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Detecting population trends for US marine mammals

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Abstract

Trend analysis can provide valuable information about marine mammal population dynamics, potentially revealing the influence of environmental factors and inform conservation and management decisions. We reviewed the marine mammal stock assessment reports (SARs) published by the US National Marine Fisheries Service and found that 80% of the selected 244 marine mammal stocks with SARs lack assessment for trends in population abundance. We compared trend analysis with another common management tool, potential biological removal (PBR), a measure of the maximum human-caused mortality that can still result in positive population growth. We found that, generally, estimates of PBR were lower for declining stocks than for increasing or stable stocks and varied by life history characteristics. As a case study, we used a resampling approach on three well-studied stocks, killer whale (*Orcinus orca*—Northern Resident), beluga (*Delphinapterus leucas*—Cook Inlet), and humpback whale (*Megaptera novaeangliae*—CA/OR/WA), to test the minimal amount of time and sampling necessary to detect population trends with high statistical power. We found seven sampling events over more than 10 years were needed for a high statistical power level for all three stocks. Altogether, these findings suggest that well-studied stocks can provide crucial information on the statistical requirements for detecting trends. Furthermore, our proposed resampling approach might enable more frequent trend analysis, even with limited time series available for many stocks.

KEYWORDS
marine mammals, population dynamics, trend analysis, population monitoring

1 | INTRODUCTION

Marine ecosystems face persistent anthropogenic stressors in pollution, exploitation from fisheries, and climate change (Davidson et al., 2012; Schipper et al., 2008). Because of historical exploitation, competition, and direct overlap with humans, top predators like marine mammals face the challenges of coping in human-dominated seascapes (Heithaus et al., 2008; Magera et al., 2013). Marine mammals are particularly impacted by anthropogenic sources of mortality (Avila et al., 2018), in part from their direct spatiotemporal and trophic overlap with fisheries,

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resulting in competition and the potential for mortality from bycatch (Heppell et al., 2000; Heppell et al., 2005; Senko et al., 2014). In addition, marine mammals often are slow to recover because of their long life histories and low fecundity.

Despite their charismatic standing with the public (Kellert, 1999) and statutory protections (i.e., Marine Mammal Protection Act [MMPA] and Endangered Species Act in the United States), there are still significant gaps in understanding marine mammal species' conservation status and global trends (Avila et al., 2018, International Union for Conservation of Nature and Natural Resources—IUCN, 2019). Conducting trend analysis using time series abundance estimates can provide insight into marine mammal population trajectories, conservation status, and the effectiveness of management and conservation interventions (Peters, 2010). Trend analysis is a valuable tool because it integrates both extrinsic (e.g., anthropogenic) and intrinsic (e.g., life history) parameters in measuring and accounting for the change in species or population abundance (Chambers et al., 2015). However, there is a lack of high-quality, long-term monitoring for many marine mammals (Avila et al., 2018; Jewell et al., 2012; Kaschner et al., 2012). While long-term time series data are valuable, they are effort-intensive, expensive, and often unable to achieve the appropriate precision and accuracy needed for trend analysis (Authier et al., 2020; Katsanevakis et al., 2012). In addition, it is not always clear how many years of sampling are needed to achieve appropriate statistical power to detect trends. However, species with high quality (low sampling error and many years of sampling) abundance sampling may yield insights for the minimal sampling requirements necessary to detect trends in other species or stocks (Fournier et al., 2019; Wauchope et al., 2019; White, 2019; White & Bahlai, 2021).

Given the constraints for gathering long-term population trend data on marine mammals, a complementary management tool, potential biological removal (PBR), is often used to identify excessive anthropogenic mortality, such as the incidental take in commercial fisheries (Wade, 1998, Robards et al., 2009, Taylor et al., 2007.). The intent of the PBR approach is to quantify a threshold level of the maximum human-caused mortality that can still result in positive population growth (Wade, 1998). PBR is an algebraic formula defined as the product of a population's minimum population estimate ($N_{\min}$), half potential net productivity rate ($R_{\max}$), and a recovery factor (Fr) that varies from 0.1 to 1.0 depending on protective status/predetermined risk (Wade, 1998) for management units (stocks). PBR is particularly applicable to stocks where fisheries mortality is the primary population threat (Robards et al., 2009; Taylor et al., 2000, 2007). However, marine mammal populations are not limited to direct human-caused mortality (e.g., ship strike, bycatch, entanglements) and usually face mortality from other threats in the environment, including disease, predation, reduced prey availability, ecosystem change, and anthropogenically caused habitat degradation (Avila et al., 2018; Lotze et al., 2011; Magera et al., 2013; Taylor et al., 2007). Thus, by accounting for these other factors, trend analysis may reveal different and complementary information about a population compared to PBR alone (Lotze et al., 2017; Robards et al., 2009; Taylor et al., 2007). For example, declining stocks may have smaller PBR values if human-caused mortality is driving the decline. Alternatively, in some stocks with little interaction with fisheries, decreasing trends may reveal nondirect sources of mortality, but the population's PBR value may remain high. Therefore, we explored the interplay between population trends and PBR to shed light on the recovery of marine mammal stocks in US waters.

