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VIEWPOINT

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Weaknesses in stock assessment modelling and management practices affect fisheries sustainability

Graham J. Edgar[1] | Trevor J. Ward[2] | Rick D. Stuart-Smith[1]

[1] Institute for Marine and Antarctic Studies, University of Tasmania, Hobart, Tasmania, Australia

[2] School of Life Sciences, University of Technology Sydney, New South Wales, Australia

Correspondence
Graham J. Edgar, Institute for Marine and Antarctic Studies, University of Tasmania, Hobart, Tasmania, 7001, Australia.
Email: g.edgar@utas.edu.au

Abstract

1. We respond to criticism of our earlier paper where we report Australia-wide declines in fisheries catches that parallel the declining trends in fish populations observed underwater, and we highlight concerns about the low levels of precaution applied when regulating fisheries catches using the avoidance of recruitment failure approach.
2. Most fished species worldwide lack the data needed for accurate stock status assessments, and consequently exploitation of these species should be managed with high precaution.
3. For the relatively few species and stocks with individually modelled assessments, the errors associated with model output are extremely large as a result of the multiplicity of confounding factors (including effects of changing climate, technological advances that increase catch efficiency, fisher behaviour, interactions with other species, and changes in habitat quality), and the compounding of error introduced by subjective assumptions in multiple parameter estimates. The magnitude of this assessment uncertainty appears to be rarely recognized and incorporated into management decisions.
4. Given the difficulties in accurately predicting and managing fishing impacts, including species interactions across space and time, a well-designed set of no-take marine reserves is critically needed. Although not a universal panacea, an effective global network of marine reserves arguably represents the most efficient and publicly acceptable next step – in addition to greenhouse gas reduction – towards solving the unfolding global dilemma confronting fish populations and ocean ecosystems.

KEYWORDS

fisheries management, fisheries stock assessment, jackass morwong, marine protected area, marine reserve, overfishing, Reef Life Survey, reef monitoring, resilience, stock status

1 | INTRODUCTION

Two sets of fishery scientists (Gaughan et al., 2019; Little et al., 2019) responded critically to our study that reported and discussed declines in Australia's fisheries (Edgar, Ward, & Stuart-Smith, 2018). Many of our differences apparently derive from different world views, including the level of trust placed in model output (Boschetti, Hughes, Jones, & Lozano-Montes, 2018), the complexity of natural systems, and in a reductionist versus holistic vision of marine ecosystems. These differences are clearly evidenced in conflicting interpretations of 'sustainability'. Should a fishery be regarded as sustainable if the relatively few primary fishery targets maintain stable stock levels (Flood et al., 2016), or should other ecosystem elements, including those upon which the target species may depend upon, such as minor fishery species, bycatch, habitat and ecosystem structure, competitors, predators, and prey, also be considered as values in resilient and fished ecosystems?

Whereas management decisions in Australia and elsewhere rely on stock models for only a small proportion of the exploited species (Dowling et al., 2019), here we question the reliability of evaluations made with even the most data-rich stock assessment methods. We affirm the recommendation of Punt et al. (2018) – a paper that includes most co-authors of the Little et al. (2019) critique – that more scrutiny and precaution is needed when applying models known to have high levels of uncertainty for management decisions. This is particularly the case in an era with changing climate when much more progress is needed in the difficult task of integrating changing natural mortality with fishing mortality in stock models (Free et al., 2019; Kritzer, Costello, Mangin, & Smith, 2019).

Although we disagree with many of the specific criticisms of the respondents, we appreciate the call for the better integration of ecological and fisheries science perspectives, welcome the opportunity for further dialogue, and were pleased to see a high level of agreement on key issues that negatively affect fisheries assessment and management practices. Key research issues highlighted in our paper that aggregate into large management issues are listed below.

