Received: 28 November 2017 | Revised: 29 April 2018 | Accepted: 22 May 2018

DOI: 10.1111/conl.12572

LETTER

WILEY Conservation Letters
A journal of the Society for Conservation Biology
Open Access

Management strategies to minimize the dredging impacts of coastal development on fish and fisheries

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Abstract

Accelerating coastal development and shipping activities dictate that dredging operations will intensify, increasing potential impacts to fishes. Coastal fishes have high economic, ecological, and conservation significance and there is a need for evidence-based, quantitative guidelines on how to mitigate the impacts of dredging activities. We assess the potential risk from dredging to coastal fish and fisheries on a global scale. We then develop quantitative guidelines for two management strategies: threshold reference values and seasonal restrictions. Globally, threatened species and nearshore fisheries occur within close proximity to ports. We find that maintaining suspended sediment concentrations below 44 mg/L (15–121 bootstrapped CI) and for less than 24 hours would protect 95% of fishes from dredging-induced mortality. Implementation of seasonal restrictions during peak periods of reproduction and recruitment could further protect species from dredging impacts. This study details the first evidence-based defensible approach to minimize impacts to coastal fishes from dredging activities.

KEYWORDS
coastal development, coastal fish, dredging, fisheries, integrated coastal zone management, marine conservation, ports, seasonal restrictions, suspended sediment, threshold reference values

1 | INTRODUCTION

Coastal development is rapidly expanding worldwide. Coastlines have been extensively modified, with alterations ranging from port development and seabed mining to beach nourishment and land reclamation (Dafforn, Mayer-Pinto, Morris, & Waltham, 2015). This trend will continue as population growth continues in coastal zones (Neumann, Vafeidis, Zimmermann, & Nicholls, 2015). Accompanying this expansion is an increase in waterborne trade. Currently, over 80% of traded goods travel by ship (Tsolaki & Diamadopoulos, 2010). As world trade grows, the number of ships are expected to increase threefold by 2060 (UNTCAD, 2011). Increasing coastal development and expansion of port facilities to accommodate higher shipping rates and new generations of large capacity vessels will require extensive dredging services in coastal areas (Yap & Lam, 2013).

Coastal ecosystems are among the most ecologically and economically important ecosystems worldwide (Barbier et al., 2011). Accelerating coastal development has contributed to widespread reductions in coastal fishes and their viability as fisheries (Barbier et al., 2011; Crain, Halpern, Beck, & Kappel, 2009). While overfishing and degradation of critical fish habitat are important drivers of declines in coastal fish communities (Barbier et al., 2011), there is a growing body of literature demonstrating that dredging can directly impact fishes, and their associated habitat (Erftemeijer & Lewis, 2006; Jones, Bessell-Browne, Fisher, Klonowski, & Slivkoff, 2016; Kjelland, Woodley, Swannack, & Smith, 2015; Wenger et al., 2017). Dredging operations have been linked to shifts in the species composition of fish communities (De Jonge, Essink, & Boddeke, 1993), loss of species (Appleby & Scarratt, 1989), bioaccumulation of contaminants and deformities (Thibodeaux & Duckworth, 2001), increased rates of disease (Landos, 2012), and decreases in fish catch per unit effort at sediment disposal sites (Hatin, Lachance, & Fournier, 2007).

Achieving a balance between preservation of coastal fish populations and coastal development is a global challenge that must be addressed through evidence-based decision-making. This must include an appropriate risk assessment of the vulnerability of fish and fisheries to dredging activities and the likely potential impacts to fish populations (Fletcher, 2014). Yet guidelines for minimizing impacts on fish communities while still enabling dredging to occur have been difficult to develop (Transportation Research Board, 2002). When knowledge gaps exist, management decision-making often relies on experience-based judgment rather than evidence-based knowledge, which can undermine effective natural resource management (Cook, Hockings, & Carter, 2010).

Two main evidence-based management practices could be used for regulating dredging impacts on fish. First, threshold reference values, the level at which a particular stressor is considered detrimental to marine life, are used to derive reference levels which, when exceeded, will trigger a management response, such as halting or restricting dredging (Foster et al., 2010). However, uncertainties surrounding the multitude of tolerance thresholds to dredging-related stressors displayed by different species and life history stages (Wilber & Clarke, 2001) has limited the development of threshold reference values for fishes. Second, seasonal restrictions involve reducing or halting dredging activities during times of the year when the risk of dredging-related impacts is perceived to be high (Suedel, Kim, Clarke, & Linkov, 2008). The use of seasonal restrictions has been encouraged during sensitive life history events, such as spawning, flowering, or migration (Commonwealth of Australia, 2009; Erftemeijer et al., 2013). Seasonal restrictions remain controversial because they are perceived not to be based on robust scientific evidence and are inconsistently applied (Dickerson, Reine, & Clarke, 1998; Suedel et al., 2008; U.S. Army Corps of Engineers 2015). Thus, despite widespread endorsement of these management tools within a dredging management framework (Commonwealth of Australia, 2009; Foster et al., 2010; Transportation Research Board, 2002; U.S. Army Corps of Engineers, 2015), there are no global, scientifically robust standards for how to protect coastal fish communities from direct dredging impacts. This results in a disconnect between management guidelines, which state that such standards should exist but provide no clear and consistent way to develop and apply them (British Marine Aggregate Producers Association, 2017; Commonwealth of Australia, 2009; Environment Protection Authority, 2001; Tomlinson et al., 2007; U.S. Army Corps of Engineers, 2015), and actual management of dredging activities to protect fish.