In the United States, NOAA Fisheries is statutorily required to develop stock assessment reports (SARs) for each stock within the US Exclusive Economic Zone using the best scientific information available on stock abundance, population trend, PBR, and total mortality and serious injury (16 USC § 1386, section 117: MMPA, 1972). However, given concerns over adequate power or sampling to detect trends or a lack of data, not all SARs have trend analyses. Therefore, we used stock assessment data to: (1) identify which SARs report trend analyses, (2) assess the relationship between trend analyses and PBR, (3) examine the biological correlates of PBR, and (4) use stocks with high-quality abundance sampling to understand minimal statistical requirements needed to determine the presence or absence of a trend over time.

1.1 | Trend analysis in US marine mammal stocks

We extracted population abundance, PBR, and trend data from published NOAA Fisheries SARs. In total, we examined 244 marine mammal stocks whose SARs were completed between 1995 and 2018. We found that only 20% ($n = 49$) of stocks had some form of trend analysis in the study period. We recorded the reported trend in each SAR (using the IUCN population trend classifications (IUCN, 2019)). Of stocks with trend analysis, 61% were increasing, 12% of stocks were decreasing, and 27% percent were defined as stable (Table S1). However, it should be noted that these trend classifications may not be current, given that some are outdated (see Table S1 for specific details). Of the 20% of stocks with trend analysis, pinnipeds had the most ($n = 24$ stocks), followed by toothed whales ($n = 15$) and baleen whales ($n = 10$).