1. Few stock assessments use or are validated by fisheries-independent data.
2. Improving technology and consequent catch efficiency is rarely realistically represented in stock assessment models.
3. When dealing with uncertainty, the most optimistic scenario for maximizing fisheries production is more often accepted than a precautionary approach.
4. The fisheries definition of 'sustainable' is extremely narrow, relating to overfishing of stocks to the point that recruitment of juveniles is inadequate to prevent population decline, rather than encompassing elements of ecosystem structure, function, and health, including the interaction of targeted species across space and time with other species and their habitats.
5. Most stock assessment models are framed using historical data, even though current climate regimes lie outside historical bounds.
6. Stock assessments relate to individual species or stocks, ignoring interspecific interactions such as the changing densities of predators and prey across space and time.
7. In Australia, financial support for marine research projects touching on issues of sustainability is concentrated in grants that require approval from the fishing sector.
8. Stock assessments often lack accessibility and thus transparency, with insufficient information publicly available for independent replication or scrutiny.
9. Stock assessment models are frequently over-parameterized, and include much higher levels of uncertainty than is recognized by managers when using the output for making decisions.

Gaughan et al. (2019) commence their critique by agreeing that most of these issues are valid concerns. Little et al. (2019) make no comment on these issues other than the last two; consequently, a broad consensus apparently exists that most of the problems listed above are real, albeit with divergence when considering their importance.

Agreement presumably also extends to a recognition that an overriding problem with fisheries assessment in Australia is insufficient resources. The limited stock assessment funds that are available need to be spread over hundreds of species, most with low economic value, so detailed investigation cannot be financially justified. Also, the funding for the Commonwealth Scientific and Industrial Research Organisation (CSIRO) and other reputable agencies to undertake stock assessments in Australia continues to decline, arguably in part because of a negative loop involving declining catch value leading to declining research allocations. Very few detailed stock assessments are conducted each year (<5% of fished species). Consequently, the vast majority of Australian stocks simply do not have enough data to underpin adequate scientific understanding and management needs.

Stocks with inadequate data are often subject to ecological risk assessment (ERA) procedures (Hobday et al., 2011); however, Australian management agencies typically fail to go beyond the first qualitative step of the ERA (expert judgement). Furthermore, the effectiveness of ERAs is presently limited by unknown/unreported identities and abundance of species caught in mixed catches, and an inability to consider cumulative impacts across species. As such, ERAs do little to prevent the severe depletion of fishable species in particular local areas, especially where unknown recreational catches or environmental impacts are co-occurring. Although acknowledging the difficulties of managing such data-poor species, we strongly advocate that managers apply a higher level of precaution that does not depend principally on estimates of stock status derived from expert judgement or the subjective so-called 'weight of evidence' approach.

The main concern of both Gaughan et al. (2019) and Little et al. (2019) is our use of catch statistics rather than modelled stock estimates to identify population trends. This is despite the RAM global compilation of stock assessments (http://www.ramlegacy.org) showing steeper declines in modelled Australian stocks than catch data indicate (Edgar et al., 2018), and hence stocks may in fact be falling more rapidly than the catch data alone imply (an update and expansion of the RAM database would provide better clarity around this observation). Moreover, we note that recent analysis of global fisheries for which data are available identifies a strong relationship between the actual catch and the catch predicted for that year from modelled biomass data (Figure S23 in Costello et al., 2016), emphasizing the information content available in empirical catch trend data.

Moreover, as was highlighted in Edgar et al. (2018), trends in very few stocks are supported by published modelled stock size estimates to enable an accurate picture of population change amongst Australia's fisheries species. Only 294 stocks (83 of an unknown but much larger number of species exploited nationally) have compiled data available publicly through the Status of Australian Fish Stocks (SAFS) reports (http://fish.gov.au). Less than 20% of SAFS stocks are managed on the basis of a stock assessment undertaken in the last 10 years, whereas many are based on catch data alone, and others, such as a large suite of demersal species in Western Australia (e.g. the redthroat emperor stock, *Lethrinus miniatus*; http://fish.gov.au/report/51-Redthroat-Emperor-2016), are managed solely on the basis of catch and effort data from other 'indicator species'.

