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RESOLVING POTENTIAL REDUNDANCY OF PRODUCTIVITY ATTRIBUTES TO IMPROVE ECOLOGICAL RISK ASSESSMENTS

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CONTENTS

1. INTRODUCTION

The Inter-American Tropical Tuna Commission (IATTC) is responsible for ensuring the long-term conservation and sustainable use of the stocks of tunas and tuna-like species and other species of fish taken by vessels fishing for tunas and tuna-like species. Under the 2003 Antigua Convention, which entered into force in 2010, it has a clear mandate and responsibilities regarding associated non-target species and the supporting ecosystems. However, complying with this mandate and responsibilities for non-target species can be a significant challenge, especially in tropical ecosystems where bycatch assemblages can be highly diverse. Because non-target species generally have little economic value, they are often not reported in logbooks, or are reported as generic taxonomic aggregations (*e.g.* small tunas). Furthermore, these species have generally not been the subject of detailed scientific studies of their biology and ecology. Thus, there are often insufficient species-specific catch and biological data available to develop robust stock assessment models for determining the status of these stocks and provide reliable information as a basis for effective management measures. Therefore, alternative methods are required to provide fishery managers with sufficient information to prioritize potential species of concern, mitigate risks to their sustainability, or collect detailed species-specific information that can be used in more traditional population assessment approaches.

Ecological Risk Assessment (ERA) is one such alternative approach that can be used to assess the relative sustainability of highly diverse, data-limited bycatch assemblages impacted by fisheries. ERA approaches range from qualitative consequence-likelihood methods driven by information derived from expert opinion (Fletcher 2005), to more data-intensive quantitative spatially-explicit population dynamics models (Zhou and Griffiths 2006). However, semi-quantitative attribute-based ERA methods are being increasingly used, in particular the Productivity-Susceptibility Analysis (PSA) that was originally developed to assess the sustainability of thousands of data-poor bycatch species caught in tropical demersal shrimp trawl fisheries (Stobutzki *et al.* 2001).

PSA measures the relative sustainability of individual species by ranking them based on several criteria (called 'attributes') related to their susceptibility to being captured, and the capacity of the population to recover from depletion. For each species, susceptibility attributes (*e.g.* geographic distribution, position in the water column relative to fishing gear depth) and productivity attributes (*e.g.* reproductive strategy, growth rate, and fecundity) are given a rank of 1 to 3, reflecting the contribution of the attribute to the overall sustainability of the species. The species having the lowest productivity and highest susceptibility ranks across all attributes are then considered to be the species at highest risk for which the catch is becoming unsustainable under current levels of fishing.

The flexibility and minimal data requirements of PSA has led to the method being used in a wide range of fisheries worldwide, from demersal trawl fisheries (Stobutzki *et al.* 2001) to tuna fisheries in the Atlantic Ocean (Arrizabalaba *et al.* 2011) and western Pacific Ocean (Kirby 2006). In recent years, IATTC staff have applied the PSA approach, as adapted to U.S. fisheries (Patrick *et al.* 2010), to the EPO purse-seine fishery, as a tool to prioritize species requiring specific research or mitigation measures in order to reduce risks from fishing (SAC-06-09). However, in the process of developing specific attributes for the purse-seine assessment, it became apparent that few previous applications of PSA considered any sensitivity analyses to determine the validity of attributes used in the PSA, given that several attributes, such as maximum size and maximum age, are strongly correlated (Froese and Binohlan 2000). This effectively creates implicit weighting for correlated attributes, creating a positive bias in productivity scores. This can overestimate species productivity, and thus underestimate the severity of the impact of a fishery on the species' sustainability.

Therefore, before applying PSA to other EPO fisheries and potentially using PSA as an ongoing assessment tool for bycatch, analyses were undertaken to explore options for improving the method and potentially decrease the data requirements, whilst retaining high information content. The primary aim of this paper is to describe statistical explorations to determine if any PSA productivity attributes are correlated, and to what extent the vulnerability status of individual species would be affected, if at all, by removal of one or more of the correlated attributes. The desired outcome would be a more parsimonious PSA model that would require fewer inputs, some of which are difficult to obtain, and produce more reliable outcomes.

2. METHODS

2.1. Existing PSA model for the fishery by large purse-seine vessels in the EPO

IATTC staff have previously examined the utility of PSA for assessing the vulnerability of incidentally-caught species of fishes, sharks, mammals, and turtles to overfishing in the EPO. The application involved 32 species that comprise the majority of the biomass removed by Class-6 purse-seine vessels (carrying capacity greater than 363 metric tons) during 2005-2013 (SAC-06-09). Using the PSA methodology of Patrick *et al.* (2009), nine productivity (Table 1) and eight susceptibility attributes (Table 2) were used, with some being modified to accommodate data types available for the tuna fisheries in the EPO. Information corresponding to the productivity attributes for each species was compiled from a variety of published and unpublished sources and EPO fisheries data to better approximate the distribution of life history characteristics observed in the species found in the EPO. Scoring thresholds for productivity attributes were derived by dividing the compiled data into equal thirds. Scoring criteria for the susceptibility attributes were taken from the example PSA of Patrick *et al.* (2009) and modified, where appropriate, for EPO fisheries. The weighted average of the productivity (*p*) and susceptibility (*s*) scores are graphically displayed in an x-y scatter plot, and the vulnerability (*v*) scores calculated from the *p* and *s* scores as the Euclidean distance from the origin of the x-y scatter plot to the datum point:

$$v = \sqrt{(p-3)^2 + (s-1)^2}$$

Because the vulnerability scores were similar for the three susceptibility measures (s_j^1 s_j^2, and s_j^3) outlined in SAC-06-09, here we use s_j^1, because the focus of this report is to determine potential redundancy of productivity attributes and s_j^1 is conceptually the most straightforward. s_j^1 is calculated as the weighted sum of the susceptibility values for species *j*, to each individual fishery (defined by set type: on dolphins, on unassociated tuna schools, and on floating objects), with weights proportional to the number of sets in each fishery:

$$s_j^1 = \sum_k s_{jk} p_k$$

where

s_j^1 is the combined susceptibility for species *j*

s_{jk} is the susceptibility for species *j* in set type *k,* computed using the attributes in Table 2. s_{jk} ranges from 1 (least susceptible) to 3 (most susceptible).

$p_k = \left(\frac{N_k}{\sum_k N_k}\right)$ and N_k is the total number of sets of set type *k* by Class-6 vessels in 2013.

2.2. Assessing the attribute weighting system

The existing PSA utilized the attribute weighting scheme initially proposed by Patrick *et al*. (2009), in which an attribute can be assigned a weight between 0 and 4. A weight of 0 effectively removes an attribute from the analysis, whereas a weight of 4 gives it high importance. Productivity attributes in the existing PSA were unweighted. One susceptibility attribute, areal overlap/geographical concentration index (the relative spatial concentration of a species within the fishing area and the relative spatial overlap of the fishery area and the species' distribution (SAC-01-INF-A)) was down-weighted to 1 based on a lack of confidence that this attribute, which was evaluated entirely from fishery-dependent data, reliably quantified true concentration and overlap. A sensitivity analysis was conducted to determine whether the vulnerability (*v*) score and associated risk status of each species changed if the weighting scheme was removed. The unweighted susceptibility and productivity scores were then displayed in an x-y plot and compared to the original PSA plot which include the down-weighted susceptibility score described above.

2.3. Sensitivity to attribute reduction

Given that many of the productivity attributes (Table 1) are dependent on, or are combined with, other attributes, a second sensitivity analysis was performed to determine whether any of these attributes are redundant in the PSA. Relationships between pairs of productivity attributes were evaluated based on several approaches to determine which, if any, could be omitted from the PSA. First, a qualitative biological theory approach established by expert opinion was used to identify attributes that are believed to be correlated (Table 3). Second, relationships between productivity attributes were evaluated graphically using a pair-wise scatter plot matrix. Third, for those attributes that were believed by experts to be correlated, simple linear regressions were fitted to the data to assess the degree of linearity of the relationships. Scatter plot and linear regression analyses were conducted in R (R Development Core Team 2017). Finally, as an additional check on linearity, generalized additive models (GAMs) were fitted using the mgcv package in R (Wood 2006) to the data of pairs of attributes for which the adjusted R^2 from the linear regression analysis was >0.5. Given the limited number of data points for each attribute (a maximum of 32 data points, corresponding to 32 species), the model parameters for these GAMs were constrained to avoid undersmoothing (the k parameter of the function 's' in the GAM was set to a value of 5).

3. RESULTS

3.1. Weighted versus unweighted attribute scores

The species positions within PSA plots were similar for the original weighted average and unweighted productivity and susceptibility scores. No species moved from one risk category to another due to the change in attribute weighting (Figure 1, Table 4). Consequently, the unweighted attribute scores were used throughout the remainder of the analysis.