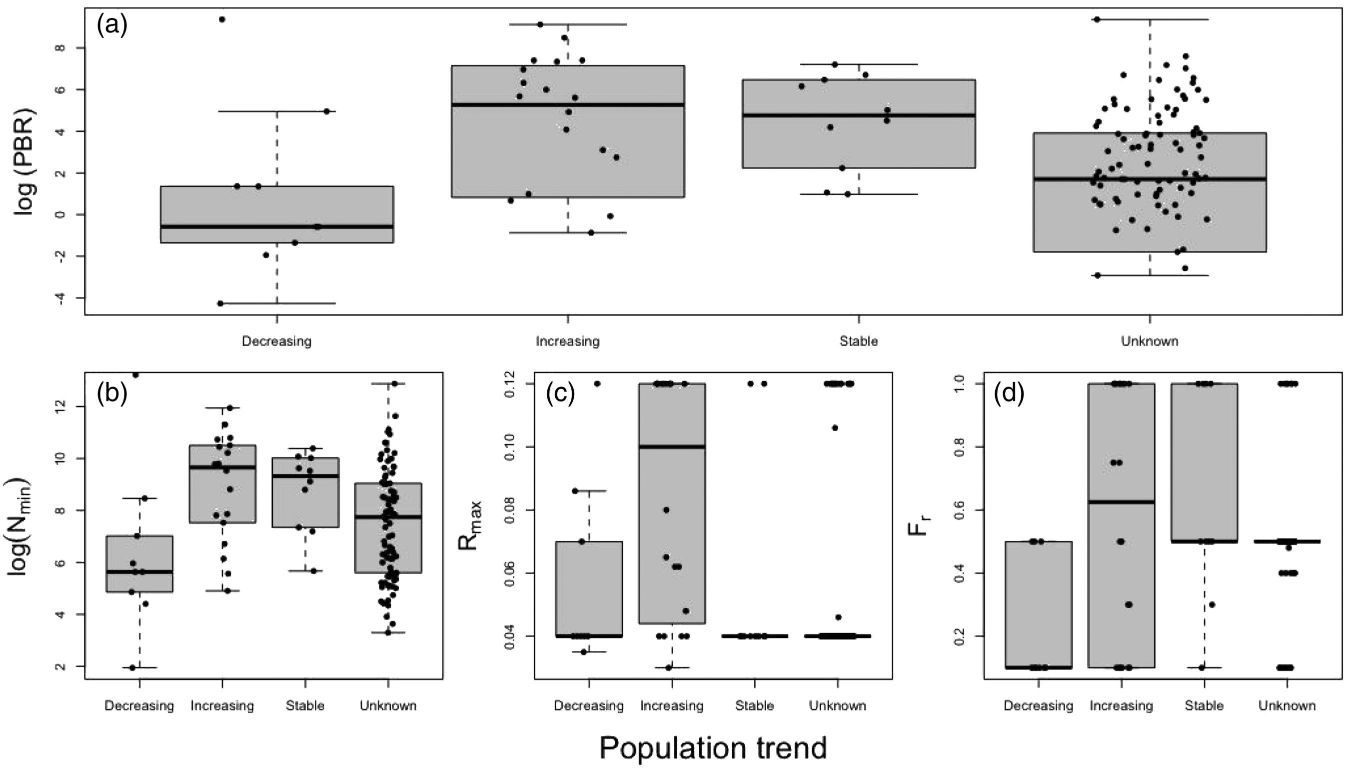

FIGURE 1 (a) log(PBR) versus the population trend for each stock. (b) Log of the minimum population estimate, log(N_{min}), versus population trend. (c) The maximum net productivity rate, R_{max}, versus population trend. (d) Recovery factor, Fr, versus population trend. Each point denotes an individual stock

1.2 | Relationship between population trends and PBR

For the 49 stocks with available trend information, we found that PBR was generally lower for declining stocks than for increasing and stable stocks for all years considered (Figure 1). This implies stocks experiencing a decline require a lower incidental mortality rate to reach or maintain an optimum sustainable population size compared to increasing or stable stocks. Populations with increasing and unknown trends exhibited broader variation in PBR. It is also useful to examine when discrepancies arise between PBR and trend analysis. For example, the northern fur seal (*Callorhinus ursinus*—Eastern Pacific Stock) exhibited a decreasing trend (from 1980 to 2014) but a comparatively high PBR of 11,295 individuals. This discrepancy between PBR and trend may suggest other nonfisheries sources of mortality for the observed population decline.

We found that PBR and trend analysis patterns were similar to those between N_{min} estimates and trend analysis (Figure 1). R_{max} and Fr were less likely to vary. For both R_{max} and Fr, default values are often used in place of estimates specific to each stock. The default R_{max} values are 0.12 for pinnipeds/sea otter stocks and 0.04 for cetaceans/manatee stocks, derived from either measured or theoretical values (Wade, 1998). Only when stock-specific, reliable values are available are nondefault values utilized. Similarly, the default Fr for stocks of endangered species is 0.1 and 0.5 for depleted and threatened stocks or unknown status stocks.

1.3 | Abundance and life history traits as predictors for stocks lacking trend analysis

Life history traits can be significant predictors for the time required to detect a trend in a population (White, 2019). Since most stocks lack trend analysis, we looked for life history correlates of PBR in stocks where these trend metrics have not yet been obtained. For example, we found that PBR was generally higher for species with a low coefficient of variation in abundance (Figure 2). This variation makes some intuitive sense as stocks with minimal intersurvey variation might be the stocks most accessible for surveying or stocks whose status is better understood and are not under threat. Alternatively, stocks with high interannual variation are likely influenced by low reliability in surveys, which means a low PBR would be a precautionary measure (Wade,

