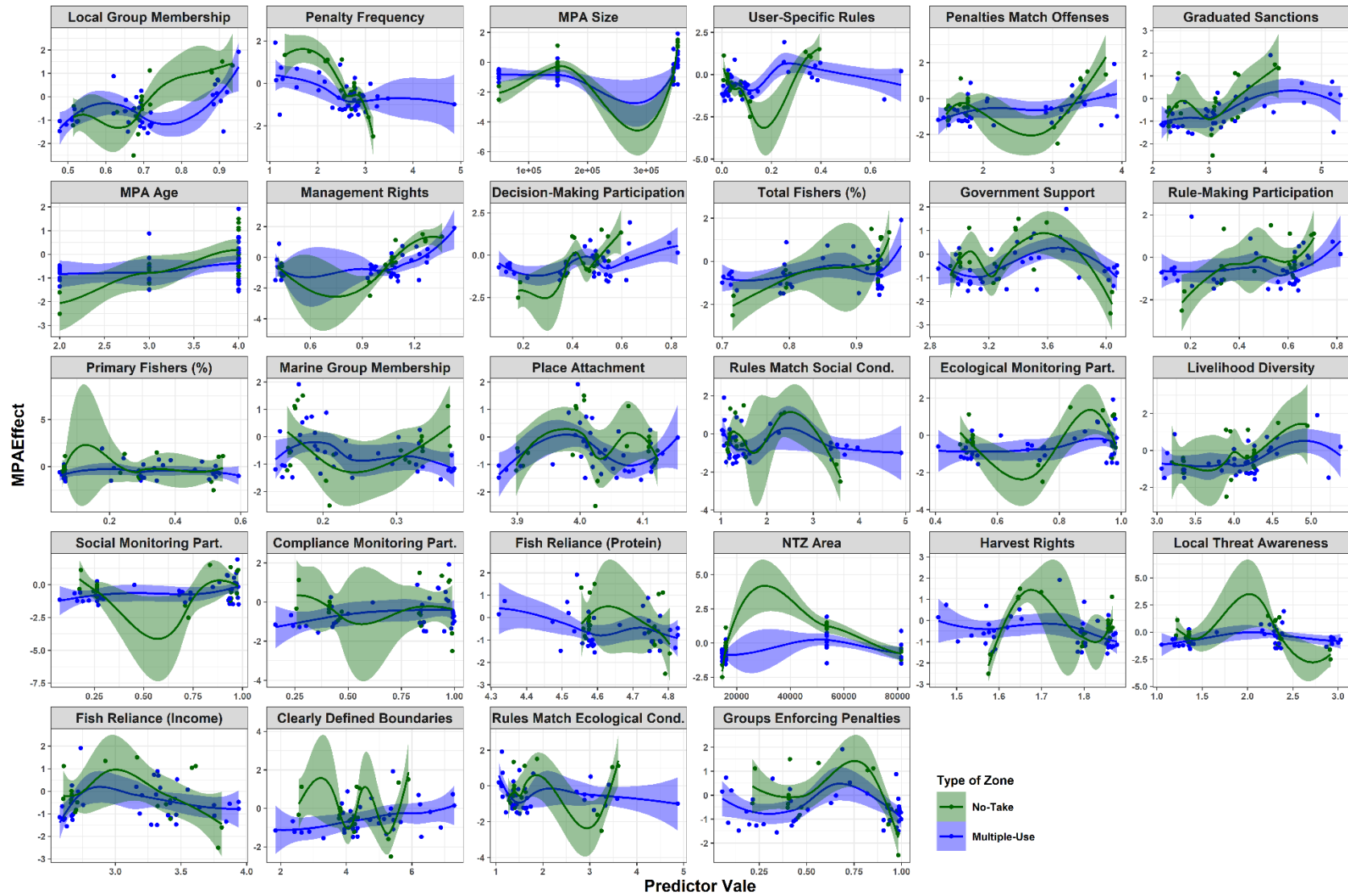
**Fig. S2. MPA<sub>Effect</sub> values against predictor values by site.** Colors represent individual MPAs, while shapes represent the fishing restrictions at each site (circle: multiple-use zone; triangle: no-take zone).



