THE SKIMMER
ON MARINE ECOSYSTEMS AND MANAGEMENT

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It’s not just about marine mammals anymore: How ocean noise can harm marine ecosystems [1]

Editor’s note: We’ve all read about how ocean noise can harm marine mammals [2]. New research reveals that it can have profound impacts on lower trophic levels as well, with likely consequences for marine ecosystems. Catch up on the latest research with this month’s Skimmer.

A little background on sound in the ocean [3]

- As we get started discussing how ocean noise affects marine animals (and marine ecosystems), there are some critical points about sound in the ocean to keep in mind:
    - Sound is a “compression wave that causes particles of matter to vibrate as it transfers from one to the next [4].” How loud or soft a sound is perceived to be is a function of the amplitude or intensity of the wave[1] and the receiver’s hearing [4]. Sound waves with higher amplitudes/intensities are perceived to be “louder” than sound waves with lower amplitudes/intensities.
    - Sound travels a lot faster and farther in seawater than through the air. Sound travels nearly five times faster in seawater than on land (1500 vs 340 m/s [5]) and can travel hundreds to thousands of kilometers [6] in seawater versus tens of kilometers on land. As a rule, lower frequency sounds travel farther than high frequency sounds [4] because lower frequency sound waves lose energy (“dissipate”) more slowly. In addition, higher amplitude/more intense/louder sounds travel farther than lower amplitude/less intense/softer sounds [4] because they have more energy to start with.
    - In the ocean, vision is limited to tens of meters [7] at best, and sense of touch even less than that, while smell and taste are greatly dependent on local environmental conditions such as water currents [8]. Consequently, many marine animals – including invertebrates [8] – use sound as their principal way of sensing the environment [9]. They use sound [10] for finding food, finding mates, locating offspring and other community members, finding appropriate habitat, avoiding predators, navigating, and more.
    - Sound in the ocean has two components: a pressure component that acts in all directions at once [8] and a particle motion component that has directionality [8]. While mammals primarily sense the pressure component of sound, marine fish and invertebrates primarily sense the particle motion component [11] of sound.
    - The “silent oceans” are anything but silent. The oceans have rich natural soundscapes [6] from both abiotic and biotic sources (e.g., rain, waves, earthquakes, animal vocalizations). Sound does not travel well across the ocean-atmosphere boundary [4], however, giving outside observers the false impression of relative silence.
    - “Noise” is simply sound that is unwanted, unpleasant, and/or disruptive [12]. If you think back to that list of things that marine animals use sound for (i.e., finding food, finding mates, locating offspring and other community members, finding appropriate habitat, avoiding predators, navigating, and more), manmade sounds have the potential to disrupt all of them. Given that manmade sound has intensified over a very short period of time in evolutionary terms [4] (50-100 years) and most animals have not had time to adapt to these new sounds [4], it is assumed that most anthropogenic sound [7] in the ocean is indeed “noise” to marine animals.

Where all the ocean noise is coming from

- In recent years, humans have added many sounds that have transformed ocean soundscapes [13]. Anthropogenic sounds now dominate ocean background noise [6] and have increased peak sound intensity levels [6] in the ocean.
- Some of the most important sources of anthropogenic sounds [7] are:
    - **Seismic surveys for oil and gas exploration:** Seismic surveys are one of the most widespread sources of anthropogenic sound in the ocean and produce some of the loudest sounds. In a typical survey, ships tow arrays of 12-48 seismic airgun [14]s that simultaneously shoot intense impulses of air downward under very high pressure, producing very high intensity sounds. This is done to map features below the seabed and identify formations where oil and natural gas deposits might be present. Airgun blasts last ~40 microseconds and are repeated roughly every 10-60 seconds for hours, days, [4] weeks, or even months [13]. Because airgun blasts have significant low frequency components and high intensities, noise from seismic surveys can travel thousands of kilometers. An often-cited study published in 2012 [15] found that sounds from seismic airguns shot off of the coast of Brazil were \

Photo credit: Noel Lopez-Fernandez

[16]heard almost 4000 km away. Seismic surveys occur continually along continental margins worldwide [6]. The 2012 study found that seismic airguns were heard nearly year-round for a decade [15] at their three study sites off of eastern Canada, northeastern Brazil, and western North Africa.