Different points of view on the validity of using modelled stock rather than catch data for trend assessment extend widely throughout the scientific community (e.g. Hilborn & Branch, 2013 versus Pauly, Hilborn, & Branch, 2013), and can arguably be traced back to differences in training between ecological and fisheries scientists, and to failures long recognized in fisheries assessment (Larkin, 1977). From very early in our careers as field ecologists, we were lectured on the dangers resulting from overfitting data and from pseudoreplication in autocorrelated situations (Forstmeier, Wagenmakers, & Parker, 2017). Very few covariates are required to develop good fits to small sets of randomly generated data (e.g. the rule-of-thumb of 10:1 subjects to predictors in multiple regression; Harrell, 2001). Consequently, we are surprised by the confidence expressed by fisheries scientists in predictions generated by sophisticated fishery models such as 'Stock Synthesis' when fitted using 15 or more separate parameters (e.g. Table 7.7 in Tuck, 2016) against time series data with very high temporal autocorrelation, and thus relatively few independent data points and low effective degrees of freedom.

Fisheries models routinely describe potential error in stock estimates by calculating asymptotic standard errors for model outputs, but such error values are very poor predictors of uncertainty in spawning stock biomass (Punt et al., 2018). They can greatly underestimate true error because error introduced in parameter estimates (amongst other considerations) is typically overlooked. For example, the Stock Synthesis model used for jackass morwong (*Nemadactylus macropterus*), the fishery discussed in Edgar et al. (2018), was found to be highly sensitive to the parameter value input for natural mortality (M). Sensitivity analysis indicated that the ratio of current biomass (B) to unexploited biomass (B_0) – the critical ratio for determining the recommended biological catch – varied from 52 to 36 to 21% depending on whether the value for M was selected as 0.20, 0.15, or 0.10 yr^{-1} (Tuck, Day, & Wayte, 2016). The M value applied in the preferred model was 0.15 for reasons of consistency with previous assessments, a critical decision that potentially affected management outcomes. A much lower M value of 0.09 had been suggested earlier in the Tuck et al. (2016) report as more appropriate for jackass morwong, which can live for more than 40 years (Jordan, 2001). Although just outside the bounds of the sensitivity analysis, extrapolation of the linear trend between M and B/B_0 indicates that B/B_0 was approximately 18% for $M = 0.09$. This is below the B/B_0 trigger ratio of 0.2 that invokes a recommended biological catch of zero and provides a signal for urgent management attention. Compounding error associated with decisions on M with errors in other parameter estimates generates uncertainty that, in our opinion, makes such model outputs unreliable when contributing to management decisions.

Our perspective is reinforced by a recent retrospective investigation of uncertainty in south-eastern Australian fish stocks – the group of fisheries with the best supporting data nationally. Punt et al. (2018) compared historical modelled estimates of stock size with the most recent, presumably most accurate, stock estimate (their Method C). They found that, across all species considered, the log standard deviation of differences was 0.60. Thus, if the error structure follows a normal distribution, only one half of earlier estimates of stock size lie within 67 and 150% of the most recent modelled estimate. The error structure was, however, skewed, reflecting the higher number of models that greatly overestimated historical stock size than the number that underestimated stock size. Moreover, the level of variation found was highly conservative, as it was calculated for a chronological sequence of assessments that extended for no more than 16 years, and mostly used the same model structure and parameter values (with updated data), rather than comprising fully independent assessments.

Predictions from such models on future stock size form the basis for an evaluation of recommended biological catch and thence 'total allowable catch', despite the huge imprecision that becomes evident when numbers are updated. Decisions made by managers using stock estimates that often decline 50% when updated a few years later are implicitly regarded as conservative by considering a 20% allowance for error (the difference between maximum sustainable yield and maximum economic yield targets; Punt et al., 2018).

Model predictions that show stock size as stable or increasing provide the basis for categorizing species such as redfish (*Centroberyx affinis*) as 'not subject to overfishing', despite concurrent recognition that the stock is 'overfished' and at <10% of virgin biomass levels (Patterson, Noriega, Georgeson, Larcombe, & Curtotti, 2017). Such logically questionable classification decisions underlie claims of sustainability, including the recent statement by the Australian Fisheries Management Authority that: 'for the fourth consecutive year the catch from all solely Commonwealth-managed fisheries has been determined by ABARES to be sustainable' (https://www.afma.gov.au/response-research-paper-edgar-et-al-regarding-australian-fishery-stocks).