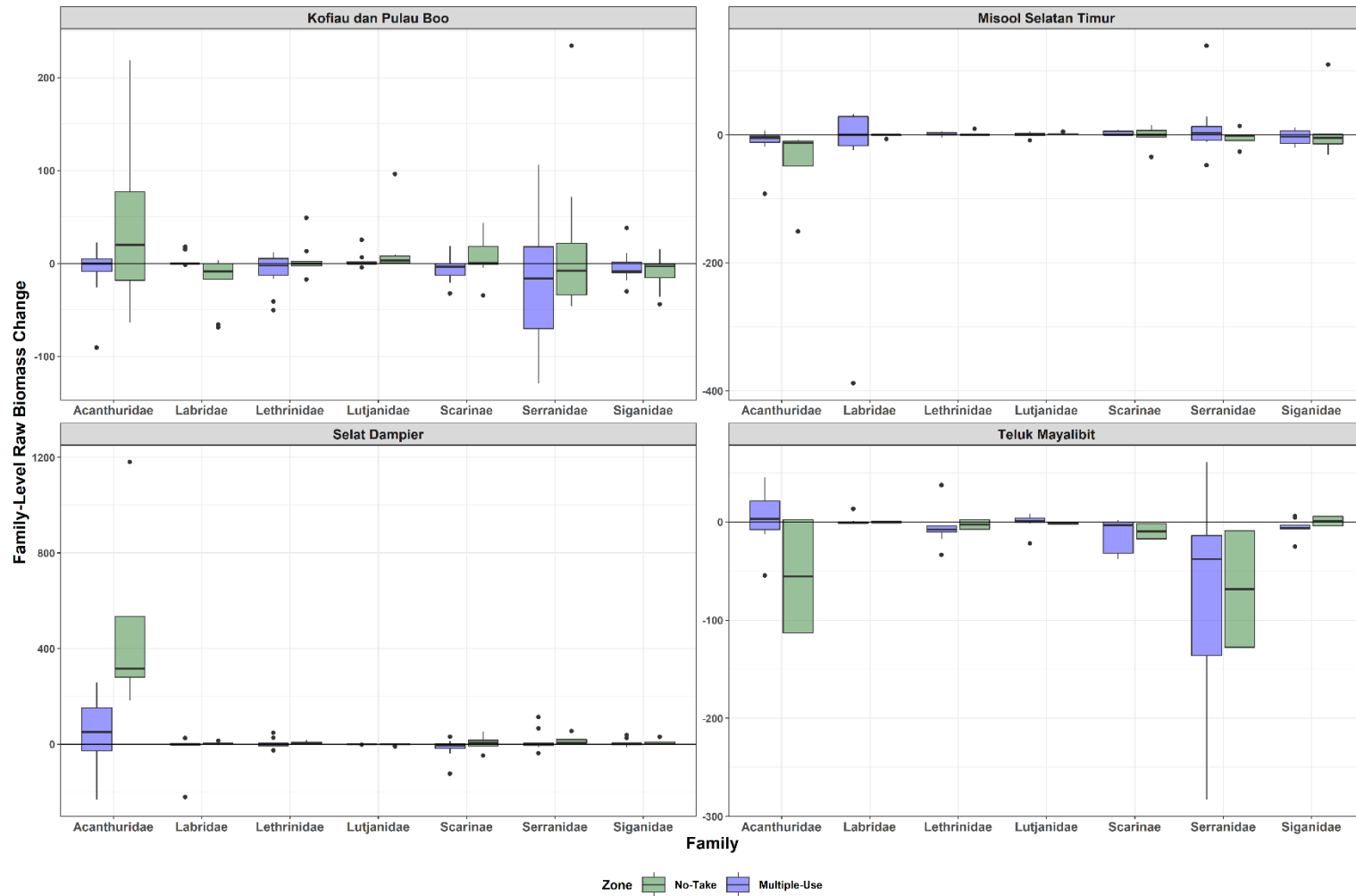
**Fig. S3. Spearman rank correlations among indicators used in analyses.** Colors represent correlative strength and direction (red: negative; blue: positive). Indicator names have been abbreviated for plot clarity; PF, primary fishers (%); TF, total fishers (%); LD, livelihood diversity; PA, place attachment; FRP, fish reliance (protein); FRI fish reliance (income); HR, harvest rights; MR, management rights; LTA, local threat awareness; MG, marine group participation; OG, other group participation; EM, ecological monitoring; SM, social monitoring; CM, compliance monitoring; GEP, groups enforcing penalties; CDB, clearly defined boundaries; USB, user-specific rules; GVS, government support; REC, rules match ecological conditions; RSO, rules match social conditions; PNF, penalty frequency; GS, graduated sanctions; PMO, penalties match offenses; AGE, MPA age; SZE, MPA size (ha); NTA, no-take area (ha).