  - **Commercial shipping:** Ships' engines, generators, and bearings [4] all generate sound, but the primary source of noise from ships is cavitation – the collapse of air bubbles created when propeller blades turn [4]. In general, the faster a propeller turns, the more cavitation [4] there is. Cavitation produces significant noise across a broad range of frequencies [6], but the higher-frequency sounds die out relatively close to the ship. Low frequency sounds from commercial vessels are a major component of ambient noise [6] throughout ocean basins, but shipping noise is greatest near shipping lanes and major ports [6].

  - **Military sonar:** With "active" sonar, transmitters create pulses of sound ("pings") while receivers (sometimes co-located) listen for reflections or echoes of those pulses. Militaries use sonar systems of varying frequencies (and thus ranges) for a number of purposes, but one of their primary uses is detecting submarines. The US Navy's low frequency active sonar system (LFA) can be detected and possibly affect marine life in an area of over ~4 million square kilometers [9].

How far does it go?

- It can be helpful to think of sound in the ocean as divided into three bands:
  - The low frequency band (10-500 Hz) is dominated by sounds from commercial shipping and seismic exploration for oil and natural gas [6]. Since low frequency sounds travel much farther [4] than high frequency sounds and can cross ocean basins, low frequency sounds comprise most of the ambient noise in the ocean [6].

  - The medium frequency band (500 Hz-25 kHz) is dominated by natural sounds such as breaking waves and rainfall [6], but sounds from some active sonar systems and smaller vessels also contribute [6] to it. Medium frequency sounds are generally limited to a few tens of kms from the source [6] because they lose energy more quickly.

  - Sounds in the high frequency band (>25 kHz) lose energy quickly (within a few kilometers of the source) [6] and thus impact much smaller areas. Their limited areal extent should not be equated with lack of impact, however, as high frequency sounds can have significant impacts on animals within their range.

- Other important sources of anthropogenic noise in the ocean [8] include:
  - Explosions for military and non-military purposes (e.g., ship shock trials, bomb tests, military drills, decommissioning of offshore structures). These sorts of explosions produce extremely intense/loud sounds [6], but they do not occur frequently.

  - Stationary industrial activities (e.g., construction of offshore oil and gas and wind platforms, other pile driving, drilling for oil and gas). Pile driving produces low frequency sounds of high intensity [6], but there is typically limited long-range propagation [6] because it generally occurs in shallow water. Sounds from oil and gas drilling (by rigs anchored or moored to the ocean floor, semi-submersible drilling vessels, and drillships) are not as intense/loud as seismic surveys but can last for longer periods of time [6].

  - Smaller vessels for fishing recreation, and commercial use. The nature of sounds emitted depends on the size and characteristics of individual vessels, but smaller vessels with inboard and outboard engines generally emit low-to-medium frequency sounds of moderate intensity [6].

  - Sonars for non-military purposes (e.g., locating the seabed, fish, or underwater objects) vary depending on their purpose but generally emit high intensity pulses at relatively high frequencies [6]. Unlike military sonars used for detecting submarines over large areas, commercial and recreational sonar pulses are generally directed downward [6] and affect a smaller area.

  - Operation of offshore wind platforms produces low frequency sounds of moderate intensity [6].

  - Acoustic deterrent and harassment devices ("pingers") use medium-to-high frequency sounds of medium-to-high intensity [6] to keep marine mammals away from fishing gear and aquaculture operations [6].

  Sources: 1 [17], 2 [18], 3 [19], 4 [20], 5 [21]

- Not only is anthropogenic sound in the ocean already pervasive, it is also increasing and spreading to new regions.

  - Oil and gas exploration and drilling have moved into deeper water in recent years. Because sound travels farther in deeper waters because of reduced attenuation, deeper exploration and drilling enable associated sounds to impact even larger areas [6].

  - Sounds from commercial shipping are also increasing. Low frequency, ambient noise in the open ocean has increased ~3.3 dB per decade from 1950-2007 [22], primarily from increases in commercial shipping activity. (*Editor's note: The dB scale is logarithmic, and humans perceive a 10dB increase in sound level as a doubling of sound loudness* [21] *and vice versa.*)

  - As the oceans become more acidic due to climate change, there will be less absorption of sound [6] and ambient noise levels will increase [6]. This increase will largely come from decreased attenuation of medium-to-high frequency sounds because there is already relatively little attenuation of low frequency sounds.