We are perplexed at the continued support provided by Little et al. (2019) for the jackass morwong stock assessment when it was clearly flawed. On the basis of a numerical model that repeatedly indicated rising stock numbers at the time of assessment, despite retrospective analyses indicating falling numbers in the year of those assessments, and contrary to the recognition of recruitment failure and to all indicators (catches, catch per unit effort (CPUE), and fisheries independent surveys) precipitously declining (with an order of magnitude decline in the case of total catch and modelled stock size; Edgar et al., 2018), this fishery remains categorized as 'not overfished' (Patterson et al., 2017) and is listed as 'sustainable' (SAFS: https://fish.gov.au/report/237-Jackass-Morwong-2018). Moreover, this diagnosis depends on a 1988 climate-induced regime shift applied in stock models from 2011, despite no ecological study or other fisheries assessment recognizing an environmental regime shift in the same year, and despite all modelled scenarios predicting a rapid monotonic increase in stocks from 2011 to 2020 (Figure 5 in Wayte, 2013). Catches have declined to 40% of 2011/12 levels (404 tonnes; http://www.agriculture.gov.au/abares/research-topics/fisheries/fisheries-data#australian--fisheries-and-aquaculture-statistics-2013) in the most recent 2017/18 catch statistics (Commonwealth logbook data: eastern stock 107 tonnes, western stock 52 tonnes; https://fish.gov.au/report/237-Jackass-Morwong-2018), invalidating predictions of rapidly rising stocks and associated decisions, including the regime shift that facilitated a reduction of B_0 to 28% of the established virgin biomass level and an increased total allowable catch.

We agree with Little et al. (2019) that we erred when discussing the 2013 recommended biological catch for jackass morwong by confusing the eastern catch with the eastern plus western catch, and also when calculating the 2015 total catch (TC)/total allowable catch (TAC) ratio for school whiting by using the Commonwealth plus State TC versus Commonwealth TAC. However, we disagree with their contention that large drops in catches when averaged across all stocks are attributable to changing markets, fisher behaviour, and management arrangements independent of fishing pressure. They cite the example of catches of blue grenadier (*Macruronus novaezelandiae*) that decreased by more than 50% from 2013 to 2016 as a result of a single vessel not fishing, but no information is given to explain why the vessel that dominated the fishery ceased fishing (and no other vessels filled the void). Low catch rates that provided an inadequate return on investment compared with other fisheries seems likely. Government buy-outs of fishing effort are a consequence of overfishing rather than the primary cause of declining catches. Millions of public dollars are unlikely to be spent to reduce fishing effort when catches are genuinely sustainable. Moreover, total fishing effort across the Oceania region (which includes Australia, New Zealand and Pacific islands) has monotonically increased with no downward trend from 1950 to at least 2015 (Rousseau, Watson, Blanchard, & Fulton, 2019).

We tested the changing markets hypothesis (i.e. that fishers abandoned fisheries because of low prices) through further analysis of the Australian Bureau of Agricultural and Resource Economics and Sciences (ABARES) catch dataset to 2014 (available at http://www.agriculture.gov.au/abares/publications/pubs?url=http://143.188.17.20/anrdl/DAFFService/pubs.php?, with a search phrase of 'fisheries'), and found that hypothesis to be unsupported. No significant relationship was apparent for change in unit price from 2001 to 2014 (calculated as total catch value/total catch weight in ABARES statistics) and change in total catch ($r = -0.16$, $n = 175$, $P > 0.05$), indicating that fishers were not disproportionately departing fisheries with falling unit price. Furthermore, the average unit price amongst fisheries increased 1.57× through the period 2001–14, a rise considerably greater than inflation costs, including fuel (the Australian Consumer Price Index rose 1.42× through this period; https://www.rba.gov.au/calculator/annualDecimal.html). Thus, most 2014 catches would generate more value adjusted for community-wide inflation and costs than 2001 catches of the same species and volume.

We dispute the criticisms of Gaughan et al. (2019), including the attribution of statements to us with which we disagree. In particular, they state that we assume 'that the declines in catches after 2005 only reflect fishery-induced declines in abundance' when we instead see other factors also contributing to declines in catches, and in fact consider climate change to be currently contributing more to declining populations of temperate Australian species than fishing pressure. Declining population trends are evident in the publicly available Reef Life Survey dataset (https://reeflifesurvey.com) for over one-third of temperate Australian reef species (both fished and unfished species), presumably largely an effect of increasing water temperature, but with greater reductions for fished species than unfished species outside marine reserves, presumably an effect of fishing.