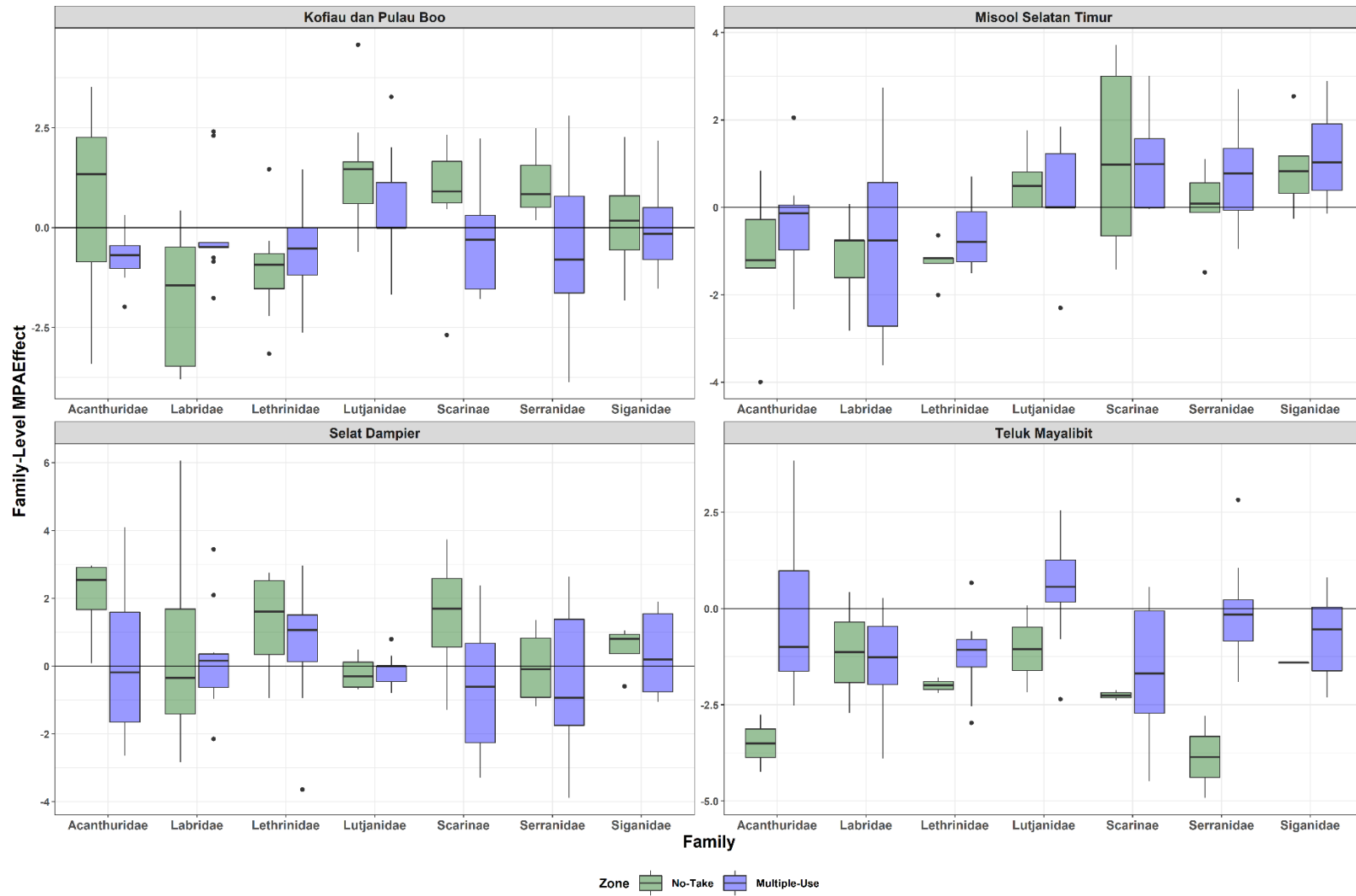
**Fig. S4.** LOESS curves of  $MPA_{Effect}$  values against predictor values by site. LOESS curves built for all values from all sites.