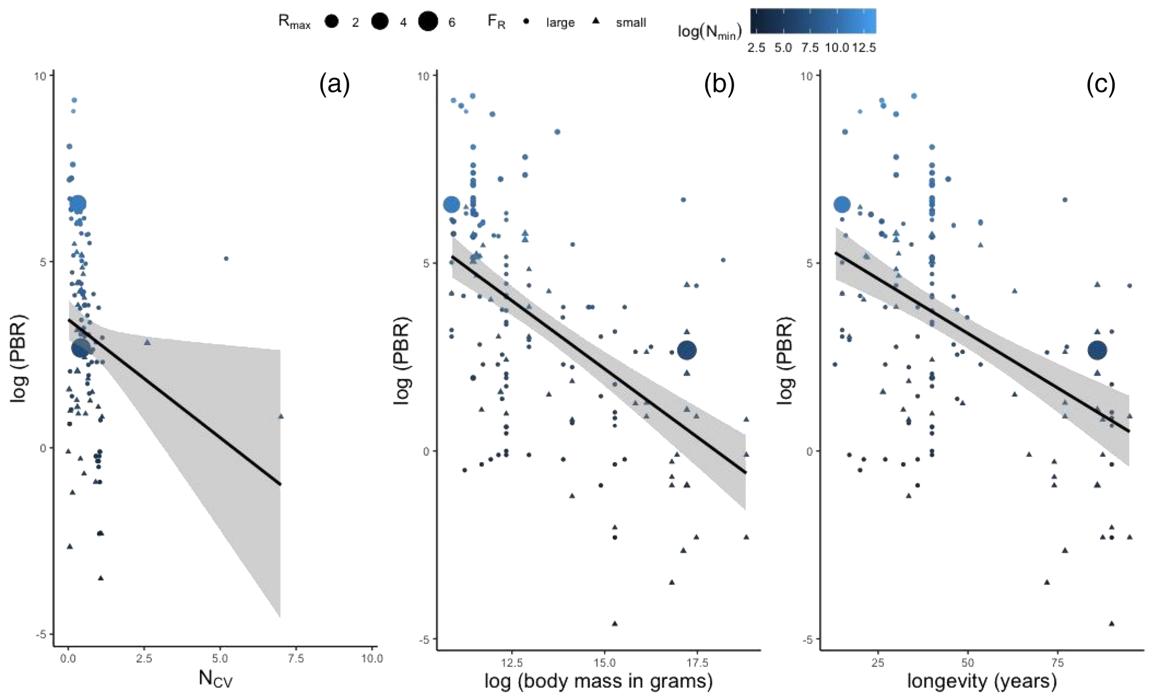

FIGURE 2 log(PBR) versus estimates of stock (a) coefficient of variation, (b) log (adult body size), and (c) longevity. Each point represents a different individual stock. The point size, shape, and color represent R_{max}, Fr (small < 0.5, large > =0.5), and log(N_{min}), respectively. The line on each plot represents the line of best fit from linear regression. The slope coefficients were all significantly different from zero (p values were <.05, <.001, <.001 for plots (a–c), respectively)

1998). We also found that species and stocks with long lifespans and larger body sizes tended to have lower PBR values (Figure 2). This is in line with how PBR is calculated since these life history factors would influence the components of the PBR calculation. We found that most of these correlations were caused by variation in the N_{min} value as R_{max} and Fr were less likely to vary strongly with these life history parameters. However, the recovery factor, Fr, tended to be larger for smaller body-sized stocks and those that live shorter lives. Smaller recovery factors are used for higher-risk stocks. For example, many large whale stocks (blue, fin, sperm whales) had the lowest possible Fr values of 0.1, suggesting a potential relationship between body size/life span and protective status/extinction risk. The interactions between PBR, life history, and trends warrant further investigation.

1.4 | Resampling and trend detection

Here, we use complete resampling of previously collected abundance data on the same three stocks to learn about the requirements for detecting trends. Unlike simulation modeling, this concept leverages existing information by relying on previously collected, long-term monitoring data for marine mammal stocks. Starting with a complete time series (left panels of Figure 3), we subsampled the time series for each possible length. In other words, for a 20-year annually surveyed time series, we obtain two 19-year samples, three 18-year samples, all the way to 19 two-year samples. For each subsample set, the fraction of subsamples that show the same trend (from simple linear regression) as the overall time series is the statistical power (White, 2019; White & Bahlai, 2021). We used this resampling of monitoring data to understand the minimal statistical requirements needed to determine the presence or absence of a trend over time (Bahlai et al., 2021; White & Bahlai, 2021).

As a case study, we used this sampling approach on three high quality (i.e., low sampling error and many years of sampling) stocks, killer whale (*Orcinus orca*—Northern Resident Stock), beluga (*Delphinapterus leucas*—Cook Inlet Stock), and humpback whale (*Megaptera novaeangliae*—CA/OR/WA stock). Then, 9–11 years of contiguous monitoring in all three stocks achieved a high statistical power level (Figure 3). For example, for the killer whale Northern Resident Stock, 11 years of monitoring were necessary to ensure 80% statistical power if sampling occurred every year (Figure 3, first row, middle column). This minimum monitoring timeframe is in line with other long-lived vertebrate species and depends on the strength of the trend, temporal autocorrelation, and population variability, which may be natural or due to sampling error (White, 2019).