The aims of the present study were to (a) assess the potential vulnerability of coastal fish and fisheries to dredging activities on a global scale, (b) develop globally applicable threshold reference values for suspended sediment, and (c) examine if an ecosystem-based fisheries management approach could be incorporated into the development of seasonal restrictions to protect coastal fish communities from dredging-related stressors. Threshold reference values could only be developed for the effects of suspended sediment on fishes due to limited comparable studies available in the literature for other dredging-related pressures, including sound, contaminated sediment, or hydraulic entrainment (Wenger et al., 2017). Thus, precautionary protection in the form of seasonal restrictions could protect a wide range of coastal fishes during vulnerable life history stages from all potential dredging-related stressors.

We use data from a comprehensive meta-analysis on the direct impacts of all potential dredging-related stressors on fish, including suspended sediment, contaminated sediment, noise, and hydraulic entrainment (Wenger et al., 2017). We use species landed by west coast Western Australian fisheries as a case study for the development of seasonal restrictions. There are extensive dredging activities in this region associated with several large-scale marine infrastructure developments in the region (EPA, 2013).

2 | METHODS

2.1 | Assessing the global risk to fishes and fisheries from dredging

We sourced port locations, in the form of point data, from a spatial layer of all existing ports, freely available from Google data (https://goo.gl/Yu8xxt). We excluded all inland ports and any duplicates, resulting in 2,646 coastal ports (Table S1). We used location of ports as a proxy for dredging, based on the prevalence of dredging activities at port facilities (Yap & Lam, 2013).

To assess the potential vulnerability of fish to dredging activities, we calculated the number of ports that exist within the geographic range of threatened fish species, using data from Jenkins and Van Houtan (2016a) and Jenkins and Van Houtan (2016b). More information on the derivation of the IUCN-listed threatened species richness map is in the Supplementary Material. We then calculated the frequency with which ports occurred within the geographic range of threatened species using the “Extract Multi Values to Points” spatial analyst tool in ArcMap (v.10.4).

To assess the potential vulnerability of fisheries to dredging activities, we used fisheries data (2010–2014) from a database of global marine commercial and small-scale fisheries (Watson, 2017). The data in the database was sourced from a range of public sources, collated and mapped to 30-minute spatial cells based on the distribution of reported taxa and fishing fleets involved (Watson, 2017). We subset the data to quantify the commercial and small-scale fisheries catch (vertebrate fishes, in tons) within 5 km of a port as this distance reflected the maximum likely spatial extent of dredging impacts, acknowledging that the spatial extent of any dredging operation will be dependent on local conditions, including dredge type, material disposal, and local currents (Table S2). We used the coordinates provided for each fisheries area, which represent the centroid, to determine distance from port. We also examined the prevalence of fisheries catches within 5 km of ports for species known to be sensitive to suspended sediment (see next section and Table S3).

2.2 | Calculating threshold reference values

From previously collated information (Wenger et al., 2017), we extracted the lowest suspended sediment concentration that elicited initial response in a species from 57 papers, resulting in 131 unique records for further analysis (Supplementary Material; Table S4). We ranked the response elicited in each study from one to four, as described in the Supplementary Material (Tables 1, S4).

We then derived threshold reference values for the four different response types, using a logistic cumulative probability distribution of species sensitivity, using the R programming language (R Development Core Team, 2014). The distribution curves fit empirical data to a cumulative probability distribution across taxonomic groups to allow the derivation of concentrations that will protect particular proportions of fish species. We report suspended sediment concentrations to protect 25%, 50%, 80%, 90%, 95%, and 99% of fish species against each response type. Confidence intervals (95%) were estimated using bootstrapping procedures ($n = 1,000$). Because some studies used the same suspended sediment concentration, we tested the sensitivity of threshold reference values to repeated concentrations (Table S5).