**Fig. S5.** LOESS curves of  $MPA_{Effect}$  values against predictor values by site. LOESS curves built individually for no-take (green) and multiple-use (blue) site.



**Fig. S6. Family-level raw biomass changes within MPAs by zone type.** Colors represent changes within no-take zones (green) and multiple-use zones (blue) between survey periods within each MPA.



**Fig. S7. Family-level  $MPA_{Effect}$  values within MPAs by zone type.** Colors represent  $MPA_{Effect}$  within no-take zones (green) and multiple-use zones (blue) between survey periods within each MPA.



**Table S1. Fish families included in analyses.** Proportion of total biomass observed across survey periods and ecological treatment (n=59) and control (n=28) sites used in final analysis.

| Family       | Description | Proportion of Biomass Survey 1 (MPAs) | Proportion of Biomass Survey 1 (Controls) | Proportion of Biomass Survey 2 (MPAs) | Proportion of Biomass Survey 2 (Controls) |
|--------------|-------------|---------------------------------------|---|---------------------------------------|---|
| Acanthuridae | Surgeonfish | 22.67%                                | 32.52%                                    | 32.49%                                | 36.61%                                    |
| Haemulidae   | Grunts      | 24.58%                                | 23.57%                                    | 26.43%                                | 27.48%                                    |
| Lethrinidae  | Emperors    | 5.47%                                 | 1.52%                                     | 5.11%                                 | 4.35%                                     |
| Lutjanidae   | Snappers    | 0.73%                                 | 1.97%                                     | 2.43%                                 | 0.66%                                     |
| Scarinae     | Parrotfish  | 8.91%                                 | 5.01%                                     | 5.53%                                 | 3.58%                                     |
| Serranidae   | Groupers    | 27.00%                                | 17.90%                                    | 20.07%                                | 17.08%                                    |
| Siganidae    | Rabbitfish  | 10.64%                                | 17.51%                                    | 7.93%                                 | 10.24%                                    |

**Table S2. Results of pre-matching random forest and Boruta analyses to select matching covariates.** For each attribute within “Tested Covariates”, the number of times an indicator was included in random forest model iterations (“Selected”), and the number of times it was confirmed by the Boruta algorithm as an important predictor of outcomes (“Confirmed”). Bold values indicate attributes that were chosen as matching covariates, as they were confirmed more than 15% of the time they were chosen (“Rate”). Calipers restricting maximum allowable differences in covariates are also presented. Additional covariates used to increase site similarity between treatment and control sites in the matching protocol are presented in “Additional Covariates” at the bottom of the table.

| Category                        | Sub-Category                                  | Attribute                            | Data Source | Selected   | Confirmed  | Rate           | Caliper     |
|---------------------------------|---|--------------------------------------|-------------|------------|------------|----------------|-------------|
| Tested Covariates               | Proximity                                     | Distance to shoreline                | Raw Data    | 756        | 45         | 5.95%          | -           |
|                                 |   | <b>Distance to 50m depth contour</b> | <b>(64)</b> | <b>736</b> | <b>118</b> | <b>16.03%</b>  | <b>None</b> |
|                                 |   | Distance to mangroves                | (63)        | 753        | 0          | 0.00%          | -           |
|                                 |   | <b>Distance to major market</b>      | <b>(66)</b> | <b>726</b> | <b>726</b> | <b>100.00%</b> | <b>None</b> |
|                                 | Land Area                                     | <b>Within 10 km</b>                  | <b>(66)</b> | <b>717</b> | <b>231</b> | <b>32.22%</b>  | <b>None</b> |
|                                 |   | Within 25 km                         | (66)        | 741        | 0          | 0.00%          | -           |
|                                 |   | Within 50 km                         | (66)        | 713        | 1          | 0.14%          | -           |
|                                 | Reef Area                                     | <b>Within 10 km</b>                  | <b>(66)</b> | <b>734</b> | <b>185</b> | <b>25.20%</b>  | <b>None</b> |
|                                 |   | Within 25 km                         | (66)        | 733        | 0          | 0.00%          | -           |
|                                 |   | Within 50 km                         | (66)        | 753        | 66         | 8.76%          | -           |
|                                 | Primary Productivity                          | <b>Mean</b>                          | <b>(66)</b> | <b>718</b> | <b>662</b> | <b>92.20%</b>  | <b>None</b> |
|                                 | Wave Energy                                   | Mean                                 | (66)        | 703        | 6          | 0.85%          | -           |
|                                 | Benthic Characteristics                       | Initial algae cover (%)              | Raw Data    | 718        | 0          | 0.00%          | -           |
|                                 |   | Initial hard coral cover (%)         | Raw Data    | 706        | 0          | 0.00%          | -           |
|                                 |   | Initial hard-bottom cover (%)        | Raw Data    | 705        | 1          | 0.14%          | -           |
|                                 |   | Initial soft coral cover (%)         | Raw Data    | 718        | 0          | 0.00%          | -           |
|                                 | Heating Weeks                                 | <b>4° heating weeks (5 km)</b>       | <b>(65)</b> | <b>723</b> | <b>346</b> | <b>47.86%</b>  | <b>None</b> |
|                                 |   | 8° heating weeks (5 km)              | (65)        | 709        | 0          | 0.00%          | -           |
|                                 | Human Population                              | Population within 10 km              | (66)        | 739        | 17         | 2.30%          | -           |
|                                 |   | Population within 25 km              | (66)        | 716        | 1          | 0.14%          | -           |
| Population within 50 km         |   | (66)                                 | 744         | 4          | 0.54%      | -              |             |
| Fish Population Characteristics | Percentage of biomass comprised of herbivores | Raw Data                             | 723         | 0          | 0.00%      | -              |             |