  - Decreases in polar ice are enabling more noise-emitting activities (e.g., shipping, oil and gas exploration, oil and gas drilling) in the Arctic [8]. [23]

Bad things ocean noise does to marine animals

- While research on the impacts of ocean noise on marine fish, reptiles, and invertebrates is still in its early stages, there have been several recent reviews (e.g., here [10], here [8], here [24], and here [25]) of primary studies. (*Editor's note: You can watch a webinar on one of these reviews here* [23] *– it summarizes 115 studies of the impacts of anthropogenic ocean noise on 66 species of marine fish and 36 species of marine invertebrate.)* These reviews found:

  - **Developmental effects** such as increased egg and larval mortality; delayed development; delays in metamorphosis and settling; slower growth rates; and bodily malformations.

  - **Anatomical effects** such as temporary or permanent hearing loss; cellular damage; temporary or permanent internal and external injuries; and even death.

  - **Physiological effects** such as increases in stress hormones; changes to metabolic rates, oxygen consumption, and heart rates; decreased immune response and resistance to disease; reduced energy reserves; and decreased reproductive rates.

  - **Behavioral effects** such as causing animals to avoid important habitat for days or years; alarm responses including hiding and flight; increased activity including moving faster, diving deeper, changing direction more frequently; increased time spent grooming nests; increased aggression; decreased anti-predator defensive behaviors; decreased nest digging and care of young; decreased courtship and spawning; decreased feeding; increases in errors or inefficiency in handling food; and uncoordinated schooling.

  - **Masking effects** (where sounds of interest are obscured by noise) such as reduced ability to use vocal communication; reducing detection distances for potential mates and predators; and reductions in larval settlement cues.

[*Editor's note: The lists above are a compilation of all impacts. Most studies found a limited number of impacts for a single or small number of species.]*

- To give a flavor for what individual studies found:

  - McCauley et al. (2000) [25] observed that caged green and loggerhead turtles exposed to airgun noise increased their swimming speeds when sound intensity levels reached 166 dB and started behaving erratically when sound intensity levels reached 175 dB.

  - Sara et al. (2007) [26] found that boat noise caused bluefin tuna to change direction and swim vertically toward the surface or bottom. It also disrupted school structure and coordination of swimming behavior and increased aggressive behavior. These effects could interfere with the accuracy of bluefin tuna migrations to spawning and feeding grounds.

  - André et al. (2011) [27] found that exposure to relatively brief periods of moderate-intensity (peak levels of 175 dB), low-frequency noise caused "massive acoustic trauma, not compatible with life" in four cephalopod species (the European squid, European common cuttlefish, common octopus, and southern shortfin squid). The noise exposure damaged the sensory hair cells of their statocysts, organs that control their balance and orientation.

  - Aguilar de Soto et al. (2013) [28] found that seismic survey noise caused significant developmental delays in New Zealand scallop larvae. In addition, nearly half of the larvae studied developed bodily abnormalities.

    [29]

  - Nedelec et al. (2014) [30] found that boat noise reduced successful development of sea hare embryos by 21% and increased mortality of recently hatched sea hare larvae by 22%.

  - Simpson et al. (2016) [31] found that motorboat noise increased metabolic rates and decreased responsiveness to simulated predatory strikes in Ambon damselfish. In field experiments, more than twice as many damselfish were consumed by predators when motorboats were passing by, suggesting the potential for significant changes in trophic dynamics in areas with heavy boat traffic.

  - Solan et al. (2016) [32] found that shipping and offshore construction (e.g., pile driving) noises changed the burrowing and bioirrigation (circulation of water within burrows) behavior of Norway lobster. Manila clams exposed to these same noises exhibited stress responses in which they moved to the sediment surface, closed their valves, and reduced movement. In addition to diminishing the growth and fitness of individuals, these responses reduce mixing and oxygenation of the upper layer of sediment and could affect seabed nutrient cycling, productivity, and biodiversity as well as fisheries productivity.

  - Wale et al. (2016) [33] found that blue mussels exposed to ship noise reduced their filtration rates by 84% and had more breaks in their DNA, likely due to the production of stress-related chemicals.

  - Day et al. (2017) [34] found that exposure to airgun noise in the field significantly increased mortality of commercial scallop. It also disrupted their typical behaviors and their reflexes during and after exposure and may have compromised their immune systems.