2.3 | Predicting likely responses at different exposure durations and suspended sediment concentrations

Since both the magnitude and duration of exposure to dredging-related stressors are important (Newcombe & Jensen, 1996; Wenger et al., 2017; Wilber & Clarke, 2001), we developed a model to predict the likely response type (1 through 4) that would occur in larvae, juveniles, and adult fish, given the concentration and exposure duration. We used Random Forest classification techniques with the randomForest package in R (Liaw & Wiener, 2002). For more detail on the Random Forest analysis, see Supplementary Material. We set potential sediment concentrations to between 1 and 200 mg/L and exposure durations to between 1 and 96 hours, based on values previously recorded during dredging operations (Table S2). We used our trained random forest model to predict the likely response type given the generated combinations of suspended sediment concentrations and exposure durations. To visualize patterns in the data, we binned suspended sediment concentrations and exposure durations into groups with a range of 20 mg/L for suspended sediment concentrations and 6 hours for exposure duration. The predicted response within each bin was averaged and a heat map was generated of the predicted elicited response in each of the

TABLE 1 The suspended sediment concentrations to protect 25%, 50%, 80%, 90%, 95%, and 99% of fish species against each response type

Proportion of species protected	Response types: 1 (avoidance)	2 (minor physical damage; moderate behavioral impacts)	3 (physiological impacts)	4 (mortality/reduced hatching success)
99	2 (0.4–8)	4 (1–12)	7 (2–21)	9 (2–28)
95	5 (1–18)	14 (5–32)	23 (9–54)	44 (15–121)
90	8 (2–24)	26 (12–58)	44 (20–96)	102 (43–232)
80	15 (6–38)	58 (29–115)	91 (45–179)	274 (125–583)
50	47 (19–111)	270 (154–491)	389 (216–680)	1,814 (965–3,584)
25	123 (48–310)	896 (449–1,711)	1,209 (624–2,290)	8,065 (3,951–16,841)

Note: The average suspended sediment concentration (mg/L) is listed with the bootstrapped upper and lower confidence intervals in parentheses.

different life history stages across the range of suspended sediment concentrations and exposure durations.

2.4 | Seasonal restrictions

The results of a meta-analysis revealed that across all dredging related stressors, eggs and larvae were most likely to experience sublethal and lethal impacts, indicating the potential for seasonal restrictions during peak spawning and recruitment periods (Wenger et al., 2017). Therefore, to determine whether ecosystem-based fisheries management could be put in place that could more effectively protect a suite of species from impacts associated with dredging during vulnerable life-history stages, we undertook a review of spawning and recruitment times of Western Australian coastal fish to identify if there were times of year most suitable for seasonal restrictions (see Supplementary Material).

3 | RESULTS

3.1 | Assessing the global vulnerability of fishes and fisheries to dredging activity

Over 2,000 ports worldwide were within the range of at least one threatened species, while 97 ports were located within the range of five or more threatened species (Figure 1). There were multiple hotspots where particular ports occurred within the geographic ranges of multiple threatened species (Figure 1). For instance, the ports of La Paz and Keelung in Mexico and Taiwan, respectively, and the majority of ports in South Africa occurred within the ranges of at least seven threatened species. The Port of East London, South Africa was located within the ranges of 12 threatened species; the top port globally in terms of the number of threatened species potentially at risk from dredging activities there.

Between 2010 and 2014, 40.9 million tons of global commercial fisheries catch and 9.3 million tons of small-scale fisheries catch was extracted within 5 km of a port (Figures 2a, b). Although the quantity of the catch within 5 km of a port is high, the proportional fisheries catch occurring within 5 km of a port compared to the total fisheries catch for each of these countries ranged from 0.001% to 0.65% for commercial fisheries and 0.001% to 0.58% for small-scale fisheries (Figures 2a, b).

Eight species with empirical information on their sensitivity to suspended sediment had fisheries records within 5 km of a port, across 23 countries (Figure 2c). Cumulatively, this amounted to 17.4 and 2.3 million tons of global commercial and small-scale fisheries, accounting for 42.5% and 24.7% of all commercial and small-scale fisheries landings near ports, respectively (Table S3; Figure 2d).

3.2 | Threshold reference values

Threshold reference values derived for each response show that low concentrations of suspended sediment impact fish (Table 1). Threshold reference values to protect fish species from minor behavioral impacts ranged from 2 mg/L (0.4–8 bootstrapped CI) to protect 99% of species to 123 mg/L (48–310) to protect 25% of species (Table 1, Figure 3a). Threshold reference values required to protect 99% of species from either physical damage or lethal impacts were relatively similar, ranging from 4 (1–12) to 9 (2–28) mg/L, respectively. In contrast, threshold values necessary to protect 25% of species from physical damage was 896 mg/L (449–1,711), while a threshold value of 8,065 mg/L (3,951–16,841) would protect 25% of species from lethal impacts (Table 1; Figures 3b–d).