|                          |                                    |  |                 |   |   |   |   |
|--------------------------|------------------------------------|--|-----------------|---|---|---|---|
|                          | Survey Period                      | <b>Survey year 1</b>                             | <b>Raw Data</b> | - | - | - | <b>2 Years</b>                            |
|                          |                                    | <b>Survey gap</b>                                | <b>Raw Data</b> | - | - | - | <b>2 Years</b>                            |
| Additional<br>Covariates | Reef Habitat                       | <b>Slope (wall / slope / flat)</b>               | <b>Raw Data</b> | - | - | - | <b>Walls &amp; Flats Can't Match</b>      |
|                          | Fish Population<br>Characteristics | <b>Initial fish biomass (kg ha<sup>-1</sup>)</b> | <b>Raw Data</b> | - | - | - | <b>0.25 SD (193.0 kg ha<sup>-1</sup>)</b> |
|                          | MPA Location                       | <b>Location</b>                                  | <b>Raw Data</b> | - | - | - | <b>Matched by Location</b>                |

**Table S3. Covariate match balance between treatment and control sites pre- and post-matching.** Mean values of each covariate for treatment (MPA) and control (Control) sites, standardized mean differences, and p-values for each covariate both pre- and post-matching, as well as the results of Chi-Square significance tests on overall covariate balance. Significant p-values are represented by bold text and indicate significant differences in individual covariates and overall covariate balance between treatment and control sites.

| Variable                     | Step          | MPA           | Control | Standardized Mean |                  |
|------------------------------|---------------|---------------|---------|-------------------|------------------|
|                              |               |               |         | Difference        | P-Value          |
| Initial Survey Year          | Pre-Matching  | 2011.87       | 2011.95 | -0.07             | 0.702            |
|                              | Post-Matching | 2011.85       | 2011.93 | -0.08             | 0.737            |
| MPA Code                     | Pre-Matching  | 4.86          | 4.23    | 0.85              | <b>&lt;0.001</b> |
|                              | Post-Matching | 4.81          | 4.34    | 0.66              | <b>0.006</b>     |
| Survey Gap                   | Pre-Matching  | 3.51          | 3.46    | 0.04              | 0.821            |
|                              | Post-Matching | 3.59          | 3.46    | 0.11              | 0.625            |
| Reef Habitat (Slope)         | Pre-Matching  | 0.99          | 0.98    | 0.01              | 0.937            |
|                              | Post-Matching | 1.02          | 0.89    | 0.15              | 0.503            |
| Primary Productivity (Mean)  | Pre-Matching  | 1315.18       | 1404.52 | -0.61             | <b>0.002</b>     |
|                              | Post-Matching | 1322.33       | 1400.48 | -0.55             | <b>0.020</b>     |
| Distance to Market           | Pre-Matching  | 373.80        | 425.68  | -0.81             | <b>&lt;0.001</b> |
|                              | Post-Matching | 372.33        | 422.68  | -0.76             | <b>0.002</b>     |
| Land Area within 10 km       | Pre-Matching  | 51.12         | 46.25   | 0.11              | 0.546            |
|                              | Post-Matching | 58.89         | 42.58   | 0.37              | 0.114            |
| Initial Fish Biomass         | Pre-Matching  | 538.68        | 364.32  | 0.23              | 0.236            |
|                              | Post-Matching | 210.68        | 213.01  | -0.02             | 0.945            |
| 4° Heating Weeks             | Pre-Matching  | 66.21         | 91.90   | -0.36             | 0.062            |
|                              | Post-Matching | 67.63         | 76.50   | -0.14             | 0.532            |
| Reef Area within 10 km       | Pre-Matching  | 20.15         | 16.72   | 0.26              | 0.170            |
|                              | Post-Matching | 21.91         | 19.56   | 0.18              | 0.440            |
| Distance to 50m Depth Isobar | Pre-Matching  | 1256.72       | 1327.58 | -0.07             | 0.707            |
|                              | Post-Matching | 1277.33       | 1330.28 | -0.05             | 0.837            |
| Overall Balance              |               | Chi-Square    |         | D.F.              | P-Value          |
|                              |               | Pre-Matching  | 66.85   | 11                | <b>&lt;0.001</b> |
|                              |               | Post-Matching | 43.59   | 11                | <b>&lt;0.001</b> |