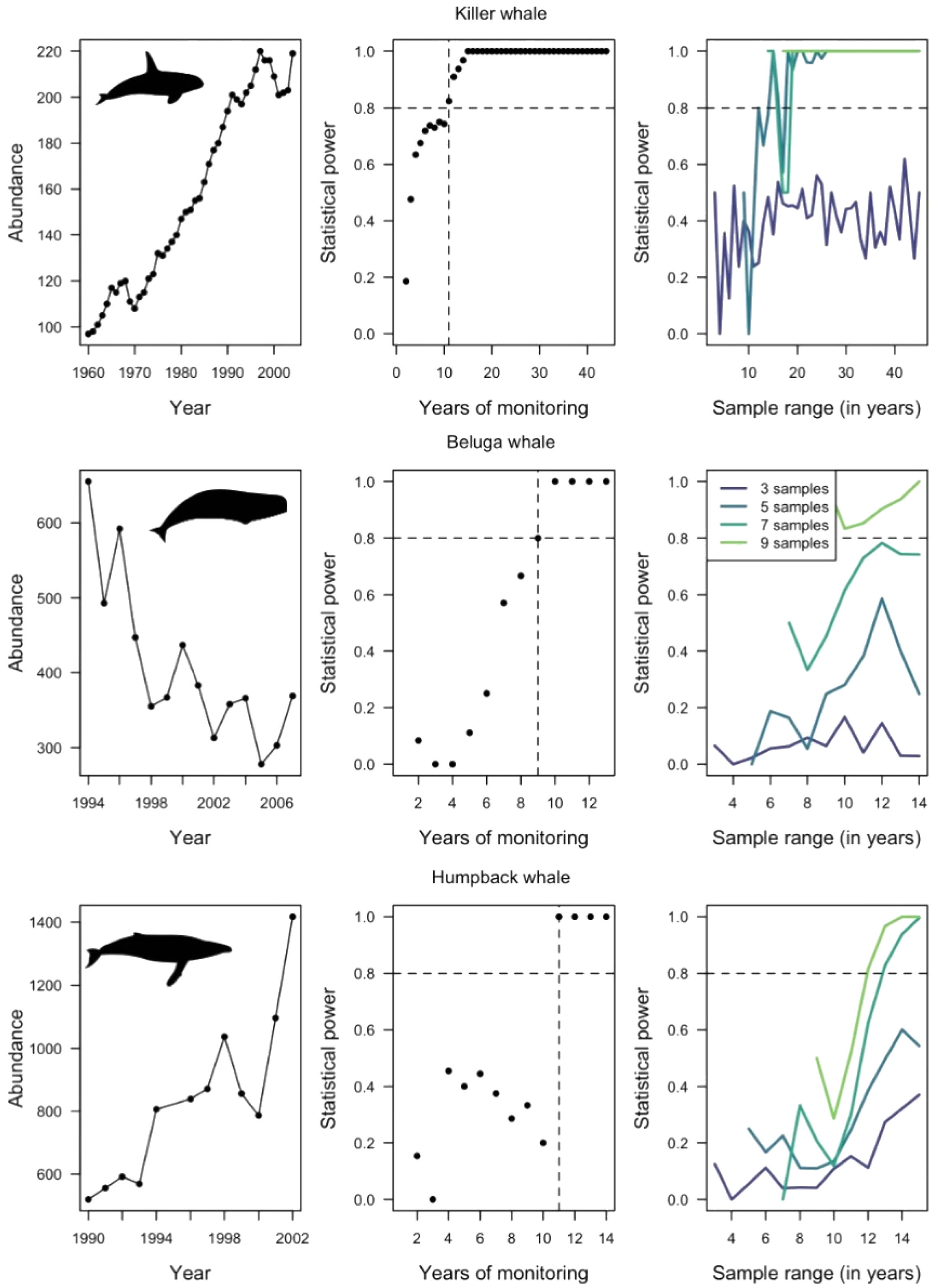

FIGURE 3 (Left column) Estimated relative abundance for three well-studied species: Killer whale (*Orcinus orca*—Northern Resident Stock), beluga whale (*Delphinapterus leucas*—Cook inlet stock), and humpback whale (*Megaptera novaeangliae*—CA/OR/WA stock); (middle column) statistical power (fraction of subsamples with significant trends from linear regression) for different lengths of sampling; (right column) statistical power as a function of the length of the time series and number of samples

Currently, the recommended minimum sampling necessary to detect population-level trends is three abundance estimates over at least 10 years (IUCN, 2019; Magera et al., 2013; NMFS, 2017). To test this, we extended previous work (Taylor et al., 2007; Wauchope et al., 2019; White, 2019) to examine not only the number of continuous samples required but also the number of sampling events needed over different time frames. We applied the same techniques as above but without the need for continuous sampling. A novel outcome of our analysis is that we found three sampling events were seldom sufficient even for our three highly studied stocks, regardless of the time range (Figure 3, third column). Instead, five or nine samples over more than 10 years were needed for 0.8 statistical power, depending on the species (Figure 3). As before, the specific sampling requirements depend on a host of factors such as trend strength, coefficient of variation in population, and autocorrelation.