3.2. Relationships between attribute pairs

Non-linear relationships were observed in most of the scatter plots (Figure 2), indicating that these productivity attributes should remain in the PSA, because if removed, the productivity score could cause a change in the overall vulnerability score, and potentially move a species into a category of higher or lower risk of depletion. Based on the linear regression analysis (and our criterion of an adjusted $R^2 > 0.5$), three pairs of productivity attributes showed some degree of linearity: (1) von Bertalanffy growth factor (k) and intrinsic rate of population growth (r) (adjusted $R^2 = 0.60$); (2) natural mortality (M) and r (adjusted $R^2 = 0.57$); and (3) age at maturity and maximum age (adjusted $R^2 = 0.55$) (Figure 3). A linear relationship indicates that two attributes may contain similar information, and thus removing one of the two attributes from the PSA would not significantly change the vulnerability score and risk position of a species within the PSA plot. The GAM analysis was a second line of statistical supporting evidence indicating that, over most of the range of data values, the pairwise relationships between these variables were roughly linear, although some departures are evident (Figures 3 and 4). The low adjusted R^2 for some pairs of attributes (*e.g.*, maximum age and maximum size, Figure 3) that are believed by experts to be correlated (Table 3) appears to be due to considerable variability in our particular data set for those quantities.

3.3. Removal of productivity attributes

PSA plots with between 1 and 4 attributes removed in a backwards stepwise approach were compared against the unweighted PSA plot (Figure 1b). The unweighted and revised vulnerability scores corresponding to the PSA plots – where categories of risk were defined as low ($v < 1.0$), moderate (≥ 1.0 $v < 2.0$), and high ($v \geq 2.0$) – are shown in Table 4 (columns v_1-v_4). For all scenarios of attribute removal, species were graphically displayed in a PSA plot (Figure 5). In the first scenario (v_1, Figure 5a), mean trophic level (TL) was excluded from the analysis, not because it was highly correlated with any other attribute, but because it was not considered to be an independent measure of any aspect of biological productivity. Trophic level describes the trophic ecology of a species, specifically the contribution to its diet made by taxa from other trophic levels (Christensen and Pauly 1992). In general, maximum size and longevity increases with trophic level, and therefore there is often an inverse relationship with productivity. However, there are many exceptions to this rule; for example, several species of whales occupy low trophic levels as they consume almost exclusively zooplankton. Given that the composition of a species' diet is not a direct measure of any aspect of that species' productivity, the mean TL attribute was considered unnecessary, despite any changes that may result in the risk status of a species. Additionally, mean TL scores in the PSA had a limited range, 3.1 to 5.3, since we considered only those species that are captured by the fishery. Therefore, lower trophic level organisms, from plankton to small fish and squids, that are highly important in the diets of pelagic predators were not represented in the PSA, thus limiting the range of the TL values.

Other attributes (r, maximum age, and M) were subsequently removed, based on the linear regressions (Figure 3), GAM analyses (Figure 4) and expert opinion. The second scenario (v_2) involved removing two of the nine attributes, mean TL and r (Figure 5b). The r attribute is a difficult parameter to estimate for data-limited bycatch species, and especially for teleosts, whose population dynamics are more commonly characterized by the k (growth rate) and L_∞ (the asymptotic length at which growth is zero) parameters of the von Bertalanffy growth model. Therefore, r values were available for only nine of the 32 species. Additionally, r combines many other productivity attributes used in the PSA, including M, fecundity, and maximum age in a stable age distribution. Scenario 3 (v_3) involved removing three attributes: mean TL, r, and maximum age (Figure 5c). Maximum age is related to M, in that low values of M are expected to be negatively correlated with maximum age (Hoenig 1983). In the last scenario (v_4), four attributes were excluded: mean TL, r, maximum age, and M (Figure 5d), M was removed due to its relation to maximum age.

3.4. Comparison of vulnerability scores

After removing the attributes, the majority of species remained in the same risk category as in the original unweighted analysis. The largest change was observed for giant manta rays, *Manta birostris*, with vulnerability scores that increased from 1.96 (moderate risk) to 2.17 (high risk) for all scenarios of attribute removal (Table 4), resulting in an increase of 10.4% for v_1-v_4. For a few species of sharks, risk status shifted from high to moderate, or vice versa depending on the scenario, although most vulnerability scores were on the borderline of the high-risk threshold. Bigeye thresher sharks, *Alopias superciliosus*, had an unweighted vulnerability score of 2.0; after removing attributes in scenarios v_1–v_3, this decreased slightly, to 1.99, 1.97, and 1.95, respectively. In contrast, when all four attributes were removed (v_4), the vulnerability score increased to 2.11 (Table 4), an increase of 5.2%. Pelagic thresher sharks, *A. pelagicus*, had a moderate unweighted vulnerability score of 1.95, which increased to 2.00 and 2.16 in scenarios v_3 (2.6% increase) and v_4 (10.5% increase), respectively (Table 4), whereas shortfin mako sharks, *Isurus oxyrinchus*, had a high unweighted vulnerability score (2.06), which decreased to 1.97 in scenario v_3 (4.6% decrease) and 1.91 in scenario v_4 (7.3% decrease) (Table 4). In general, the vulnerability scores in the various approaches produced similar results, as shown by the alignment of most species close to the 1-to-1 line (Figure 6). Together, the results of these analyses suggest that a more parsimonious approach to productivity attribute selection could be used in future PSAs.

4. DISCUSSION

Assessing ecological sustainability in fisheries has become increasingly important with the widespread adoption of the principles of ecosystem-based fisheries management (EBFM) and a growing requirement for some types of fishery certifications and ecolabeling. However, demonstrating ecological sustainability quantitatively is a significant challenge in many fisheries, including the EPO tuna fisheries, where bycatches are diverse and the availability of data required to assess populations using traditional approaches is limited (SAC-08-07b, SAC-08-07d). PSA is one ecological risk assessment approach that can rapidly prioritize potentially vulnerable species, allowing managers to mitigate risks, or subject species to further research in order to assess their status more quantitatively.

This paper described the outcomes of a methodological assessment of the PSA approach of Patrick *et al*. (2009) that was adapted to the EPO purse-seine fishery. The sensitivity analysis of the nine productivity attributes showed significant redundancy among the attributes, with a clear correlation between three of the attribute pairs. The most highly correlated attribute pairs were intrinsic rate of population growth (r) and von Bertalanffy growth coefficient (k), r and natural mortality (M), and age at maturity and maximum age. Removing any of these attributes from the PSA resulted in a change to the risk status of the giant manta ray and some shark species, for one or more of the scenarios of attribute removal.

The intrinsic rate of population growth (*r*) was removed from our analysis due to the unavailability of reliable estimates for this attribute for most non-target species, especially teleosts. It is useful for describing population dynamics and recovery trajectories, but is difficult to measure, because it requires data on age- or life stage-specific mortality, and the number of offspring. For pelagic fishes that produce millions of oocytes per spawning, the latter can be difficult to estimate with confidence. However, recently methods for improving estimates of *r*, particularly for long-lived species like sharks, have been proposed (Dillingham *et al.* 2016, Pardo *et al*. 2016).

Correlates of life history parameters have also been reported in the literature. For example, *M* has been identified as a correlate of other life history parameters (Pascual and Iribarne 1993, Jennings *et al.* 1998, Denney *et al.* 2002, Goodwin *et al.* 2006, Zhou *et al.* 2012). Some argue that *M* is a sufficient biological reference point for estimating fishing mortality, and the use of other life history parameters in semi-quantitative risk assessments such as the PSA is redundant (Zhou *et al.* 2012). However, *M* is a notoriously difficult parameter to measure, and is most often estimated from empirical models using the von Bertalanffy growth function parameters L_∞ and *k* (Pauly 1980, Pascual and Iribarne 1993, Zhou *et al.* 2012). Others have suggested that a life history parameter that is widely measured may be sufficient for predicting rates of recovery after exploitation (Jennings *et al.* 1998, Denney *et al.* 2002), and body size may be used as an index of *r* if that is the only biological data available (Denney *et al.* 2002). Cortés (2000) documented correlations between life history patterns and maximum size, reproduction, and age and growth in sharks, and concluded that estimates of these parameters, in conjunction with estimates of breeding frequency, allows for the parameterization of demographic models.

The correlation and redundancy of attributes observed in the present study and reported in the literature further supports the use of fewer productivity attributes in semi-quantitative PSAs. Productivity indices that combine life history parameters, including reproductive strategy, length at maturity and maximum size, into a single productivity index have been reported (Kirby 2006, Arrizabalaba *et al.* 2011). It may be useful to explore one such index, the intrinsic vulnerability index (Cheung *et al.* 2005), in the development of future PSAs for EPO fisheries. Major changes in the risk status of many species were not observed across the various scenarios assessed. This suggests future work should seek to include exploratory analyses to understand the driving mechanism for the somewhat anchored risk status observed in this study.