  - Fitzgibbon et al. (2017) [35] found that seismic airgun noise suppressed the immune systems and harmed the nutritional condition of spiny lobsters for up to 120 days after exposure.

  - McCauley et al. (2017) [36] found that noise from a single airgun decreased zooplankton abundance within a 1.2-km range (the maximum distance sampled) and caused a two- to three-fold increase in larval and adult zooplankton mortality.

  - Paxton et al. (2017) [37] looked at fish abundance on two temperate reefs for three days before and three days during a nearby seismic survey. They found that fish abundance on the reef during evening hours – when fish utilization of the reef was highest prior to the seismic survey – declined by 78% once the seismic survey began. This change represents lost opportunities for reef fish to aggregate, forage, and mate.

  - Charifi et al. (2018) [38] found that ship noise decreased feeding and growth rates in Pacific oysters by a factor of ~2.5 and represents a risk to ecosystem productivity.

    - Maud et al. (2018) [39] found that boat noise decreased the ability of juvenile Ambon damselfish to learn to recognize predators, and that fish trained in the presence of boat noise had substantially higher mortality when placed in a natural setting.

    - Fakan and McCormick (2019) [40] found that exposure to boat noise in a laboratory increased the heart rates and negatively affected the development of embryos of two coral reef damselfish species. The noise did not affect mortality rates for the embryos in the laboratory, but the physiological and morphological changes that were observed could affect mortality in the field or fitness in later life stages.

    □ [41]

- As evidenced by the reviews and studies described above, ocean noise can impact most of the key life functions of marine animals [8] – e.g., movement, migration, locating preferred habitat, locating and capturing food, feeding, growth, maturation, reproduction, care of young, response to predators, communication. These impacts, in turn, impair individuals' growth, survival, and reproductive rates [8]. And these impacts, in turn, affect populations – population size, biomass, age structure, spatial distribution, and genetic diversity [8] – and communities of species and their interactions [23] (including trophic linkages [42]).

- There is also now strong evidence (see the studies described above) that ocean noise negatively impacts ecosystem productivity and the provision of ecological services [23], including water filtration, sediment mixing, and nutrient cycling.

- Finally, ocean noise has also been observed to negatively impact the fishing industry:

    - A study that looked at the distribution of commercial fish species in the central Barents Sea before, during, and after seismic shooting found that trawl catches of cod and haddock and longline catches of haddock went down by 70% in the shooting area [43] during shooting and were reduced up to 29 kilometers from the shooting area [43]. Five days after shooting ended, abundance and catch rates had still not returned to pre-distribution levels [43].

    - Another study found that a single airgun blast at the base of rockfish aggregations along the central California coast reduced catch-per-unit effort for a hook-and-line fishery by 52% [44], amounting to a 50% economic loss [44] for the fishery.

Are marine fish, reptiles, and invertebrates uniquely vulnerable to ocean noise?

Most studies of the impacts of ocean noise on marine animals have looked at marine mammals because of their reliance on sound for communication, feeding, and navigation. Marine fish, reptiles, and invertebrates are also vulnerable to the impacts of ocean noise, however – perhaps even uniquely vulnerable in some ways.

- While most marine fish and some marine reptiles are able to "hear" sound in some capacity [5][2], even animals unable to "hear" can be harmed by noise because sudden changes in sound pressure – particularly high frequencies with rapid rise [8] – can damage gas-filled body cavities and tissues [8]. Animals that are sessile at some stage in their life cycle (e.g., coral, barnacles, bivalves, anemones, etc.), have limited mobility (e.g., sea cucumbers), and/or exhibit high site fidelity (e.g., many reef fish) are unable to move away from harmful ocean noise.

- Marine invertebrates and some marine fish and invertebrates primarily sense the particle motion component of sound rather than the pressure component. In addition, benthic animals – largely invertebrates – are often sensitive to sound transmitted through substrates [8].

- Many ocean noise sources are more prevalent in coastal waters [6], which are critical marine habitat for many marine fish, reptiles, and invertebrates.