Our primary concern in the context of climate change is the additional impact of fishing mortality on top of natural mortality when natural mortality is increasing. How should a fishery with sustained historical fishing mortality (F) of 0.10 on top of natural mortality (M) of 0.10 be managed when M jumps to 0.15, 0.20, or even higher, through climate impacts? We see little consideration of this issue in stock assessments, or in decisions on fisheries quota allocation (other than when environmental change is used as a post hoc rationale for falling stocks). Nevertheless, the incorporation of ecological impacts of changing climate into models could be achieved to some extent by coupling information on rate of increase in sea temperature within regions with predicted changes in local abundance and presence based on temperature and species traits (Bates, Stuart-Smith, Barrett, & Edgar, 2017; Day, Stuart-Smith, Edgar, & Bates, 2018; Pinsky, Worm, Fogarty, Sarmiento, & Levin, 2013). Rather than attempt to increase fishing mortality F with increasing natural mortality M, as for jackass morwong, stock models that decrease F with increasing M to accommodate the impacts of climate change also offer advances, providing that the large uncertainty inherent in the estimates of M is appropriately addressed (Kritzer et al., 2019).

Gaughan et al. (2019) list six sets of examples where declines in catches are considered to be unrelated to fishing pressure. Three involve management actions (increased controls following low recruitment, more conservative harvest strategies, and the protection of spawning areas) that are arguably responses to declining catches and stocks rather than the cause. Declining catches unrelated to fishing pressure are also attributed to environmental change, but with no consideration given to cumulative impacts involving both fishing and climate, as is critical. Another example given relates to habitat changes in the highly regulated Murray River freshwater flow, even though our study is confined to marine fisheries. They further argue that observed catch patterns relate to changes in fishing costs and markets, presumably a reference to the changing markets hypothesis, which, for Australian fisheries, was tested above and was found to lack support.

In any case, contrary to the statement of Gaughan et al. (2019) that we would categorize many of these stocks as collapsed, none of their listed examples involved a 90% decline in catches solely on the basis of the stated cause. Thus, none would qualify as collapsed using our definition unless fishing mortality or other factors contributed to additional population decline.

Gaughan et al. (2019) criticize the restriction of our analysis to the period 2005–15 and the use of citizen science data. The time period selected allowed the use of the greatest density of fishery-independent field data, and corresponded with the roll-out of the Commonwealth Harvest Strategy Policy (http://www.agriculture.gov.au/fisheries/domestic/harvest_strategy_policy), so provides a test of whether this new strategy is working. We strongly challenge the unsupported claim that data collected by citizen scientists are inferior to data collected by professional scientists when a rigorous training regime is involved and when statistical analysis cannot distinguish the two groups (Edgar & Stuart-Smith, 2014). Few scientists doubt the ability of the best amateur birdwatchers to identify and count species. The same is true for the enthusiastic divers participating in the Reef Life Survey, who spend hours poring over fish and invertebrate identification guides and are screened before and after training. Moreover, <10% of the data analysed in our study was obtained from observers without science qualifications.

We do not dispute that the field dataset used in our study is biased towards inshore tropical species or state that our analysis is comprehensive. We also acknowledge that recreational fisheries catches are uncapped and may be the primary source of fisheries impacts on the shallow reefs surveyed. Our study should be seen as an initial step in the independent validation of management effectiveness. We simply applied normal scientific method to test the predictions of two competing hypotheses that explain why Australian fishery catches have consistently declined over the past decade: 1, fishery management has become more precautionary, with more fish left in the sea, thereby generating stable or rising stocks underwater; or 2, declining fishery catches reflect declining stock abundances. Our test – the only broad-scale test conducted so far that is independent of stock models and industry-funded stock surveys – involved the comparison of population trends for fished species observed underwater versus a control set of unfished species at hundreds of sites, and a comparison of trends in fished versus control locations where fishing is prohibited (no-take reserves). Outcomes consistently supported hypothesis 2 and not hypothesis 1.