2 | CONCLUSIONS

Gathering sufficient time series abundance data for marine mammal populations is logistically challenging and resource-intensive (Authier et al., 2017). We found that 80% of the 244 marine mammal stocks with SARs in the US lack assessment for trends in population abundance, but for those with trend information, 88% were increasing or stable. In addition, PBR was generally lower for stocks with decreasing trends (Figure 1). PBR was negatively correlated with body size, interannual variation in population abundance, and longevity (Figure 2), suggesting abundance and life history traits can be used when other information is not available.

As an alternative to simulation approaches, we show that stocks with high-quality data sets can be used to estimate the sampling requirements of less well-studied stocks. For our limited set of case studies, 10 or more years of monitoring was required to detect population trends (Figure 3), but this will differ based on the stock-specific differences in life history traits and sampling practices (White, 2019). However, our results suggest that the current recommendation of only three estimates over at least 10 years (NMFS, 2017) is insufficient. Instead, we found that seven or more sampling events were needed over 10 or more years, even for well-studied stocks such as the killer whale Northern Resident Stock, beluga whale Cook Inlet Stock, and humpback whale CA/OR/WA Stock (Figure 3). Most US stocks have been monitored for over 10 years, and thus, our results suggest the limiting factor for trend analysis in US marine mammal stocks is the necessary number of abundance estimates. Any of these simple rules-of-thumb will vary depending on the specifics of the population since the ability to detect a trend varies with the strength of the trend, temporal autocorrelation, and population variability (natural or due to sampling error). But, since we have some information on predicted growth rates (R_{max}) and sampling error for most stocks, our subsampling technique can be used to determine how many years of monitoring are necessary even for stocks without detailed surveys. We believe this type of subsampling can and should be expanded to more species and stocks of marine mammals. In addition to simple linear trends, these resampling approaches can be used to identify other population patterns, including cyclic dynamics and abrupt shifts (Bruel & White, 2021; White & Bahlai, 2021).

Trend analysis is a powerful tool for tracking population dynamics, conservation status, and the effectiveness of management and conservation actions (Magurran et al., 2010; Peters, 2010; White, 2019). Recent work has shown that PBR is a robust framework for reducing bycatch (Punt et al., 2020), the primary driver of marine mammal mortality worldwide (Lewison et al., 2014). However, because the calculation of the PBR does not include nondirect anthropogenic sources of mortality, the PBR framework alongside trend analysis offers a comprehensive approach toward marine mammal conservation and management. Integrating both has the potential to aid conservation and management efforts by revealing nondirect mortality sources contribute to population declines. We believe the interplay between population trends and PBR merits further investigation and can shed light on marine mammal conservation efforts. Finally, our proposed resampling method reveals information on the statistical power required to detect trends, with the goal of performing trend analysis more often.

CONFLICT OF INTEREST

The authors certify that they have no affiliations with or involvement in any organization or entity with any financial interest.

AUTHOR CONTRIBUTIONS

Easton R. White: Conceptualization, data curation, investigation, methodology, project administration,, analysis writing-original draft, writing-review, and editing. Zachary Schakner: Conceptualization, formal analysis, writing-original draft, writing- review, and editing. Amber Bellamy: Data curation, investigation, methodology. Mridula Srinivasan: Writing, review, and editing.

DATA AVAILABILITY STATEMENT

The data supporting the conclusions of this article will be made available by the authors, without undue reservation.

ETHICS STATEMENT

The authors confirm this material is the authors' own original work, which has not been previously published elsewhere. The paper reflects the authors' own research and analysis in a truthful and complete manner. The paper properly credits the meaningful contributions of coauthors and coresearchers. The results are appropriately placed in the context of prior and existing research.

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SUPPORTING INFORMATION

Additional supporting information may be found in the online version of the article at the publisher's website.

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