Why ocean noise research is so tricky

- Not only has research on the impacts of ocean noise on marine fish, reptiles, and invertebrates only recently begun, it is also incredibly difficult for a number of reasons:

    - Laboratory experiments in tanks may not fully represent what will happen in natural conditions [8] because sound fields in tanks are extremely complex and do not necessarily correspond to in situ sound conditions. In addition, marine animals are unable to move in response to noise in the same way in tanks as they might in open water. Given the difficulties and limitations of in situ experimentation, however, most information we have is actually based on laboratory experiments. For instance, in a 2018 meta-analysis of the effects of ocean noise on fish [45], 36 of the 42 studies analyzed were based on laboratory experiments.

    - Physiological and behavioral responses of marine animals – even those of the same species – vary tremendously by individual [46], life stage [8], time of year [8], activity at the time of sound exposure [8] (e.g., feeding, mating, migrating), prior experiences [7], and a host of other factors [7]. For instance, for mobile species, individuals in good condition may move away [7] from a noise while individuals in poor condition may be less able to do so.

    - Many different characteristics of sound [7] – frequency of sound waves, amplitude/intensity of sound waves, duration of a sound, rise time (the time it takes a sound to reach maximum amplitude), directionality (width of the broadcast beam), duty cycle (proportion of time a sound is present [8]), and repetition rate (how frequently a sound is repeated) – may be important to organismal response. Sound is often inadequately described in terms of peak intensity levels [8] without considering additional factors such as repetition and rise time. For instance, the effects of exposure to 100 strikes of a pile driver once per second may be different [8] that the effects of 100 strikes of that same pile driver once every 10 minutes.

    - Sound in the ocean is usually described in terms of sound pressure while many marine fish and invertebrates are more sensitive to particle motion [8]. There are relatively few sensors for measuring particle motion [8], and it is generally estimated from models that do not perform well for laboratory or shallow water conditions [8]. And given the dearth of sensors for particle motion, we lack the field data to validate/improve these models.

    - Most studies examine short-term responses due to time constraints, but short-term responses may not be representative of long-term impacts [7] on individuals and populations.

    - Sound attenuation in the ocean depends on many factors – e.g., sound frequency; whether the sound comes from a point source or an array; water depth, temperature, salinity, and pressure [47]; seabed characteristics. For example, while low-frequency noise can travel vast distances in deep water, it attenuates relatively quickly in shallow water [8]. Most models used to estimate the distances that sound will travel are not sufficiently validated with field data [8] and do not accurately predict propagation in shallow water or near boundaries [8] such as the ocean surface or seabed.

    - Finally, noise exposure is just one of many stressors for marine animals [8], and an understanding of how it interacts with other stressors and their cumulative impacts is critical for fully understanding the impacts of ocean noise on marine animals.

What we can do to make things better (or at least keep them from getting worse)

- Current management practices for ocean noise (e.g., setting regulatory limits on noise levels for areas or activities, establishing safety zones around noise-producing activities) are almost exclusively for marine mammals [8]. As a growing body of research reveals that ocean noise negatively affects other marine animals [48], there is a pressing need to establish quantitative management targets for noise levels [46] (e.g., "safe" noise thresholds [7], allowable harm limits [49], acceptable risk levels [46]) for these populations. Some specific needs related to this include:
    - Increasing research on the impacts of ocean noise, particularly particle motion, on marine fish, reptiles, and invertebrates – including impacts to individuals, populations, ecosystems, and ecosystem services. Weilgart (2018) provides a detailed list of many of these research needs [10].
    - Increasing research on the way sound travels in the ocean, particularly modeling of particle motion and shallow and bathymetrically complex areas.
    - Increasing monitoring of oceanic noise levels, particularly of particle motion and shallow and bathymetrically complex areas. [50]
    - Developing impact assessment tools for ocean noise [8] and incorporating ocean noise into cumulative impact assessments.
    - Increasing coordination among agencies that manage ocean resources and ocean activities (e.g., transportation, ocean energy, and resource management agencies and the military) [51].
    - Including marine fish, reptiles, and invertebrates in environmental impact assessments for proposed ocean activities that produce noise.
- Spatial management can also play a critical role in preventing harm from ocean noise to critical animal populations and ecosystems. Some approaches include:
    - Protecting critical habitats that are currently quiet to maintain this status [42].
    - Including the acoustic environment in the protections that marine protected areas provide, including implementing acoustic buffer zones [7] around existing marine protected areas.
    - Incorporating noise into marine spatial planning activities, including identifying priority areas for mitigation (quiet MPAs, Q-MPAs) [49].
    - Protecting biologically important areas (e.g., spawning grounds, nursery areas) at critical times of year (e.g., spawning) [10].
    - Moving shipping lanes and other noise-producing activities [52] away from sensitive or critical populations and habitats, including biodiversity hotspots.

