Weaknesses in stock assessment modelling and management practices affect sustainability of fisheries

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Abstract

1. We respond to criticism of our earlier paper where we report Australia-wide declines in fisheries catches that parallel declining trends in fish populations observed underwater (Edgar et al. 2018), and we highlight concerns about 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, consequently exploitation of these species should be managed with high precaution.
3. For the relatively few species and stocks with individually modelled assessments, error associated with model output is extremely large due to the multiplicity of confounding factors (including effects of changing climate, technological advances that increase catch efficiency, fisher behaviour, interactions with other species, 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 recognised and incorporated into management decisions.
4. Given 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. While not a universal panacea, an effective global network of marine reserves arguably represents the most efficient and publicly acceptable next step – additional to greenhouse gas reduction – towards solving the unfolding global dilemma confronting fish populations and ocean ecosystems.

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

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 et al., 2018). Many of our differences apparently derive from different world views, including the level of trust placed in model output (Boschetti et al., 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 such as minor fishery species, bycatch, habitat and ecosystem structure, competitors, predators and prey also be considered as values in resilient and fished ecosystems?

While management decisions in Australia and elsewhere rely on stock models for only a small proportion of 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 et al., 2019).

While we disagree with many of the specific criticisms of the respondents, we appreciate the call for 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 include:

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 maximising 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 in time/space 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 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-parameterised, and include much higher levels of uncertainty than recognised by managers when using 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 issues other than the last two; consequently, a broad consensus apparently exists that most of the listed problems above are real, albeit with divergence when considering their importance.

Agreement presumably also extends to 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, funding for CSIRO and other reputable agencies to undertake stock assessments in Australia continues to decline, arguably in part due to 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 an 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 severe depletion of fishable species in particular local areas, especially where unknown recreational catches or environmental impacts are co-occurring. While 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), hence stocks may in fact be falling more rapidly than catch data alone imply (an update and expansion of the RAM database would provide better clarity around this observation). And, we note that recent analysis of global fisheries for which data are available identifies a strong relationship between actual catch and catch predicted for that year from modelled biomass data (Fig. S23 in Costello et al., 2016), emphasising 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, while 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; 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 through the scientific community [e.g. (Hilborn and Branch, 2013) versus (Pauly et al., 2013)], and can arguably be traced back to differences in training between ecological and fisheries scientists, and to failures long recognised in fisheries assessment (Larkin, 1977). From very early in our careers as field ecologists, we were lectured on dangers resulting from overfitting data and from pseudoreplication in autocorrelated situations (Forstmeier et al., 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, 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 et al., 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. report as more appropriate for jackass morwong, which can live more than 40 years (Jordan, 2001). While just outside the bounds of the sensitivity analysis, extrapolation of the linear trend between M and B/B_o indicates B/B_o is approximately 18% for M = 0.09. This is below the B/B_o 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 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), and found that, across all species included, the log standard deviation of differences was 0.60. Thus, if 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. 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 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 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 categorising 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 et al., 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 is clearly flawed. On the basis of a numerical model that repeatedly indicates rising stock numbers at the time of assessment despite retrospective analyses indicating falling numbers in the year of those assessments, and contrary to recognition of recruitment failure and to all indicators (catches, catch-per-unit-effort (CPUE), fisheries independent surveys) precipitously declining (an order of magnitude decline in the case of total catch and modelled stock size, Edgar et al., 2018), this fishery remains categorised 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 recognising an environmental regime shift in the same year, and all modelled scenarios predicting a rapid monotonic increase in stocks from 2011 to 2020 (Fig. 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-2017) in the most recent 2017/18 catch statistics (162 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 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 vs 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 that decreased by more than 50% from 2013 to 2016 due to 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 to 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.

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? searchphrase = fisheries) and found that hypothesis to be unsupported. No significant relationship was apparent between change from 2001 to 2014 in unit price (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. Further, average unit price amongst fisheries increased 1.57x through the period 2001-2014, a rise considerably greater than inflation representing costs including fuel (the Australian Consumer Price Index rose 1.42x 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 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 (www.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 climate change context is the additional impact of fishing mortality on top of natural mortality when the latter is increasing. How should a fishery with sustained historical fishing mortality (F) of 0.1 on top of natural mortality (M) of 0.1 be managed when M jumps to 0.15, 0.2 or even greater 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, 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 et al., 2017; Day et al., 2018; Pinsky et al., 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 impacts of climate also offer advances, providing that the large uncertainty inherent in 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, 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, is tested above and found to lack support.

In any case, contrary to the statement of Gaughan et al. (2019) that we would categorise 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) criticise restriction of our analysis to the period 2005-2015 and the use of citizen science data. The time period selected allowed use of the greatest density of fishery-independent field data, and corresponded with rollout 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 statistical analysis cannot distinguish the two groups (Edgar and 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 Reef Life Survey who spend hours poring over fish and invertebrate identification guides and are screened before and after training. Moreover, <10% of 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 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, generating stable or rising stocks underwater; or (2) declining fishery catches reflect declining stock abundances. Our test – the only broad-scale test so far conducted 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 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 generalised. 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 issues of population resilience and persistence across habitats in space and time (such as, for example, may be derived from size spectra, Blanchard et al., 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 summarise, as field ecologists we place more trust in direct observations using standardised 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 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 few fished species; and
- include numerous subjective assumptions/decisions, each of which compound error such that final assessment 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 recognise the professional and skilled contributions of fishery science and scientists.

Our different opinions on the sustainability of current practices should be unequivocally resolved over 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 nation-wide impacts of fishing will continue to intensify unless a network of effective marine reserves is developed. Additionally, we predict mismatches between model predictions and actual catch rates will increasingly be attributed to changing climate, even though the impacts of climate change are partly predictable and should be accommodated *a priori* in models and through precautionary 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), when not 'no-take' or effectively enforced (Edgar et al., 2014; Kritzer, 2004), or for countering climatic impacts that require global controls on carbon emissions (Bruno et al., 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 both for Australia's marine ecosystems and globally.

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