3.3 | Predicting likely responses at different exposure durations and suspended sediment concentrations

Among all life history stages, there was a clear relationship between suspended sediment concentration and exposure duration (Table S7; Figure 4). For instance, exposure of larvae to concentrations up to 60 mg/L did not have a lethal impact until after 24 hours. The Random Forest model also highlighted the differential vulnerability of different life history stages to suspended sediment exposure. While adults are unlikely to experience lethal impacts in the examined ranges,

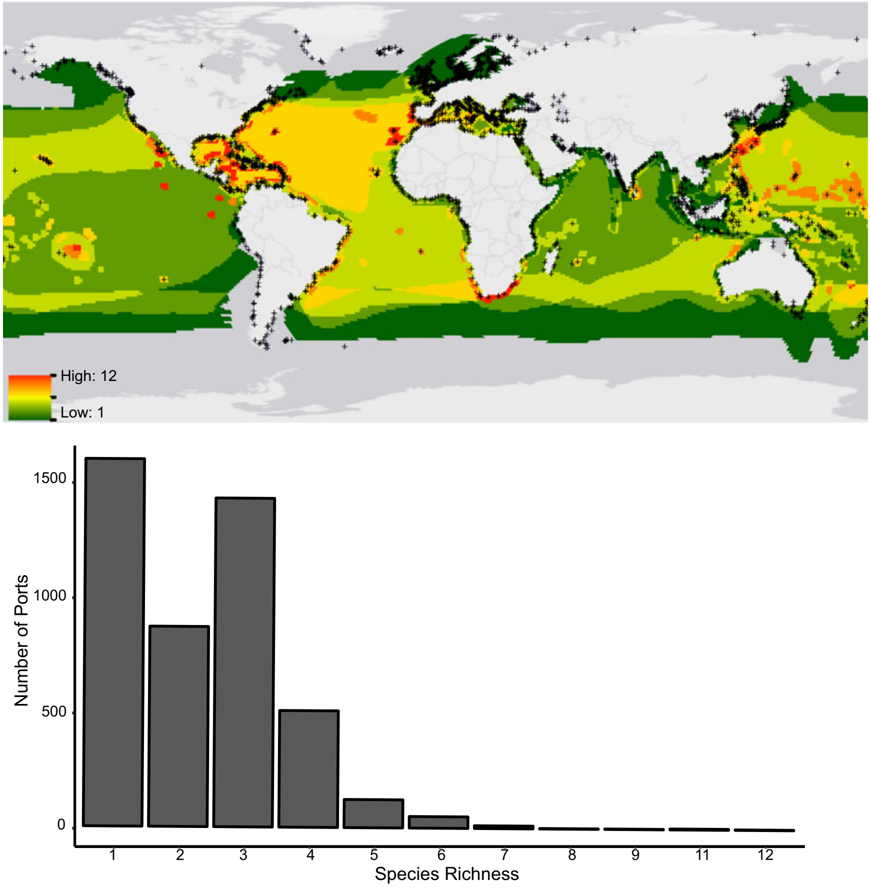

FIGURE 1 The global overlap between coastal ports and threatened marine fishes. The map shows the spatial distribution of threatened species, with the colors denoting the number of threatened species within particular areas. The black crosses indicate the presence of a port. The graph indicates the number of ports that fall within the geographic range of one or more threatened species

larvae and juveniles are much more vulnerable and will experience lethal impacts at concentrations and exposure durations found during dredging activities (Table 1; Figure 4).

3.4 | Seasonal restrictions

Peak spawning occurred during the austral summer, with more than 60% and 75% of temperate and tropical species, respectively, spawning between November and February (Table S8). In contrast, 30% and 20% of temperate and tropical species spawned during the lowest period of spawning activity (July) (Figure 5a). Peak recruitment occurred over 4 months for tropical species (December to March), with more than 75% of species recruiting in March (Figure 5b). Temperate species had high rates of recruitment from December through to April (Figure 5b).

4 | DISCUSSION

The expansion of coastal development indicates the scale and frequency of dredging operations will intensify (Dafforn et al., 2015; Yap & Lam, 2013), increasing the potential for impacts to coastal fishes. In this study, we demonstrate that globally, large numbers of ports are located within the geographic range of many threatened coastal fishes. Furthermore, we identified several countries where fishing for species known to be sensitive to sediment occurs within close proximity to ports, highlighting the need for consideration of potential impacts to fish communities within dredging management plans. The development of quantitative management guidelines has enabled an explicit assessment of the likely impacts on coastal fish communities that could occur across a range of sediment concentrations and exposure durations. Our results show that fish species, especially during early life history stages, are at risk to lethal and sublethal impacts at concentrations and exposure durations regularly occurring during dredging operations.

Larval supply directly influences the recruitment of fishes and thus the regulation of fish populations. Recruitment rates can heavily influence age structure and mortality rates (Fairclough et al., 2014; Newman, Williams, & Russ, 1996; Wakefield et al., 2016) and therefore are crucial to managing fisheries species. Thus, anthropogenic actions and processes that affect recruitment success may have adverse impacts