Few shifts in vulnerability scores were observed in our analysis of productivity attribute reduction. Giant manta rays were assigned a low productivity score (*p*) of 1 for all attributes except mean TL (p = 3), and data were unavailable for *r* and *M*. Thus, when mean TL, *r*, maximum age and *M* were removed from the analysis, the overall vulnerability increased due to the low productivity assigned to each of the other attributes. We think that this higher vulnerability is more realistic, as the giant manta ray is particularly vulnerable due to its *K*-selected (*i.e.*, species whose populations fluctuate at or near carrying capacity *K*) life history characteristics, *e.g.* delayed ovoviparous reproduction, extremely low fecundity, and delayed age of first reproduction, as outlined in Croll *et al*. (2016). For bigeye thresher sharks, all productivity scores were set at 1 except *M,* which was assigned a score of 2. Thus, when the low-scoring attributes of mean TL, *r*, and maximum age were removed, the overall vulnerability decreased slightly compared to the original unweighted vulnerability, and shifted this species into the moderate risk category. However, these vulnerability scores were on the borderline of high risk, with a decrease of less than 1.5% from the unweighted vulnerability score. When the higher-scoring attribute *M* was removed, the corresponding vulnerability increased, moving the species back into the high-risk category. Bigeye thresher sharks were also reported as high risk in other ERAs (Cortés *et al.* 2010), as they are the slowest-growing of the three species of thresher sharks, have low fecundity (typically two pups/year), and are late to mature (Young *et al.* 2016). Given the life history characteristics of this species, and that changes to the vulnerability scores were on the threshold of high risk for three of the four vulnerability scenarios (*v_1-v_3*) assessed here, and in the high-risk category for the v_4 scenario, we believe that reducing the number of productivity attributes in the PSA is warranted.

Pelagic thresher sharks also scored 1 for all attributes except maximum age and M (p = 2). Thus, when these higher-ranked attributes were removed in scenarios v_3 and v_4, the overall vulnerability of this species shifted from a moderate to a high-risk category. We believe this shift is logical, as common thresher sharks have similar life history characteristics to bigeye thresher sharks, although they are slightly shorter-lived (Dulvy *et al.* 2008).

Lastly, the shortfin mako shark had low productivity scores (p = 1) for all attributes except maximum size (L_{max}) and fecundity (p = 2). It had the third-smallest L_{max} (after oceanic whitetip and silky sharks) of all the sharks assessed in this study, and a moderate fecundity, with an average litter size of 13 pups (Dulvy *et al.* 2008). These higher-scoring attributes were retained in the analysis, and the lower-scoring attributes that were removed caused a shift from high to moderate risk in scenarios v_3 and v_4, which included only six (two moderate and four low productivity scores) and five (two moderate and three low productivity scores) attributes, respectively. However, it is worth noting that, in scenario v_3, the overall vulnerability score was 1.97, on the borderline of high risk, while in scenario v_4 a decrease of 7% was observed.

5. RECOMMENDATIONS

We found no evidence that the weighting scheme used in the PSA analysis presented here results in any appreciable improvement in the differentiation of species with regard to their vulnerability score and risk status. Previous weighting schedules used in PSAs (Stobutzki *et al.* 2001, Patrick *et al.* 2009) appear to be arbitrarily derived to emphasize the perceived importance of an attribute, with little consideration given to the potential for excessive weighting of attributes that are already implicitly weighted due to their correlation with one or more related attributes. We recommend that PSAs undertaken in future, at least for EPO fisheries, make use of unweighted attributes, but that greater attention be given to the category splits within each attribute to maximize the differentiation between species.

The redundancy in productivity attributes in the PSA approaches currently used in US fisheries suggests that PSAs can be conducted more rapidly, and with fewer data inputs, than in previous implementations, and that the resulting productivity scores – and therefore overall vulnerability scores and risk rankings – for individual species will be similar. For teleosts and sharks, the main bycatch groups in the EPO purse-seine fisheries, we recommend the use of no more than one attribute to describe each of the following five principal components of the productivity scores:

1) The rate of population growth (*e.g.* von Bertalanffy growth coefficient k, or intrinsic rate of population increase, r),
2) Maximum extent of growth in terms of length (L_∞ or L_{max}) or age (*e.g.* longevity in years),
3) Timing of reproductive maturity in terms of length ($L_{50\%}$) or age ($A_{50\%}$) at which half the population is mature, relative to length or age at capture in a particular fishery,
4) Reproductive output (*e.g.* fecundity, number of pups), and
5) Frequency of reproductive output (*e.g.* seasonally, annually).

For some species groups, such as marine mammals or seabirds, additional productivity attributes may be required, and possibly separate PSAs using attributes specific to the life histories of these groups. Future work will evaluate the use of productivity indices that combine attributes into a single productivity index (Cheung *et al.* 2005, Kirby 2006, Arrizabalaba *et al.* 2011). It is strongly recommended that preliminary analyses be undertaken prior to finalizing PSA assessments to ensure attribute values are not correlated and cause cryptic weighting of correlated attributes.

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7. REFERENCES

Arrizabalaba, H., P. de Bruyn, G.A. Diaz, H. Murua, P. Chavance, A. Delgado de Molina, D. Gaertner, J. Ariz, J. Ruiz, and L.T. Kell. 2011. Productivity and susceptibility analysis for species caught in Atlantic tuna fisheries. Aquatic Living Resources 24: 1-12.

Cheung, W.W.L., T.J. Pitcher, and D. Pauly. 2005. A fuzzy logic expert system to estimate intrinsic extinction vulnerabilities of marine fishes to fishing. Biological Conservation 124: 97-111.

Christensen, V., and D. Pauly. 1992. ECOPATH II - a software for balancing steady-state ecosystem models and calculating network characteristics. Ecological Modelling 61: 169-185.

Cortés, E. 2000. Life history patterns and correlations in sharks. Reviews in Fisheries Science 8(4): 299-344.

Cortés, E., F. Arocha, L.R. Beerkircher, F. Carvalho, A. Domingo, M. Heupel, H. Holtzhausen, M.N. Santos, M. Ribera, and C. Simpfendorfer. 2010. Ecological risk assessment of pelagic sharks caught in Atlantic pelagic longline fisheries. Aquatic Living Resources 23: 25-34.

Croll, D.A., H. Dewar, N.D. Dulvy, D. Fernando, M.P. Francis, F. Galván-Magaña, M. Hall, S. Heinrichs, A. Marshall, D. McCauley, K.M. Newton, G. Notarbartolo-di-Sciara, M.O. O'Malley, J. O'Sullivan, M. Poortvliet, M. Roman, G. Stevens, B.R. Tershy, and W.T. White. 2016. Vulnerabilities and fisheries impacts: the uncertain future of manta and devil rays. Aquatic Conservation: Marine and Freshwater Ecosystems 26: 562-575.

Denney, N.H., S. Jennings, and J.D. Reynolds. 2002. Life–history correlates of maximum population growth rates in marine fishes. Proceedings of the Royal Society of London. Series B: Biological Sciences 269: 2229-2237.

Dillingham, P.W., J.E. Moore, D. Fletcher, E. Cortés, K.A. Curtis, K.C. James, and R.L. Lewison. 2016. Improved estimation of intrinsic growth r_{max} for long-l ived species: integrating matrix models and allometry. Ecological Applications 26(1): 322-333.

Dulvy, N.K., J.K. Baum, S. Clarke, L.J.V. Compagno, E. Cortés, A. Domingo, S. Fordham, S. Fowler, M.P. Francis, C. Gibson, J. Martínez, J.A. Musick, A. Soldo, J.D. Stevens, and S. Valenti. 2008. You can swim but you can't hide: the global status and conservation of oceanic pelagic sharks and rays. Aquatic Conservation: Marine and Freshwater Ecosystems 18(5): 459-482.

Fletcher, W.J. 2005. The application of qualitative risk assessment methodology to prioritise issues for fisheries management. ICES Journal of Marine Science 62: 1576-1587.

Froese, R., and C. Binohlan. 2000. Empirical relationships to estimate asymptotic length, length at first maturity and length at maximum yield per recruit in fishes, with a simple method to evaluate length frequency data. Journal of Fish Biology 56: 758-773.

Goodwin, N.B., A. Grant, A.L. Perry, N.K. Dulvy, and J.D. Reynolds. 2006. Life history correlates of density-dependent recruitment in marine fishes. Canadian Journal of Fisheries and Aquatic Sciences 63: 494-509.

Hoenig, J.M. 1983. Empirical use of longevity data to estimate mortality rates. Fishery Bulletin 82: 898-902.

Jennings, S., J.D. Reynolds, and S.C. Mills. 1998. Life history correlates of responses to fisheries exploitation. Proceedings of the Royal Society of London. Series B: Biological Sciences 265: 333-339.