Examples of spatial management measures taken to protect marine mammal populations [7] include a moratorium on military use of active sonar around the Canary Islands, moratoria on seismic surveys and seasonal vessel traffic in a marine mammal protection zone in the Great Australian Bight, and a moratorium on seismic surveys off the Bahia e do Espírito Santo in Brazil during the breeding season for humpback whales.

- Finally, there are many measures that can be taken to reduce ocean noise levels in general. These include:
    - Outfitting new vessels and retrofitting existing vessels with quieter propulsion systems [22] (e.g., non-cavitating propellers, SkySails [53], four-stroke rather than two-stroke engines [10] for small boats) and sound isolating/dampening mechanisms (e.g., mufflers [54], engine mounts not in direct contact with the hull of the ship [14]). The International Maritime Organization (IMO) has developed voluntary noise reduction guidelines [55] for commercial shipping.
    - Switching to quieter/less acoustically harmful seismic surveying technologies (e.g., marine vibroseis [56], autonomous seafloor seismic survey vehicles [7], using suppressor devices to reduce high frequency noise byproducts [7]) for oil and gas exploration.
    - Eliminating duplicative seismic surveying [7] (i.e., seismic surveying of the same area by different, often competing, entities).
    - Switching to quieter or silent alternatives to existing military sonar technologies for detecting underwater targets (e.g., new optical fiber technology) [7].
    - Requiring vessel speed reductions, particularly near critical habitats [52].
    - Enabling/requiring vessels in port to use shore power rather than generators [10].
    - Eliminating automatic turn-on features for recreational boat echo sounders [10] so that they are only used when actually needed.

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[1] A sound wave's amplitude is the change in pressure as it passes a given point and is related to the amount of energy it carries [57]. The sound wave's power (measured in watts) is the amount of energy it carries per unit time [57]. The sound wave's intensity (measured in watts per square meter) is the amount of power transmitted through a specified area in the direction in which the sound is traveling [57] and is a function of the wave's amplitude. Sound intensity is often specified in decibels (dB) rather than watts per square meter [57], however. Decibels are 10 times the logarithm of the ratio of the intensity of a sound wave to a reference intensity [57], so they are a relative unit of measure rather than an absolute measure [57]. Different reference levels are used for air and water, so decibels in air are not directly comparable to decibels in water.

[2] The auditory capabilities of different fish species [8] vary dramatically. For example, fish species that do not have swim bladders are believed to sense particle motion and to sound pressure at a narrow range of frequencies [8], while fish with swim bladders that are closely connected to their ears are believed to be sensitive primarily to sound pressure but at a wide range of frequencies [8].

Latest Marine Ecosystem News and Resources for Planners and Managers [58]

- Nearly 60% of ocean experiencing significantly increasing cumulative impact [59]
- Marine wildlife populations decreased by half in past 40 years [60]
- High European fisheries profits linked to sustainable practices [61]
- US's first large-scale offshore wind development held up by fisheries concerns [62]
- Top ocean science research priorities for sustainable development identified [63]
- New research brings spatial analysis approach to coastal adaptation planning [64]
- New navigator helps practitioners find ecosystem-based climate adaptation tools and methods [65]
- New toolkit assists with climate adaptation of coastal and marine protected areas [66]
- Reports provide information [67] and decision support [68] for coral reef interventions
- Global atlas of surface ocean carbon-dioxide observations available [69]

- New interactive map connects US home values and risk of sea-level-rise-related flooding [70]
- New website compiles resources for deep-ocean stewardship [71]
- Marine planning and management trainings added to database [72]
- Responses request for surveys on US marine and coastal adaptation [73] and capacity development for ocean projects [74]

And if you're interested in some more reading, some other recent news articles that caught our eye were about:

- What Brexit means for fisheries [75]
- A large oceanic hotspot off the coast of Uruguay [76]
- How plastic bag bans can be better [77].