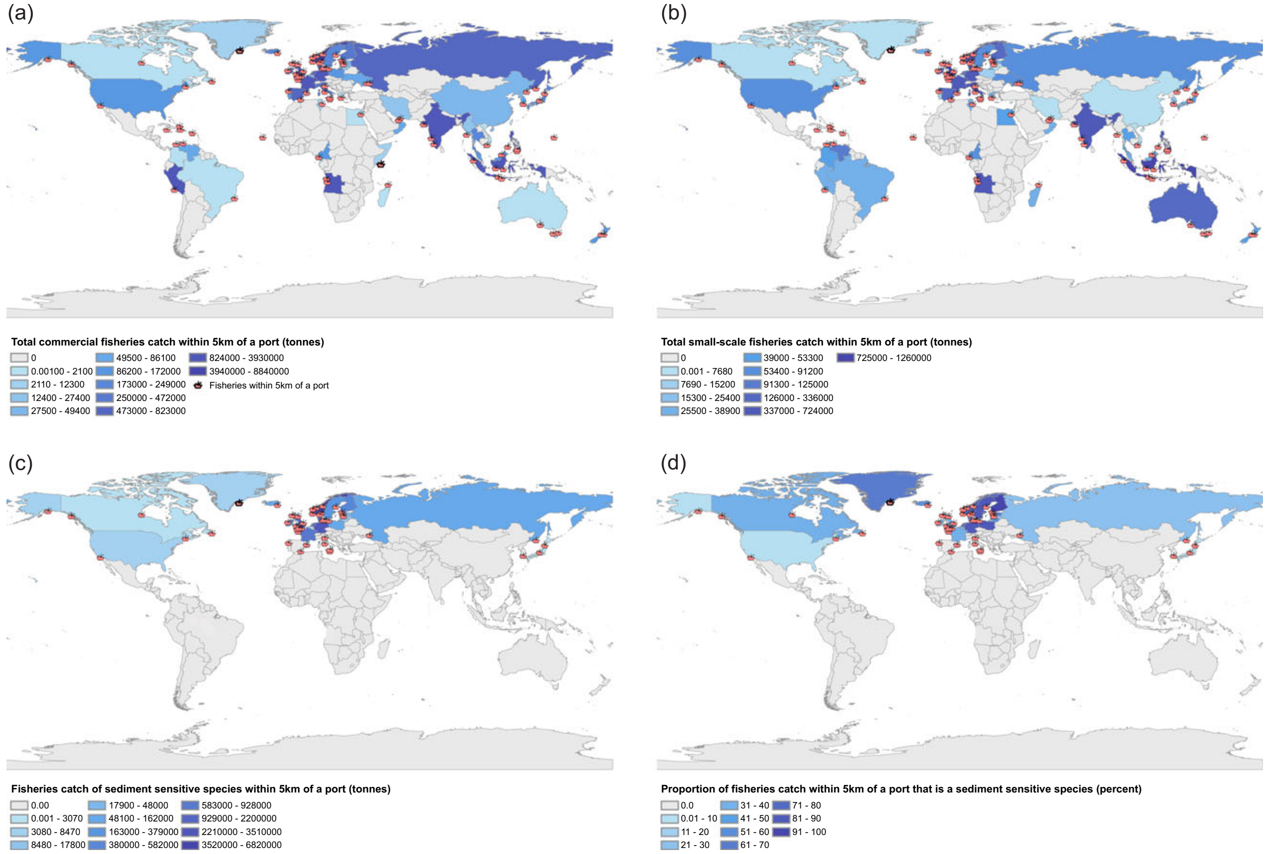

FIGURE 2 The spatial distribution and quantity of fishing activity that occurs within 5 km of a port. (a), (b) The location of commercial and small-scale fishing activities and the quantity of catch in tons for each country where fishing activity occurs within 5 km of a port. (c) The countries where fishing of species known to be sensitive to sediment (see Table S3) occurs within 5 km of a port and the quantity of the catch. (d) The proportion of the fisheries catch of sediment-sensitive species compared to the total fisheries catch that comes from within 5 km of a port for each country

on population persistence. Dredging, if undertaken during the critical window of larval development, has the potential to directly constrain larval supply by contributing to higher mortality rates of fish larvae or lowering recruitment success (Wenger et al., 2017) and references therein. However, the potential impacts to vulnerable life history stages from dredging-related stressors could be reduced through the introduction of threshold reference values that elicit a management response and/or the application of seasonal restrictions to dredging.

The current study has identified a range of thresholds, based on the proportion of species that are likely to be impacted and the types of responses that could occur, rather than identifying one value above which significant impacts occur (Groffman et al., 2006). The results reflect the variation in the response of fishes to suspended sediment and allow for an explicit examination of the potential risks to fishes during dredging operations. For instance, the most conservative threshold value, 2 mg/L to protect 99% of species from avoidance behavior, is unrealistic given natural wind and wave driven fluctuations in turbidity in nearshore environments (Wenger, Whinney, Taylor, & Kroon, 2016). Similarly, prevention of mortality in only a low proportion of the fish assemblage occurs at extraordinarily high concentrations, which are unlikely to be reached during dredging operations. However, suspended sediment concentrations generated during many dredging operations (Table S2) are likely to cause lethal and sublethal impacts in 10–20% of fish species respectively, which could be minimized through management. Decisions on acceptable levels of species protection also need to consider the composition of fish assemblages, including functionally, culturally, or commercially important species, and threatened species, which our risk assessment helped identify.