Kirby, D.S. 2006. Ecological risk assessment for species caught in WCPO tuna fisheries: inherent risk as determined by productivity-susceptibility analysis. WCPFC-SC-2006/EB WP-1, 24 p.

Pardo, S.A., H.K. Kindsvater, J.D. Reynolds, and N.D. Dulvy. 2016. Maximum intrinsic rate of population increase in sharks, rays, and chimaeras: the importance of survival to maturity. Canadian Journal of Fisheries and Aquatic Sciences 73: 1159-1163.

Pascual, M.A., and O.O. Iribarne. 1993. How good are empirical predictions of natural mortality? Fisheries Research 16: 17-24.

Patrick, W.S., P. Spencer, J. Link, J. Cope, J. Field, D. Kobayashi, P. Lawson, T. Gedamke, E. Cortés, O. Ormseth, K. Bigelow, and W. Overholtz. 2010. Using productivity and susceptibility indices to assess the vulnerability of United States fish stocks to overfishing. U.S. National Marine Fisheries Service, Fishery Bulletin 108: 305-322.

Patrick, W.S., P. Spencer, O. Ormseth, J. Cope, J. Field, D. Kobayashi, T. Gedamke, E. Cortés, K. Bigelow, W. Overholtz, J. Link, and P. Lawson. 2009. Use of Productivity and Susceptibility Indices to Determine Stock Vulnerability, with Example Applications to Six U.S. Fisheries. 90 pp.

Pauly, D. 1980. On the interrelationships between natural mortality, growth parameters, and mean environmental temperature in 175 fish stocks. Journal du Conseil International pour l'Exploration de la Mer 39: 175-192.

R Development Core Team. 2017. R: A language and environment for statistical computing. R Foundation for Statistical Computing, Vienna, Austria, URL http://www.R-project.org/.

Stobutzki, I.C., M. Miller, and D. Brewer. 2001. Sustainability of fishery bycatch: a process for assessing highly diverse and numerous bycatch. Environmental Conservation 28: 167-181.

Wood, S.N. 2006. Generalized Additive Models: An Introduction with R. Chapman and Hall/CRC, New York. 391 pp.

Young, C.N., J.K. Carlson, M. Hutchinson, D. Kobayashi, C. McCandless, M.H. Miller, S.L.H. Teo, and T. Warren. 2016. Status review report: common thresher shark (*Alopias vulpinus*) and bigeye thresher shark (*Alopias superciliosus*). . Final Report to National Marine Fisheries Service, Office of Protected Resources, March 2016. 199 pp

Zhou, S., and S.P. Griffiths. 2006. Sustainability Assessment for Fishing Effects (SAFE): an application to diverse elasmobranch bycatch in a tropical Australian prawn trawl fishery. *In* D. Brewer, S. P. Griffiths, D. S. Heales, S. Zhou, M. Tonks, Q. Dell, P. M. Kuhnert, S. Keys, W. Whitelaw, A. M. Burke, and E. Raudzens (eds.), Design, trial and implementation of an integrated, long-term bycatch monitoring program, road tested in the NPF, Final Report on FRDC Project 2004/024 p. 179-207. CSIRO Marine and Atmospheric Research, Cleveland.

Zhou, S., S. Yin, J.T. Thorson, A.D.M. Smith, and M. Fuller. 2012. Linking fishing mortality reference points to life history traits: an empirical study. Canadian Journal of Fisheries and Aquatic Sciences 69: 1292-1301.

TABLE 1. Productivity attributes and scoring thresholds used in the PSA of the purse-seine fishery in the eastern Pacific Ocean. Includes only Class-6 vessels (carrying capacity > 363 t).
TABLA 1. Atributos de productividad y umbrales de puntuación usados en el APS de la pesquería de cerco en el Océano Pacífico oriental (OPO). Incluye solamente buques de clase 6 (capacidad de acarreo > 363 t).

	Ranking - Clasificación		
Productivity attribute Atributo de productividad	**Low - Bajo (1)**	**Moderate-Moderado (2)**	**High-Alto (3)**
Intrinsic rate of population growth (*r*) Tasa intrínseca de crecimiento de la población (*r*)	≤ 0.1	> 0.1, ≤ 1.3	>1.3
Maximum age (years) Edad máxima (años)	≥ 20	> 11, < 20	≤ 11
Maximum size (cm) (L_{max}) Talla máxima (cm) (L_{max})	> 350	> 200, ≤ 350	≤ 200
von Bertalanffy growth coefficient (*k*) Coeficiente de crecimiento de von Bertalanffy (*k*)	< 0.095	0.095 – 0.21	> 0.21
Natural mortality (*M*) Mortalidad natural (*M*)	< 0.25	0.25 – 0.48	> 0.48
Fecundity (measured) Fecundidad (medida)	< 10	10 – 200,000	> 200,000
Breeding strategy Estrategia reproductora	≥ 4	1 to-a 3	0
Age at maturity (years) Edad de madurez (años)	≥ 7.0	≥ 2.7, < 7.0	< 2.7
Mean trophic level Nivel trófico medio	> 5.1	4.5 – 5.1	< 4.5

TABLE 2. Susceptibility attributes and scoring thresholds used in the PSA of the purse-seine fishery in the eastern Pacific Ocean. Includes only Class-6 vessels (carrying capacity > 363 t).

	Ranking		
Susceptibility attribute	**Low (1)**	**Moderate (2)**	**High (3)**
Management strategy	Management and proactive accountability measures in place	Stocks specifically named in conservation resolutions; closely monitored	No management measures; stocks closely monitored
Areal overlap - geographical concentration index	Greatest bycatches outside areas with the most sets and stock not concentrated (or not rare)	Greatest bycatches outside areas with the most sets and stock concentrated (or rare), OR Greatest bycatches in areas with the most sets and stock not concentrated (or not rare)	Greatest bycatches in areas with the most sets and stock concentrated (or rare)
Vertical overlap with gear	< 25% of stock occurs at the depths fished	Between 25% and 50% of the stock occurs at the depths fished	> 50% of the stock occurs in the depths fished
Seasonal migrations	Seasonal migrations decrease overlap with the fishery	Seasonal migrations do not substantially affect the overlap with the fishery	Seasonal migrations increase overlap with the fishery
Schooling/Aggregation and other behavioral responses to gear	Behavioral responses decrease the catchability of the gear	Behavioral responses do not substantially affect the catchability of the gear	Behavioral responses increase the catchability of the gear
Potential survival after capture and release under current fishing practices	Probability of survival > 67%	33% < probability of survival ≤ 67%	Probability of survival < 33%
Desirability/value of catch (percent retention)	Stock is not highly valued or desired by the fishery (< 33% retention)	Stock is moderately valued or desired by the fishery (33-66% retention)	Stock is highly valued or desired by the fishery (> 66% retention)

TABLE 3. Expected relationships between pairs of productivity attributes based on expert opinion. Cells marked with an 'x' indicate attribute pairs that are expected to be correlated.
TABLA 3. Relaciones esperadas entre parejas de atributos de productividad basadas en opinión experta. Las casillas marcadas con 'x' indican parejas de atributos que se espera estén correlacionadas.

	Productivity attribute **Atributo de productividad**	1	2	3	4	5	6	7	8	9
1	Intrinsic rate of population growth (*r*) Tasa intrínseca de crecimiento de la población (*r*)									
2	Maximum age Edad máxima									
3	Maximum size (L_{max}) Talla máxima (L_{max})	x	x							
4	von Bertalanffy growth coefficient (*k*) Coeficiente de crecimiento de von Bertalanffy (*k*)	x								
5	Natural mortality (*M*) Mortalidad natural (*M*)	x	x		x					
6	Fecundity Fecundidad									
7	Breeding strategy Estrategia de reproducción						x			
8	Age at maturity Edad de madurez		x			x		x		
9	Mean trophic level (TL) Nivel trófico (NT) medio	x			x	x				

TABLE 4. Productivity (*p*) and susceptibility (*s*) scores used to compute the overall vulnerability measure (*v*). Susceptibility scores are computed as a weighted combination of the individual fishery values, s_j^1; see text for details. Original productivity (p_{orig}), susceptibility (s_{orig}), and vulnerability (v_{orig}), scores using all 9 productivity attributes are provided. Revised productivity (p_1-p_4), susceptibility (s_{rev}), and vulnerability (v_1-v_4) scores are also shown; p_1 = without mean trophic level, p_2 = attributes in p_1 and without intrinsic rate of population growth *r*, p_3 = attributes in p_2 and without maximum age, p_4 = attributes in p_3 and without natural mortality; v_1, - v_4 scores computed using the unweighted susceptibility (s_{rev}) and corresponding productivity scores (p_{orig}, p_1- p_4). Risk: green = low, yellow = moderate, red = high.