Further research is needed to understand how far these empirical findings can be generalized. Nevertheless, fishery assessment and management processes are broadly similar across the various Australian state and national jurisdictions, with many of the same problems we identify associated with assessment and decision making (Box 1 in Edgar et al., 2018). Consequently, hypothesis 2 seems much more likely than hypothesis 1 to apply to fisheries across Australia (and worldwide), in our opinion.

Our paper was not designed to provide recommendations for dealing with all of the many wicked problems associated with fisheries stock analysis and management, but we attempt to identify, from the independent perspective of trends observed in fish populations, the key challenges to be addressed by the next cohort of modellers and managers. A fishery management system is needed that can achieve high-quality environmental as well as economic outcomes by applying appropriate precaution coupled with empirical fishery-independent evaluation of the effectiveness of management strategies.

To meet ecosystem-level sustainability objectives for harvested fish populations, such strategies will need to progress well beyond the present conceptually weak implementation of the recruitment failure paradigm. Management strategies should also incorporate ecological performance metrics that reflect at least the issues of population resilience and persistence across habitats in space and time (that may be derived from size spectra, for example; Blanchard, Heneghan, Everett, Trebilco, & Richardson, 2017). Within a decision analytic framework, the key message for future fishery initiatives from our analysis here is simple: even the best achievable implementation of the current concept and strategies for avoidance of recruitment failure does not enable system-level sustainability objectives to be achieved for Australia's marine fisheries.

To summarize, as field ecologists we place more trust in direct observations using standardized quantitative methods at 533 sites continent-wide than the theoretical constructions that are the basis of modelled stock assessments. Modelled population predictions typically:

- fail to account for many elements of natural and societal complexity, including the impacts of climate, technological advances that increase catch efficiency, fisher behaviour, interactions with other species and habitats (fish numbers and their various cohorts depend on available food and predation pressure that vary in space and time);
- relate to only a few fished species; and
- include numerous subjective assumptions or decisions, each of which compound assessment errors such that the final uncertainty is massive.

We agree with our respondents that constructive collaboration between field ecologists and fisheries modellers represents an important step for improved decision making, with potential benefits for conservation, the fishing sector, and the public, who all have much to gain from well-regulated fisheries with long-term sustainable yields. We certainly also recognize the professional and skilled contributions of fishery science and scientists.

Our different opinions on the sustainability of current practices should be unequivocally resolved over the coming years by comparing future trends with alternative predictions. We predict that the fall in catches will continue at a similar or increasing rate unless management models and processes are improved, and that nationwide impacts of fishing will continue to intensify unless a network of effective marine reserves is developed. Additionally, we predict that mismatches between model predictions and actual catch rates will increasingly be attributed to the changing climate, even though the impacts of climate change are partly predictable and should be accommodated from the start in models and management decisions.

We have no illusions that marine reserves represent a perfect management tool, particularly when deliberately located in marginal areas that allow business to continue as usual (Devillers et al., 2015), or when ‘no take’ is not effectively enforced (Edgar et al., 2014; Kritzer, 2004), or for countering climatic impacts that require global controls on carbon emissions (Bruno, Côté, & Toth, 2019). Regardless, we maintain the view that in addition to greenhouse gas reduction, a well-designed and managed set of no-take reserves represents the most effective, efficient, and publicly acceptable next step in solving the unfolding global dilemma confronting fish populations and ocean ecosystems. This is the case for marine ecosystems in Australia and globally.

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ORCID

Graham J. Edgar https://orcid.org/0000-0003-0833-9001

REFERENCES

Bates, A. E., Stuart-Smith, R. D., Barrett, N. S., & Edgar, G. J. (2017). Biological interactions both facilitate and resist climate-related functional change in temperate reef communities. *Proceedings of the Royal Society B: Biological Sciences*, *284*, 20170484, 1–7. https://doi.org/10.1098/rspb.2017.0484

Blanchard, J. L., Heneghan, R. F., Everett, J. D., Trebilco, R., & Richardson, A. J. (2017). From bacteria to whales: Using functional size spectra to model marine ecosystems. *Trends in Ecology & Evolution*, *32*, 174–186. https://doi.org/10.1016/j.tree.2016.12.003