The development of threshold reference values and random forest models could not account for all variations in data types. These limitations are a product of data availability, emphasizing the need for further studies across a broader array of species, life history stages, and potential endpoints. However, by combining the two approaches, the information developed here provides the first evidence-based defensible guidelines of likely impacts and the proportion of species that potentially affected across a range of suspended sediment concentrations and exposure durations. Ultimately, the risk of detrimental impacts will depend on local physical and

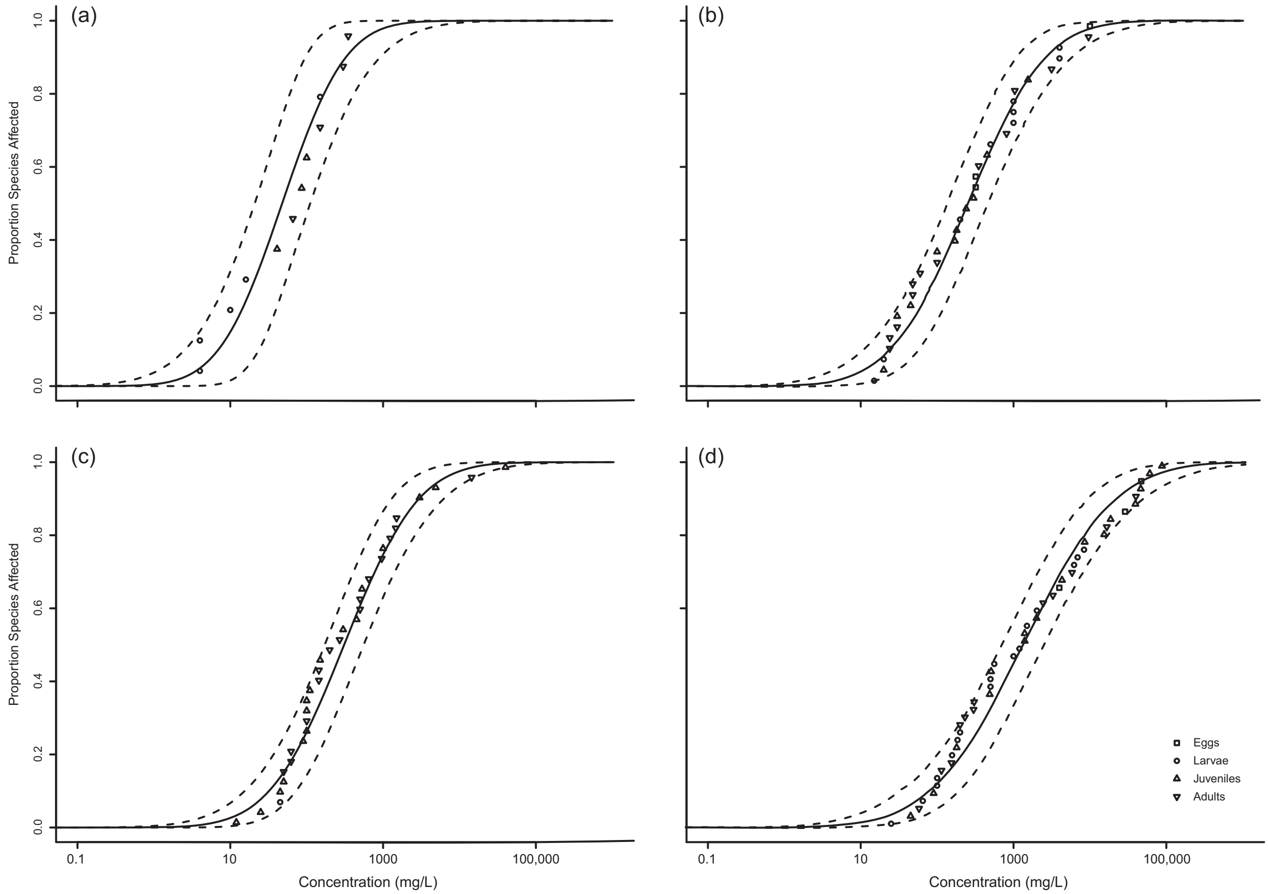

FIGURE 3 Cumulative probability distribution for suspended sediment concentrations (mg/L) that result in the following response type: (a) avoidance, (b) minor physical damage; moderate behavioral impacts, (c) physiological impacts, and (d) mortality/reduced hatching success. Dashed lines represent bootstrapped 95% confidence intervals