TABLA 4. Puntuaciones de productividad (*p*) y susceptibilidad (*s*) usadas para calcular la medida general de vulnerabilidad (*v*). Se calculan las puntuaciones y susceptibilidad como combinación ponderada de los valores de las pesquerías individuales, s_j^1; ver detalles en el texto. Se presentan las puntuaciones originales de productividad (p_{orig}), susceptibilidad (s_{orig}), y vulnerabilidad (v_{orig}), que usan todos los 9 atributos de productividad. Se incluyen también las puntuaciones de productividad (p_1-p_4), susceptibilidad (s_{rev}), y vulnerabilidad (v_1-v_4); p_1 = sin nivel trófico medio, p_2 = atributos en p_1 sin la tasa intrínseca de crecimiento de población *r*, p_3 = atributos en p_2 sin edad máxima, p_4 = atributos en p_3 sin mortalidad natural; v_1, - v_4 puntuaciones calculadas usando la susceptibilidad no ponderada (s_{rev}) y las puntuaciones de productividad correspondientes (p_{orig}, p_1- p_4). Riesgo: verde = bajo, amarillo = moderado, rojo = alto.

Group Grupo	Species Especie	Common name Nombre común	Species code Código especie	p_{orig}	s_{orig}	v_{orig}	s_{rev}	v_{rev}	p_1	p_2	p_3	p_4	v_1	v_2	v_3	v_4
Tunas Atunes	*Thunnus albacares*	Yellowfin tuna Atún aleta amarilla	YFT	2.78	2.38	1.40	2.29	1.30	2.88	2.86	2.83	2.80	1.29	1.29	1.30	1.30
	Thunnus obesus	Bigeye tuna Atún patudo	BET	2.33	1.70	0.97	1.66	0.94	2.38	2.43	2.50	2.40	0.91	0.87	0.82	0.89
	Katsuwonus pelamis	Skipjack tuna Atún barrilete	SKJ	2.78	1.73	0.76	1.68	0.72	2.88	2.86	2.83	2.80	0.69	0.70	0.70	0.71
Billfishes Peces picudos	*Istiompax indica*	Black marlin Marlín negro	BLM	2.00	2.39	1.71	1.34	1.70	2.13	2.29	2.17	2.00	1.78	1.75	1.86	1.83
	Makaira nigricans	Blue marlin Marlín azul	BUM	2.00	2.39	1.71	1.34	1.81	2.13	2.29	2.33	2.40	1.90	1.89	1.86	1.83
	Kajikia audax	Striped marlin Marlín rayado	MLS	2.33	2.54	1.68	1.27	1.69	2.50	2.71	2.67	2.60	1.77	1.74	1.69	1.62
	Istiophorus platypterus	Indo-Pacific sailfish Pez vela del Indo-Pacífico	SFA	2.44	2.54	1.64	2.34	1.67	2.50	2.71	2.67	2.60	1.60	1.52	1.58	1.67
Dolphins Delfines	*Stenella attenuata*	Spotted dolphin Delfín manchado	DPN	1.33	1.36	1.71	2.34	1.67	1.25	1.29	1.17	1.20	1.60	1.52	1.50	1.47
	Stenella longirostris	Spinner dolphin Delfín tornillo	DSI	1.22	1.36	1.81	2.57	1.71	1.13	1.14	1.17	1.20	1.65	1.60	1.61	1.62
	Delphinus delphis	Common dolphin Delfín común	DCO	1.33	1.29	1.69	2.57	1.67	1.25	1.29	1.33	1.40	1.65	1.60	1.61	1.62
Sharks Tiburones	*Carcharhinus longimanus*	Oceanic whitetip shark Oceánico punta blanca	OCS	1.67	1.70	1.51	1.74	1.52	1.75	1.71	1.67	1.60	1.45	1.48	1.52	1.58

Group Grupo	Species Especie	Common name Nombre común	Species code Código especie	p_{orig}	s_{orig}	v_{orig}	s_{rev}	v_{rev}	p_1	p_2	p_3	p_4	v_1	v_2	v_3	v_4
	Carcharhinus falciformis	Silky shark Tiburón sedoso	FAL	1.44	2.10	1.91	2.14	1.93	1.50	1.57	1.67	1.60	1.89	1.83	1.76	1.81
	Sphyrna lewini	Scalloped hammerhead Cornuda común	SPL	1.33	1.91	1.90	1.89	1.89	1.38	1.29	1.33	1.40	1.85	1.93	1.89	1.83
	Sphyrna zygaena	Smooth hammerhead Cornuda cruz	SPZ	1.33	1.91	1.90	1.89	1.89	1.38	1.29	1.33	1.40	1.85	1.93	1.89	1.83
	Sphyrna mokarran	Great hammerhead Cornuda gigante	SPK	1.33	1.97	1.93	1.90	1.89	1.38	1.29	1.33	1.40	1.86	1.94	1.89	1.84
	Alopias superciliosus	Bigeye thresher shark Tiburón marrajo ojón	BTH	1.11	1.72	2.02	1.67	2.00	1.13	1.14	1.17	1.00	1.99	1.97	1.95	2.11
	Alopias pelagicus	Pelagic thresher shark Tiburón marrajo pelágico	PTH	1.22	1.87	1.98	1.81	1.95	1.25	1.29	1.17	1.00	1.93	1.89	2.00	2.16
	Alopias vulpinus	Common thresher shark Tiburón marrajo común	ALV	1.67	1.87	1.59	1.81	1.56	1.75	1.71	1.67	1.40	1.49	1.52	1.56	1.79
	Isurus oxyrinchus	Shortfin mako shark Tiburón marrajo dientuso	SMA	1.22	2.12	2.10	2.04	2.06	1.25	1.29	1.33	1.40	2.04	2.01	1.97	1.91
Rays Mantarrayas	*Manta birostris*	Giant manta ray Manta gigante	RMB	1.22	1.90	1.99	1.83	1.96	1.00	1.00	1.00	1.00	2.17	2.17	2.17	2.17
	Mobula japanica	Spinetail manta	RMJ	1.78	1.90	1.52	1.83	1.48	1.63	1.71	1.67	1.80	1.61	1.53	1.57	1.46
	Mobula thurstoni	Smoothtail manta	RMO	1.67	1.90	1.61	1.83	1.57	1.50	1.57	1.50	1.60	1.72	1.65	1.72	1.63
Large fishes Peces grandes	*Coryphaena hippurus*	Common dolphinfish Dorado común	DOL	2.78	1.64	0.68	1.63	0.67	2.88	2.86	2.83	2.80	0.64	0.65	0.65	0.66
	Coryphaena equiselis	Pompano dolphinfish Dorado pompano	CFW	2.89	1.48	0.50	1.45	0.46	3.00	3.00	3.00	3.00	0.45	0.45	0.45	0.45
	Acanthocybium solandri	Wahoo Peto	WAH	2.67	1.57	0.66	1.55	0.64	2.75	2.71	2.67	2.80	0.60	0.62	0.64	0.59
	Elagatis bipinnulata	Rainbow runner Salmón	RRU	2.78	1.46	0.51	1.45	0.50	2.75	2.71	2.67	2.60	0.51	0.53	0.56	0.60
	Mola mola	Ocean sunfish Pez luna	MOX	1.78	1.49	1.32	1.50	1.32	1.63	1.71	1.83	2.00	1.46	1.38	1.27	1.12
	Caranx sexfasciatus	Bigeye trevally Jurel voraz	CXS	2.56	1.25	0.51	1.23	0.50	2.50	2.43	2.50	2.60	0.55	0.62	0.55	0.46
	Seriola lalandi	Yellowtail amberjack Medregal rabo amarillo	YTC	2.44	1.49	0.74	1.48	0.73	2.38	2.57	2.50	2.80	0.79	0.64	0.69	0.52
Small fishes Peces pequeños	*Canthidermis maculata*	Rough triggerfish Pez ballesta	CNT	2.33	1.35	0.75	1.35	0.75	2.25	2.14	2.17	2.20	0.83	0.93	0.90	0.87
	Sectator ocyurus	Bluestriped chub Chopa	ECO	2.22	1.38	0.86	1.35	0.85	2.13	2.14	2.17	2.20	0.94	0.93	0.90	0.87
Turtles Tortugas	*Lepidochelys olivacea*	Olive Ridley turtle Tortuga golfina	LKV	1.89	1.73	1.33	1.82	1.38	1.75	1.86	2.00	1.80	1.49	1.40	1.29	1.45