**Table S4. Data sources, calculations, and descriptive statistics for all environmental covariates and governance, social, and property-rights indicators used in analyses.** Data sources listed as "FGD" came from focus group discussions, "KII" from key informant interviews, "HHS" from household surveys, and "RD" from raw data. An asterisk (\*) on an Attribute indicates that more details regarding the survey question and subsequent calculations can be found in Table S6.

| Category                       | Sub-Category                     | Attribute  | Data Source | Calculation at Community Level   | Mean  | SD    | Min   | Max   |
|--------------------------------|----------------------------------|--|-------------|--|-------|-------|-------|-------|
| Governance Indicators (Ostrom) | Clearly Defined Boundaries       | Clearly Defined Boundaries*                      | FGD         | Total number of ways boundaries are communicated to the community  | 4.54  | 1.19  | 1.84  | 7.30  |
|                                | Participation in Decision Making | Participation in Local Marine Organizations      | HHS         | Percentage of respondents indicating they are members of a local marine organization   | 24.2% | 8.3%  | 13.6% | 37.9% |
|                                |                                  | Participation in Other Local Organizations       | HHS         | Percentage of respondents indicating they are members of other local organizations   | 70.7% | 13.0% | 47.8% | 95.1% |
|                                |                                  | Participation in Decision Making                 | FGD         | Percentage of respondents reporting participation in either establishing MPAs, setting boundaries, or administration of MPAs | 43.9% | 16.0% | 10.2% | 82.7% |
|                                |                                  | Participation in Rule Making                     | FGD         | Percentage of respondents reporting participation in making rules about resource management                                  | 47.9% | 20.4% | 8.3%  | 81.4% |
|                                | Accountable Monitoring           | Social Monitoring Participation                  | FGD         | Percentage of user groups reported to be active in social monitoring   | 64.5% | 33.0% | 7.5%  | 98.1% |
|                                |                                  | Compliance Monitoring Participation              | FGD         | Percentage of user groups reported to be active in compliance monitoring   | 71.8% | 27.5% | 15.8% | 99.0% |
|                                |                                  | Ecological Monitoring Participation              | FGD         | Percentage of user groups reported to be active in ecological monitoring   | 75.4% | 20.8% | 40.9% | 98.7% |
|                                |                                  | Penalty Frequency*                               | KII         | Frequency of penalty enforcement (1-5)   | 2.54  | 0.65  | 1.12  | 4.87  |
|                                |                                  | Penalty Enforcement Participation                | FGD         | Percentage of user groups reported to be active in enforcing penalties on rule breakers                                      | 62.1% | 32.4% | 5.6%  | 99.0% |
|                                | Congruence with Local Conditions | User-Specific Rules                              | KII         | Percentage of user groups for which special rules apply  | 13.4% | 16.2% | 0.2%  | 72.5% |
|                                |                                  | Rule Flexibility to Local Ecological Conditions* | KII         | How often rules change based on ecological conditions (1-5)  | 1.90  | 0.88  | 1.06  | 4.88  |
|                                |                                  | Rule Flexibility to Local Ecological Conditions* | KII         | How often rules change based on social conditions (1-5)  | 1.78  | 0.94  | 1.04  | 4.91  |