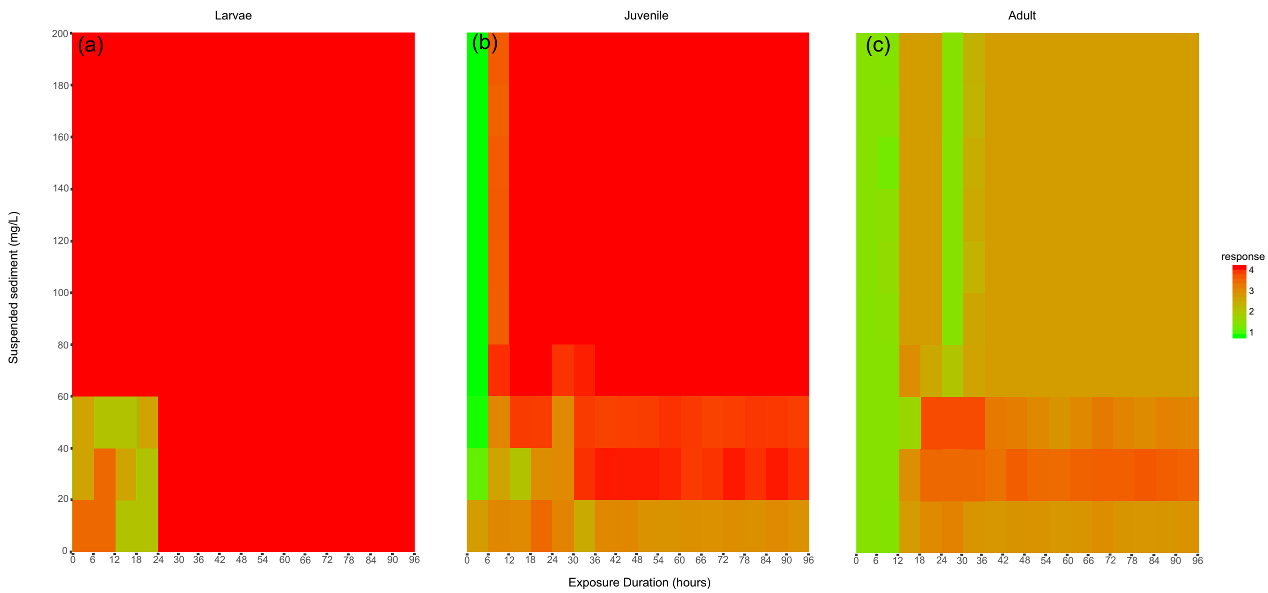

FIGURE 4 A heat map showing the likely response type elicited in (a) larvae, (b) juveniles, and (c) adults due to varying suspended sediment concentrations and exposure durations, as predicted by a trained random forest model generated in R