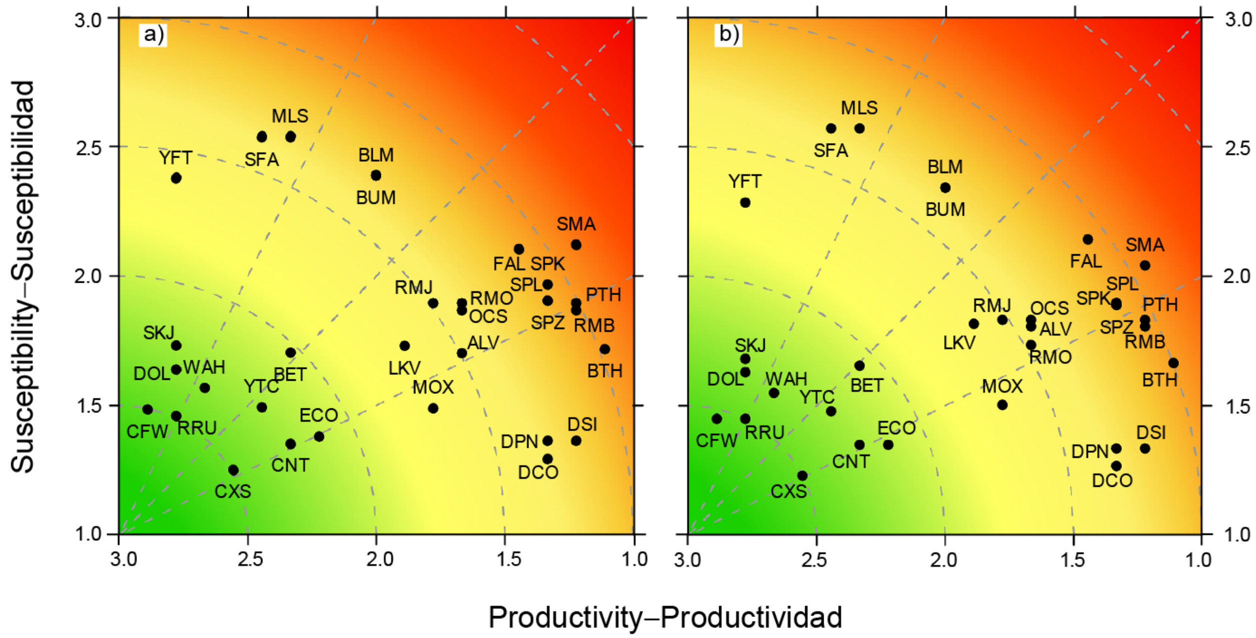

FIGURE 1. Productivity and susceptibility x-y plot for target and bycatch species caught by the purse-seine fishery of the EPO during 2005-2013, based on: (a) the original unweighted PSA productivity scores and a down-weighted susceptibility score for the areal overlap/geographical concentration attribute; and (b) unweighted susceptibility scores. See Table 4 for species codes. Risk: green = low, yellow = moderate, red = high

FIGURA 1. Gráfica x-y de productividad y susceptibilidad para especies objetivo y de captura incidental capturadas por la pesquería cerquera del OPO durante 2005-2013, basada en (a) las puntuaciones de productividad no ponderadas del APS original y una puntuación de susceptibilidad con ponderación reducida para el atributo de solape zonal/concentración geográfica y (b) puntuaciones de susceptibilidad no ponderadas. Ver la Tabla 4 para los códigos de especies. Riesgo: verde = bajo, amarillo = moderado, rojo = alto.

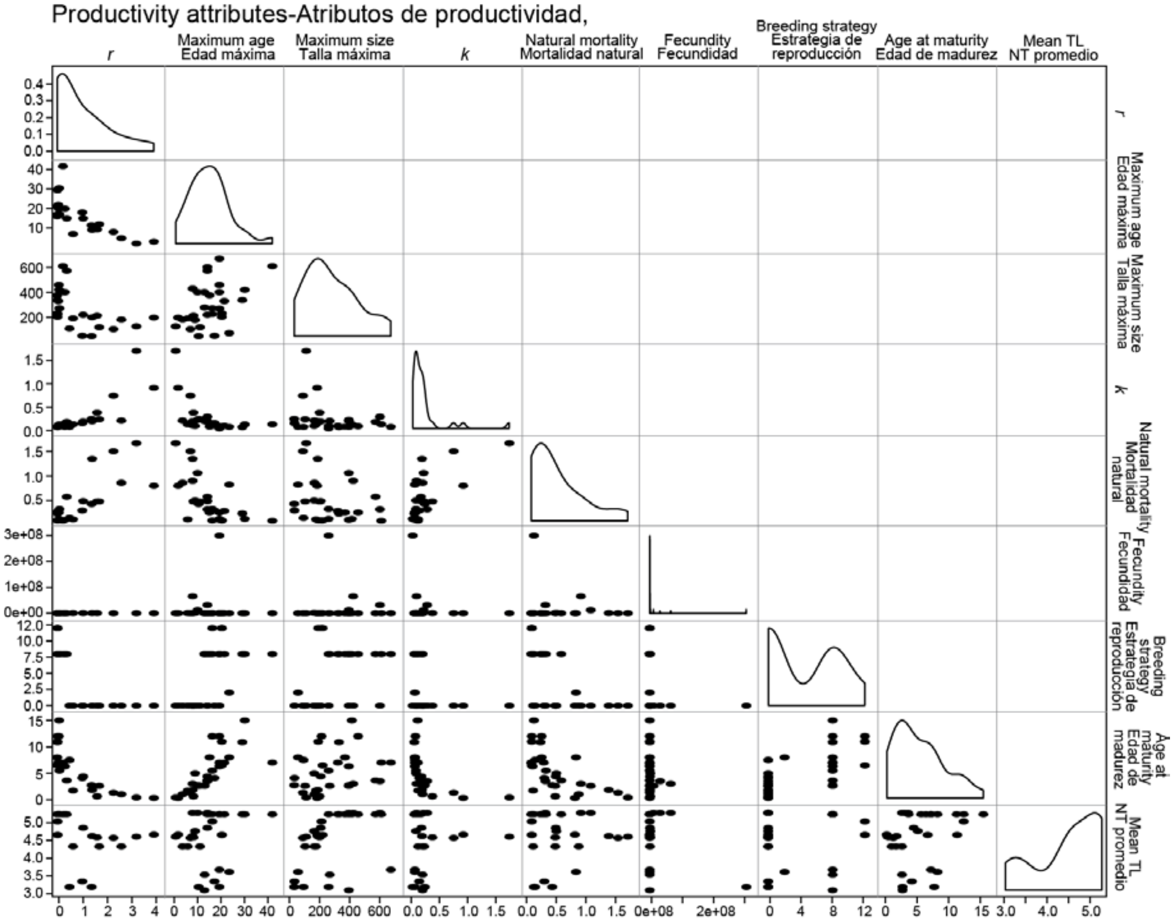

FIGURE 2. Scatterplot matrix of relationships between pairs of productivity attributes: intrinsic rate of population growth (*r*), maximum age (years), maximum size (L_{max}; cm), von Bertalanffy growth coefficient (*k*), natural mortality (*M*), fecundity, breeding strategy, age at maturity (years), mean trophic level (mean TL). Information on productivity attributes for each species was compiled from published and unpublished sources and EPO fisheries data used in the IATTC staff's previous PSAs.

FIGURA 2. Matriz de relaciones entre parejas de atributos de productividad: tasa intrínseca de crecimiento de población (*r*), edad máxima (años), talla máxima (L_{max}; cm), coeficiente de crecimiento de von Bertalanffy (*k*), mortalidad natural (*M*), fecundidad, estrategia reproductora, edad de madurez (años), nivel trófico medio (NT medio). Se compiló la información sobre los atributos de productividad de cada especie de fuentes publicadas e inéditas y de datos de la pesca del OPO usados en los ASP previos del personal de la CIAT.