|                                |                              |   |           |   |         |         |        |         |
|--------------------------------|------------------------------|---|-----------|---|---------|---------|--------|---------|
| Governance Indicators (Ostrom) | Graduated Sanctions          | Graduated Sanctions are Enforced on Rule Breakers*                  | FGD / KII | Total number of increased severity of sanctions enforced on rule breakers. data collected in both KIIs and FGDs. mean of values if both present, otherwise single representative value. | 3.19    | 0.84    | 2.16   | 5.34    |
|                                |                              | Sanctions Match Severity of Offense*                                | KII       | Number of qualifications considered for penalties based on the severity of the offense (0-4)  | 2.37    | 0.85    | 1.35   | 3.93    |
|                                | Recognition by Authorities   | Government Support of Local Rights*                                 | KII       | Level of support for local user rights from national government (1-5)   | 3.36    | 0.37    | 2.85   | 4.07    |
| Social Indicators              | Reliance on Marine Resources | Primary Fishers   | HHS       | Percent of respondents indicating "fisher" as their primary livelihood  | 26.4%   | 18.5%   | 4.8%   | 59.4%   |
|                                |                              | Primary, Secondary, or Tertiary Fishers                             | HHS       | Percent of respondents indicating "fisher" as their primary, secondary, or tertiary livelihood  | 86.1%   | 8.8%    | 70.0%  | 96.7%   |
|                                |                              | Diversity of Livelihoods  | HHS       | Number of unique livelihoods listed as "primary" within community   | 4.03    | 0.53    | 3.06   | 5.38    |
|                                |                              | Reliance on Fish for Income*  | HHS       | Amount of household income derived from fishing (1-5)   | 3.15    | 0.44    | 2.58   | 3.94    |
|                                |                              | Reliance on Fish for Food*  | HHS       | Amount of household protein intake derived from fish (1-5)  | 4.65    | 0.12    | 4.32   | 4.83    |
|                                | Attachment to Place          | Place Attachment*   | HHS       | Number of qualifications indicating cultural or emotional attachment to mpas (0-6)  | 4.03    | 0.07    | 3.87   | 4.16    |
|                                | Self-Efficacy                | Local Ecological Threat Awareness*                                  | HHS       | Number of local threats to marine resources identified  | 2.05    | 0.62    | 1.05   | 3.03    |
| Property-Rights Indicators     | Tenure Rights                | Harvest Rights  | HHS       | Exercise of rights to "access" MPAs and "harvest" resources from them in the past 12 months (0-2)   | 1.74    | 0.13    | 1.46   | 1.88    |
|                                |                              | Management Rights   | HHS       | Exercise of rights to "manage" MPAs, "exclude" others from MPAs, and "transfer" rights to others in the past 12 months (0-3)  | 0.95    | 0.30    | 0.40   | 1.43    |
| MPA Characteristics            | Size No-Take Area            | Total MPA Size (Ha)   | RD        | -   | 224,186 | 121,536 | 49,451 | 353,531 |
|                                |                              | Total No-Take Area (Ha)   | RD        | -   | 39,095  | 27,528  | 14,684 | 81,394  |
|                                | Age                          | Years After Implementation of Zonation when Repeat Surveys Occurred | RD        | -   | 3.44    | 0.77    | 2.00   | 4.00    |
|                                |                              | Fishing Restrictions at Individual Sites (No-Take or Multiple-Use)  | RD        | -   | -       | -       | -      | -       |

**Table S5. Survey questions and details regarding quantitative calculations for selected indicators.** Specific phrasing of questions, possible responses, and calculations for indicators that were unable to be converted to percentages prior to analyses.