Boschetti, F., Hughes, M., Jones, C., & Lozano-Montes, H. (2018). On decision makers' perceptions of what an ecological computer model is, what it does, and its impact on limiting model acceptance. *Sustainability*, *10*, 2767. https://doi.org/10.3390/su10082767

Bruno, J. F., Côté, I. M., & Toth, L. T. (2019). Climate change, coral loss, and the curious case of the parrotfish paradigm: Why don't marine protected areas improve reef resilience? *Annual Review of Marine Science*, *11*, 307–334. https://doi.org/10.1146/annurev-marine-010318-095300

Costello, C., Ovando, D., Clavelle, T., Strauss, C. K., Hilborn, R., Melnychuk, M. C., & Leland, A. (2016). Global fishery prospects under contrasting management regimes. *Proceedings of the National Academy of Sciences of the United States of America*, *113*, 5125–5129. https://doi.org/10.1073/pnas.1520420113

Day, P. B., Stuart-Smith, R. D., Edgar, G. J., & Bates, A. E. (2018). Species' thermal ranges predict changes in reef fish community structure during 8 years of extreme temperature variation. *Diversity and Distributions*, in press, *24*, 1036–1046. https://doi.org/10.1111/ddi.12753

Devillers, R., Pressey, R. L., Grech, A., Kittinger, J. N., Edgar, G. J., Ward, T., & Watson, R. (2015). Reinventing residual reserves in the sea: Are we favouring ease of establishment over need for protection? *Aquatic Conservation: Marine and Freshwater Ecosystems*, *25*, 480–504. https://doi.org/10.1002/aqc.2445

Dowling, N. A., Smith, A. D. M., Smith, D. C., Parma, A. M., Dichmont, C. M., Sainsbury, K., … Cope, J. M. (2019). Generic solutions for data-limited fishery assessments are not so simple. *Fish and Fisheries*, *20*, 174–188. https://doi.org/10.1111/faf.12329

Edgar, G. J., & Stuart-Smith, R. D. (2014). Systematic global assessment of reef fish communities by the Reef Life Survey program. *Scientific Data*, *1*, 140007, 1–140007, 8. https://doi.org/10.1038/sdata.2014.7

Edgar, G. J., Stuart-Smith, R. D., Willis, T. J., Kininmonth, S., Baker, S. C., Banks, S., … Thomson, R. J. (2014). Global conservation outcomes depend on marine protected areas with five key features. *Nature*, *506*, 216–220. https://doi.org/10.1038/nature13022

Edgar, G. J., Ward, T. J., & Stuart-Smith, R. D. (2018). Rapid declines across Australian fishery stocks indicate global sustainability targets will not be achieved without expanded network of 'no-fishing' reserves. *Aquatic Conservation: Marine and Freshwater Ecosystems*, *28*, 1337–1350. https://doi.org/10.1002/aqc.2934

Flood, M. J., Stobutzki, I., Andrews, J., Ashby, C., Begg, G. A., Fletcher, R., … Wise, B. S. (2016). Multijurisdictional fisheries performance reporting: How Australia's nationally standardised approach to assessing stock status compares. *Fisheries Research*, *183*, 559–573. https://doi.org/10.1016/j.fishres.2016.02.002

Forstmeier, W., Wagenmakers, E. J., & Parker, T. H. (2017). Detecting and avoiding likely false-positive findings–a practical guide. *Biological Reviews*, *92*, 1941–1968. https://doi.org/10.1111/brv.12315

Free, C. M., Thorson, J. T., Pinsky, M. L., Oken, K. L., Wiedenmann, J., & Jensen, O. P. (2019). Impacts of historical warming on marine fisheries production. *Science*, *363*, 979–983. https://doi.org/10.1126/science.aau1758

Gaughan, D., Caputi, N., Molony, B., Wise, B., Begg, G., Mayfield, S., … Saunders, T. (2019). Comments on Edgar et al. (2018) paper for south-western Australia. *Aquatic Conservation: Marine and Freshwater Ecosystems*. in press https://doi.org/10.1002/aqc.3045

Harrell, F. E. (2001). *Regression modeling strategies: with applications to linear models, logistic regression, and survival analysis*. New York: Springer. https://doi.org/10.1007/978-1-4757-3462-1