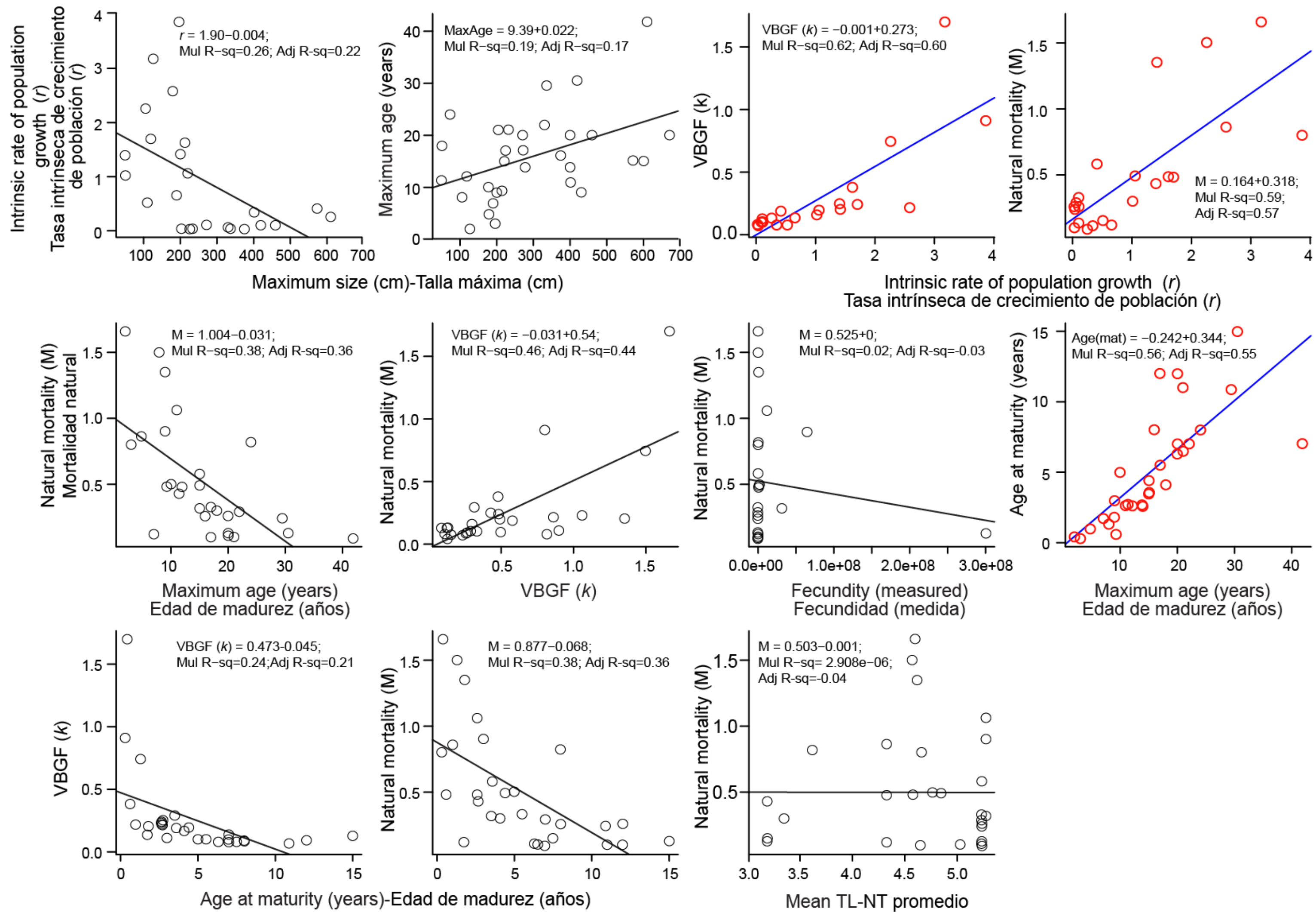

FIGURE 3. Simple linear regressions (and equations) for pairs of productivity attributes expected to be correlated based on expert opinion outlined in Table 3. Red represents relationships with an adjusted $R^2 > 0.5$. VBGF (*k*) = von Bertalanffy growth factor (*k*).

FIGURA 3. Regresiones lineales simples (y ecuaciones) para parejas de atributos de productividad que se espera estén correlacionadas con base en la opinión experta resumida en la Tabla 3. Rojo representa relaciones con un R^2 ajustado > 0.5. VBGF (*k*) = factor de crecimiento de von Bertalanffy (*k*).

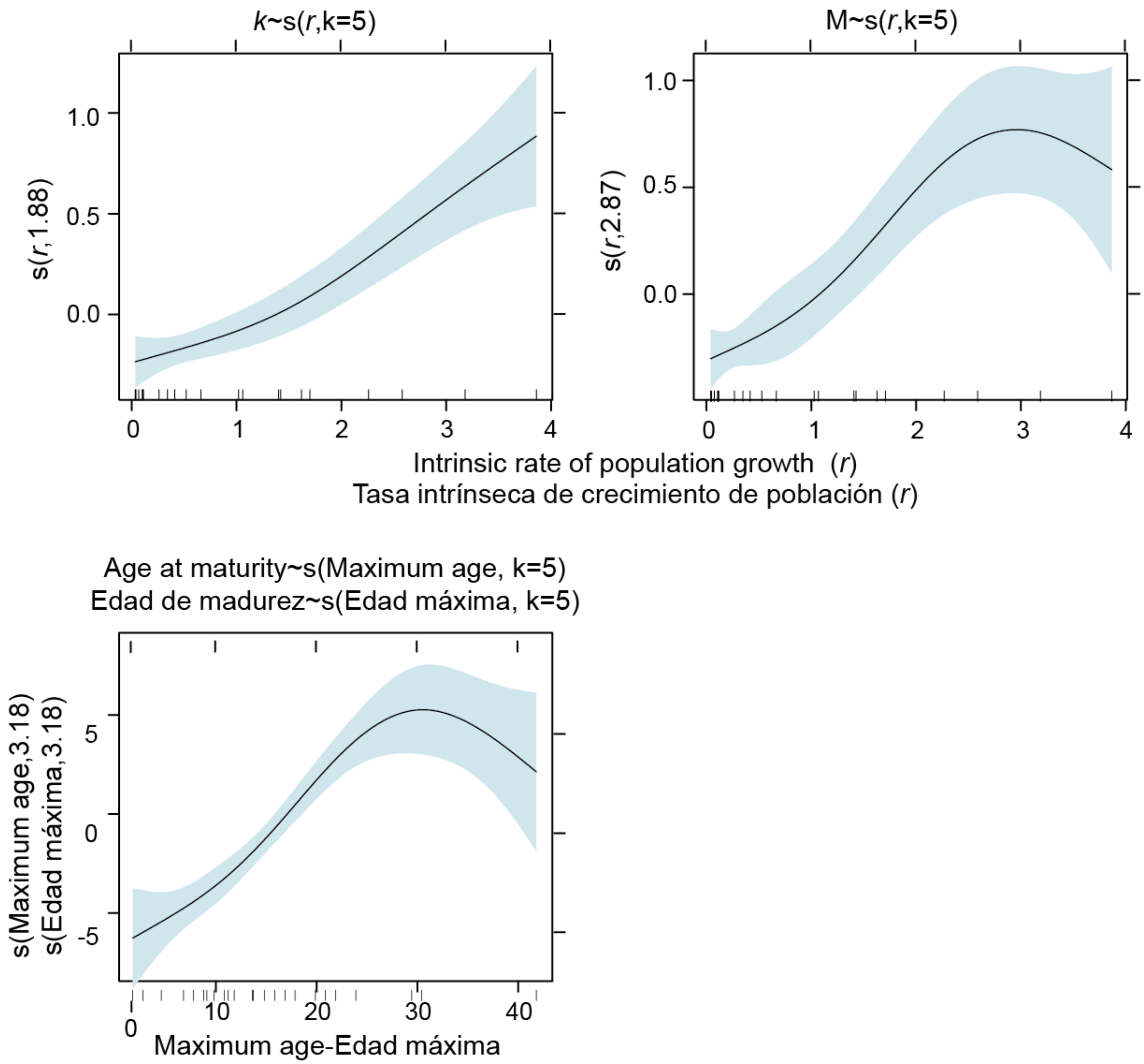

FIGURE 4. Smooth terms obtained from the GAMs fitted to the three pairwise relationships with an adjusted R^2 > 0.5 (Figure 3); (a) von Bertalanffy growth coefficient *k* modeled as a smooth term of the intrinsic rate of population growth (*r*); (b) natural mortality (*M*) modeled as a smooth term of *r*; and (c) age at maturity modeled as a smooth term of maximum age.

FIGURA 4. Términos suavizados obtenidos de los MAG ajustados a las tres relaciones emparejadas con un R^2 ajustado > 0.5 (Figura 3); (a) coeficiente de crecimiento de von Bertalanffy *k* modelado como término suavizado de la tasa intrínseca de crecimiento de la población (*r*), (b) mortalidad natural (*M*) modelada como término suavizado de *r*, y (c) edad de madurez modelada como término suavizado de la edad máxima.