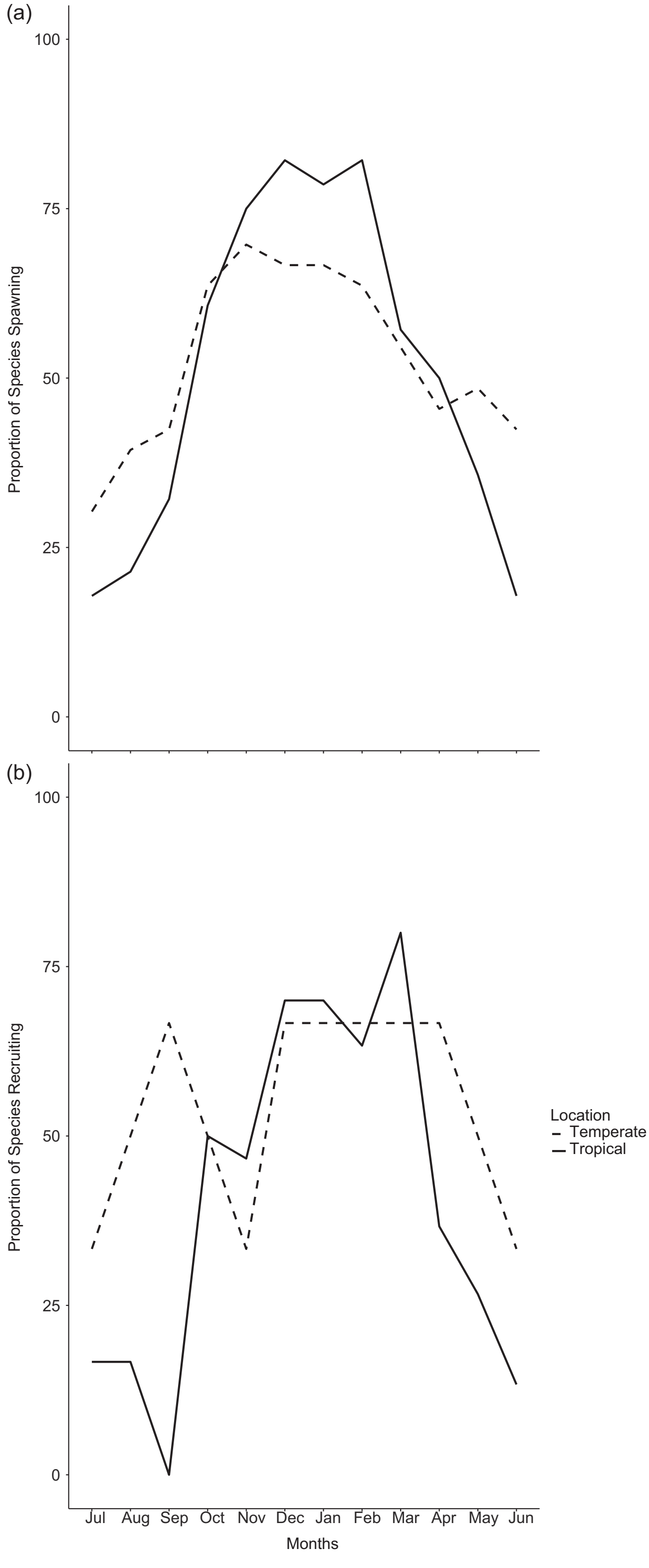

FIGURE 5 Known (a) spawning and (b) recruitment times for West Australian fish species. Gray line represents temperate species and black line represents tropical species

environmental conditions and on the tolerance thresholds to the various stressors for species of concern (Bridges, Ells, & Hayes, 2008; Browne, Tay, & Todd, 2015). However, these guidelines should be used as a legitimate evidence-based guide until region-specific reference values are developed. They can be used as a starting point in an adaptive management framework, wherein responses of fishes to dredging are monitored and threshold reference values are raised or lowered, depending on whether anticipated responses are observed (CEDA, 2015). Moreover, wherever possible, dredging projects should implement a systematic monitoring program that enables a thorough evaluation of the effectiveness of different management strategies at mitigating impacts to fish and fisheries.

When mitigation of potential risks to fishes from dredging through implementation of threshold reference values or other management approaches is not feasible, conservative protection in the form of seasonal restrictions during peak spawning and recruitment for a range of coastal fishes should be considered. This approach is in line with ecosystem-based fisheries management, which advocates for the need to manage fisheries beyond single-species models toward long-term sustainability of stocks and ecosystems (Pikitch et al., 2004). Basing decision-making regarding seasonal restrictions on robust scientific information to identify times of year where management could be most effective should help reduce the criticisms of how seasonal restrictions are currently set (Suedel et al., 2008; U.S. Army Corps of Engineers, 2015). Further, this approach also targets another perceived weakness of seasonal restrictions, which is that they are overly focused on mitigating the risks of dredging to species at the individual level and have not adequately considered population and ecosystem-level impacts (Transportation Research Board, 2002). Although an ecosystem-based fisheries management approach requires extensive life history data across a range of species, this information could be gathered during the environmental impact assessment phase of a project, which has been called for previously (Tomlinson et al., 2007). Where there are constraints to gathering such data, resources should focus on obtaining spawning and recruitment data for species of high ecological, conservation, and economic importance.

While previous research on dredging impacts focused primarily on habitat-forming biota (Erftemeijer & Lewis, 2006; Jones et al., 2016), future research should also explicitly examine the direct impacts on fish communities, given their economic, ecological, and conservation importance (Barbier et al., 2011). Although general guidelines can never account for local conditions or dynamics, in the absence of any quantitative guidelines, dredging management decisions regarding fish communities will continue to be subjective, at best (Transportation Research Board 2002; U.S. Army Corps of Engineers, 2015), or not considered at all (Foster et al., 2010). Moreover, the use of robust and transparent evidence-based information as the basis for management interventions or regulations can reduce controversy and lead to better compliance and actually reduce the overall cost of dredging. This is due to having seasonal restrictions more appropriately set to times of year when risks are actually high and having threshold reference values for multiple endpoints, which can allow dredging activities to be modified or reduced, rather than halted (CEDA, 2015; Dickerson et al., 1998; U.S. Army Corps of Engineers, 2015). Furthermore, greater consideration of the impacts to fisheries and consultation with stakeholders throughout the planning process can reduce conflicts with stakeholders involved in commercial and recreational fishing, which could enable greater support for dredging projects (British Marine Aggregate Producers Association, 2017; Tomlinson et al., 2007). While decisions about specific dredging project management practices generally involve compromises between environmental protection and necessary dredging activities, this study details an evidence-based, defensible approach that enables natural resource managers and dredging operators to effectively include protection of coastal fishes into dredging management plans.

ACKNOWLEDGMENTS

This project was funded by the Western Australian Marine Science Institution as part of the WAMSI Dredging Science Node, made possible through investment from environmental offsets and coinvestment from WAMSI Joint Venture partners. Commercial investors and data providers had no role in data analysis, data interpretation, manuscript preparation, or decision to publish. We acknowledge Gabby Mitsopoulos and Sam Moyle from the Western Australian Department of Primary Industries and Regional Development for assistance in compiling the information presented in Supplementary Material.

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SUPPORTING INFORMATION

Additional supporting information may be found online in the Supporting Information section at the end of the article.

How to cite this article: Wenger AS, Rawson CA, Wilson S, et al. Management strategies to minimize the dredging impacts of coastal development on fish and fisheries. *Conservation Letters*. 2018;11:e12572. https://doi.org/10.1111/conl.12572