Hilborn, R., & Branch, T. A. (2013). Fisheries: Does catch reflect abundance? No, it is misleading. *Nature*, *494*, 303+305–303+306. https://doi.org/10.1038/494303a

Hobday, A., Smith, A., Stobutzki, I., Bulman, C., Daley, R., Dambacher, J., … Furlani, D. (2011). Ecological risk assessment for the effects of fishing. *Fisheries Research*, *108*, 372–384. https://doi.org/10.1016/j.fishres.2011.01.013

Jordan, A. R. (2001). Age, growth and spatial and interannual trends in age composition of jackass morwong, *Nemadactylus macropterus*, in Tasmania. *Marine and Freshwater Research*, *52*, 641–660. https://doi.org/10.1071/MF99157

Kritzer, J. P. (2004). Effects of noncompliance on the success of alternative designs of marine protected-area networks for conservation and fisheries management. *Conservation Biology*, *18*, 1021–1031. https://doi.org/10.1111/j.1523-1739.2004.00022.x

Kritzer, J. P., Costello, C., Mangin, T., & Smith, S. L. (2019). Responsive harvest control rules provide inherent resilience to adverse effects of climate change and scientific uncertainty. *ICES Journal of Marine Science*, in press. https://doi.org/10.1093/icesjms/fsz038

Larkin, P. A. (1977). An epitaph for the concept of maximum sustained yield. *Transactions of the American Fisheries Society*, *106*, 1–11. https://doi.org/10.1577/1548-8659(1977)106<1:AEFTCO>2.0.CO;2

Little, L. R., Day, J., Haddon, M., Klaer, N., Punt, A. E., Smith, A. D., … Tuck, G. N. (2019). Comments on the evidence for the recent claim on the state of Australian fish stocks. *Aquatic Conservation: Marine and Freshwater Ecosystems*, *29*, 329–330. https://doi.org/10.1002/aqc.2992

Patterson, H., Noriega, R., Georgeson, L., Larcombe, J., & Curtotti, R. (2017). *Fishery status reports 2017*. Canberra: Australian Bureau of Agricultural and Resource Economics and sciences.

Pauly, D., Hilborn, R., & Branch, T. A. (2013). Fisheries: Does catch reflect abundance? *Nature*, *494*, 303–306. https://doi.org/10.1038/494303a

Pinsky, M. L., Worm, B., Fogarty, M. J., Sarmiento, J. L., & Levin, S. A. (2013). Marine taxa track local climate velocities. *Science*, *341*, 1239–1242. https://doi.org/10.1126/science.1239352

Punt, A. E., Day, J., Fay, G., Haddon, M., Klaer, N., Little, L. R., … Sporcic, M. (2018). Retrospective investigation of assessment uncertainty for fish stocks off southeast Australia. *Fisheries Research*, *198*, 117–128. https://doi.org/10.1016/j.fishres.2017.10.007

Rousseau, Y., Watson, R. A., Blanchard, J. L., & Fulton, E. A. (2019). Evolution of global marine fishing fleets and the response of fished resources. *Proceedings of the National Academy of Sciences*. https://doi.org/10.1073/pnas.1820344116

Tuck, G. N. (2016). *Stock assessment for the Southern and Eastern Scalefish and Shark Fishery: 2015 Part 1: Tier 1 assessments. Report 2014/0818*. Canberra.: Australian Fisheries Management Authority.

Tuck, G. N., Day, J., & Wayte, S. (2016). Assessment of the eastern stock of Jackass Morwong (*Nemadactylus macropterus*) based on data up to 2014. In G. N. Tuck (Ed.), *Stock assessment for the southern and eastern Scalefish and shark fishery: 2015 part 1: tier 1 assessments. Report 2014/0818* (pp. 156–204). Canberra: Australian Fisheries Management Authority.

Wayte, S. E. (2013). Management implications of including a climate-induced recruitment shift in the stock assessment for jackass morwong (*Nemadactylus macropterus*) in south-eastern Australia. *Fisheries Research*, *142*, 47–55. https://doi.org/10.1016/j.fishres.2012.07.009

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