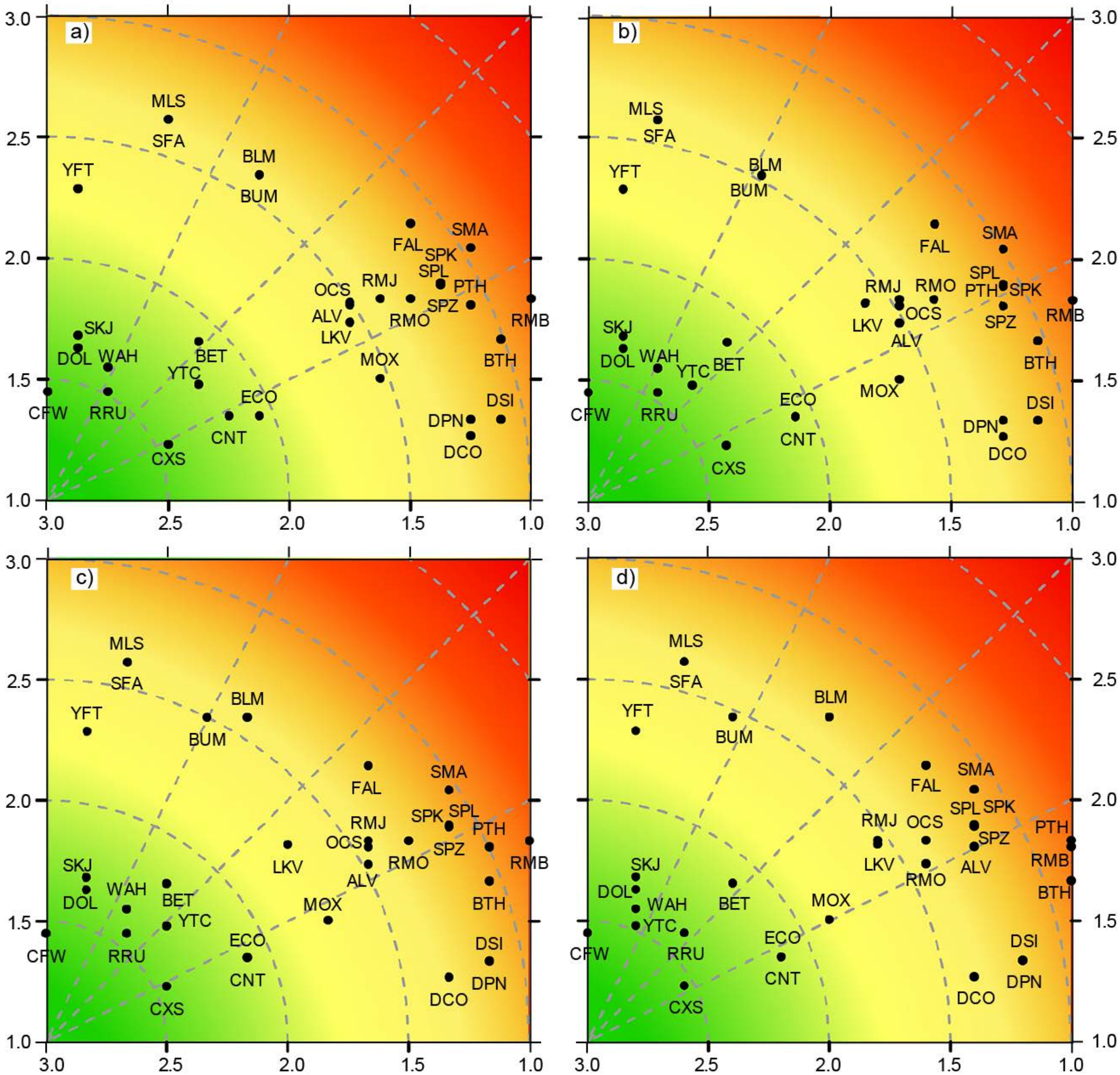

FIGURE 5. PSA plots after productivity parameter reduction: (a) one attribute removed: mean trophic level (TL), (b) two attributes removed: mean TL and the intrinsic rate of population growth (*r*), (c) three attributes removed: mean TL , *r*, and maximum age, and (d) four attributes removed: mean TL, *r*, maximum age, and natural mortality (*M*). The susceptibility scores are based on the unweighted s_j^1 (s_{rev} in Table 4). The 3-alpha species codes are defined in Table 4. Risk: green = low, yellow = moderate, red = high

FIGURA 5. Gráficas de ASP después de reducción de parámetros de productividad: (a) un atributo eliminado: nivel trófico (NT) medio; (b) dos atributos eliminados: NT medio y la tasa intrínseca de crecimiento de población (*r*); (c) tres atributos eliminados: NT medio, *r*, y edad máxima; y (d) cuatro atributos eliminados: NT medio, *r*, edad máxima, y mortalidad natural (*M*). Las puntuaciones de susceptibilidad se basan en s_j^1 no ponderado (s_{rev} en la Tabla 4). En la Tabla 4 se definen los códigos de especies 3-alfa. Riesgo: verde = bajo, amarillo = moderado, rojo = alto.

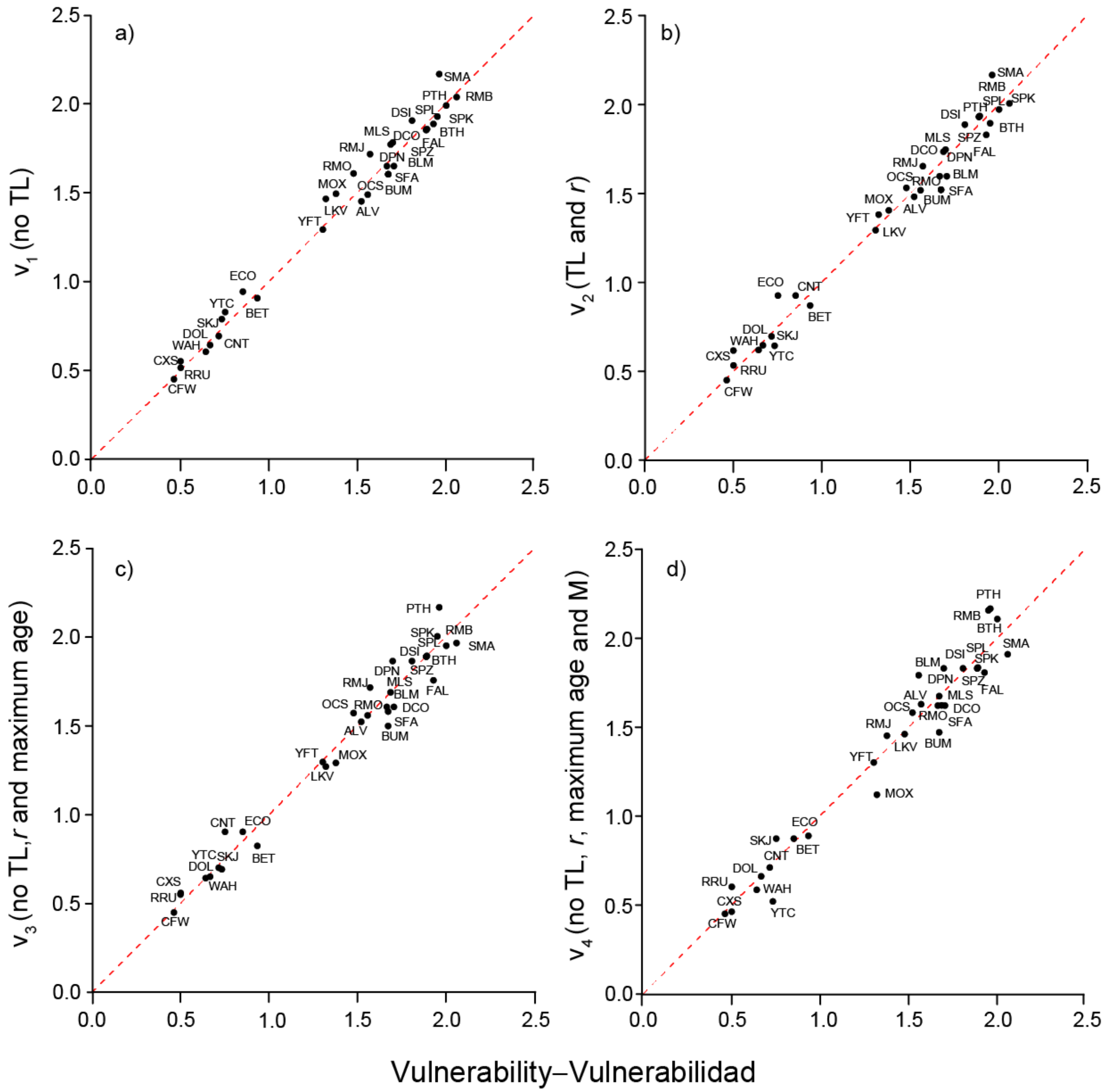

FIGURE 6. Comparison of overall unweighted vulnerability (*v*) scores using all 9 productivity attributes (*v* unweighted) and (a) 8 attributes, with mean trophic level (TL) removed; (b) 7 attributes, with mean TL and the intrinsic rate of population growth (*r*) removed; (c) 6 attributes, with mean TL, *r*, and maximum age removed; and (d) 5 attributes, with mean TL, *r*, maximum age, and natural mortality (*M*) removed. The 3-alpha species codes are defined in Table 4. The dashed lines show the 1-to-1 line.

FIGURA 6. Comparación de puntuaciones de vulnerabilidad (*v*) general no ponderada, usando todos los 9 atributos de productividad (*v* no ponderada) y (a) 8 atributos, con nivel trófico (NT) medio eliminado; (b) 7 atributos, con NT medio y la tasa intrínseca de crecimiento de población (*r*) eliminados; (c) 6 atributos, con NT medio, *r*, y edad máxima eliminados; y (d) 5 atributos, con NT medio, *r*, edad máxima, y mortalidad natural (*M*) eliminados. En la Tabla 4 se definen los códigos de especies 3-alfa. Las líneas de trazos representan la correspondencia 1:1.