| Category                       | Sub-Category                     | Attribute   | Calculation at Community Level  | Survey Question Details   |
|--------------------------------|----------------------------------|---|---|---|
| Governance Indicators (Ostrom) | Clearly Defined Boundaries       | Clearly Defined Boundaries                        | Total number of ways boundaries are communicated to community   | How are the boundaries of the MPA made clear to individuals that use marine resources? (+1 for each): Aligned with local landmarks?; Demarcated with boundary markers?; Communicated via signs?; Announced via government notice?; Communicated via written outreach?; Communicated via audio outreach?; Communicated via video outreach? Spread through word of mouth?; Other? |
|                                | Accountable Monitoring           | Penalty Frequency                                 | Frequency of penalty enforcement (1-5)  | If caught breaking rules in the MPA, how often do rule-breakers receive penalties? (1) Never; (2) Rarely; (3) Sometimes; (4) Usually; (5) Always.   |
|                                | Congruence with Local Conditions | Rule Flexibility to Local Ecological Conditions   | How often rules change based on ecological conditions (1-5)   | Do the rules governing marine resources change based on changes in ecological conditions in and around MPA? (1) Never; (2) Rarely; (3) Sometimes; (4) Usually; (5) Always.  |
|                                |                                  | Rule Flexibility to Local Ecological Conditions   | How often rules change based on social conditions (1-5)   | Do the rules governing marine resources change based on changes in social conditions in and around MPA? (1) Never; (2) Rarely; (3) Sometimes; (4) Usually; (5) Always.  |
|                                | Graduated Sanctions              | Graduated Sanctions are Enforced on Rule Breakers | Total number of increased severity of sanctions enforced on rule breakers. Data collected in both KIIs and FGDs. mean of values if both present, otherwise single representative value. | Both KII & FGD: What penalties exist to encourage compliance with rules governing marine resource use? (+1 for each): Verbal Warnings; Written Warnings; Loss of access to marine resources?; Confiscation of equipment?; Fines?; Incarceration?; Other?  |
|                                |                                  | Sanctions match Severity of Offense               | Number of qualifications considered for penalties based on the severity of the offense  | What factors influence the choice of penalties on rule breakers? (+1 for each): Number of previous offenses; Ecological impact; Economic impact; Social impact.   |
|                                | Recognition by Authorities       | Government Support of Local Rights                | Level of support for local user rights from national government (1-5)   | To what extent does that national government oppose or support the rights of users to develop their own rules governing marine resources? (1) Strongly Oppose; (2) Oppose; (3) Neither oppose nor support; (4) Support; (5) Strongly support.   |

|                   |                              |                                   |  |  |
|-------------------|------------------------------|-----------------------------------|--|--|
| Social Indicators | Reliance on Marine Resources | Reliance on Fish for Income       | Amount of household income derived from fishing (1-5)                              | In the last 6 months, how much of household income came from fishing? (1) None; (2) Some; (3) About half; (4) Most; (5) All.   |
|                   |                              | Reliance on Fish for Food         | Amount of household protein intake derived from fish (1-5)                         | In the last 6 months, how often did your household eat fish? (1) Once or never; (2) A few times; (3) A few times per month; (4) A few times per week; (5) More than a few times per week.  |
|                   | Attachment to Place          | Place Attachment                  | Number of qualifications indicating cultural or emotional attachment to MPAs (0-6) | One point for each positive response: "I am happiest when I'm in the MPA"; "The MPA is my favorite place to be"; "I miss the MPA when I'm away too long"; "The MPA is the best place to do the things I enjoy"; "I wouldn't want to fish anywhere other than the MPA"; "I feel I can be myself when I'm in the MPA." |
|                   | Self-Efficacy                | Local Ecological Threat Awareness | Number of local threats identified   | What are the threats to the health of the local marine environment?  |



**Table S6. Indicators for which data imputation was conducted and the percentage of data missing for each indicator.** Data imputation was conducted for indicators when <15% of data was unavailable from settlement-level surveys. Indicators not listed below contained no missing data.

| Indicator                                 | Missing (%) |
|---|-------------|
| Clearly Defined Boundaries                | 3.1%        |
| Compliance Monitoring                     | 3.1%        |
| Decision-Making Participation (%)         | 3.1%        |
| Ecological Monitoring                     | 9.4%        |
| External Governmental Support             | 9.4%        |
| Groups Enforcing Rules                    | 6.2%        |
| Penalty Frequency                         | 6.2%        |
| Rule Flexibility to Ecological Conditions | 6.2%        |
| Rule Flexibility to Social Conditions     | 12.5%       |
| Rule-Making Participation (%)             | 3.1%        |
| Sanctions Match Nature of Offense         | 6.2%        |
| Social Monitoring                         | 12.5%       |
| User-Specific Rules                       | 6.2%        |