New tools for dynamic ocean management: EcoCast vs. Marxan and more [78]

Editor's note: Heather Welch is a research associate with the University of California at Santa Cruz and the (US) NOAA Southwest Fisheries Science Center's Environmental Research Division. The Skimmer spoke with her about her research, which focuses on understanding and planning for the spatial and temporal dynamics of large-scale marine processes.

The Skimmer: We last covered dynamic ocean management [79] and dynamic ocean management tools [80] in 2014. Can you tell us a bit about how the field has progressed since then?

One area of progress is that dynamic ocean management is now better located within the larger field of dynamic management, allowing us to borrow concepts and methodologies from more established disciplines. Weather science has been developing dynamic management tools such as weather forecasts [81] and hurricane forecast tracks [82] for over a century. While on land, established dynamic management tools track floods [83], wildfires [84], and disease outbreaks [85]. Understanding the parallels between dynamic ocean management and dynamic management in other realms allows us to leverage lessons learned and avoid reinventing the wheel.

Another area of advancement is that dynamic ocean management tools are moving towards producing forecasts. Initially, tools were producing hindcasts and nowcasts, i.e., predicting where species were last month and where species are today, respectively. Now, dynamic ocean management tools are forecasting species distributions days to seasons in advance. For example, the Atlantic Sturgeon Risk Model [86] predicts Atlantic sturgeon habitat one to three days in advance to help fishers avoid the bycatch of these endangered fish. A seasonal forecasting system [87] in the Great Australia Bight predicts the distribution of Southern bluefin tuna several months into the future to help fishers efficiently locate and harvest their target species. These types of forecasts give end-users time to plan ahead for future conditions.

Lastly, dynamic ocean management is moving from single-species tools to multi-species tools that can address greater proportions of biodiversity. Single-species management was a natural starting point for the field, but established methodologies and technological advances now allow for more complex tools. For example, TurtleWatch [88] helps fishers avoid the bycatch of loggerhead and leatherback turtles. On the US west coast, EcoCast [89] helps fishers maintain their target catch of swordfish while avoiding the bycatch of loggerhead turtles, California sea lions, and blue sharks.

The Skimmer: Can you tell us about your new research and what you found?

As dynamic ocean management continues to shift towards multi-species management, decision support tools will be critical to help determine which areas to prioritize for protection. In a paper that we just published in *Conservation Biology* [90], we compared two decision support tools: the algebraic algorithm that underpins EcoCast and the simulated annealing algorithm that powers the reserve design software Marxan. While EcoCast's algebraic algorithm was explicitly designed for dynamic ocean management and Marxan was developed as a conservation planning tool, Marxan has functionality (e.g., consideration of cost and boundary complexity) that could confer advantages over EcoCast. We compared the performance of both tools over time using a dynamic ocean management scenario for fisheries sustainability. We found that the relationship between EcoCast solutions and the underlying species distributions was more linear and less noisy, while Marxan solutions had more contrast between waters that were good to fish and poor to fish.

The Skimmer: When might a manager use one of these tools versus the other?

One of the biggest drivers of decision support tool selection is managers' preferences for how species importance is assigned. In EcoCast's algebraic algorithm, species importance is assigned relatively, e.g., species X is twice as important as species Y. In Marxan, species importance is assigned absolutely, e.g., protect 20% of species X's habitat and 15% of species Y's habitat.

Both decision support tools were designed to be responsive to changing management priorities. For example, a recent bycatch event might change management priorities. We found EcoCast's algebraic algorithm was better able to reflect changing management priorities, meaning that it might be the more appropriate tool for management scenarios that emphasize flexibility. On the other hand, Marxan outperformed EcoCast's algebraic algorithm as more species were added, meaning that it might be the more appropriate tool for management scenarios that aim to manage many species. Table 4 in the paper (figure below) outlines 10 considerations that could affect manager preference regarding tool selection.

The Skimmer: Are there other possible marine management situations where a dynamic Marxan might be useful?

Certainly. The dynamic configuration of Marxan could be useful to any dynamic ocean management scenario that aims to manage multiple features. These features might be species, hydrological events such as temperature anomalies or seasonal upwelling, or socio-economic factors such as fishing ground quality and shipping channel efficiency. In addition, Marxan will be particularly useful in dynamic ocean management scenarios where there is a cost constraint.

The Skimmer: What are your next steps for this research?

One area of future development will be moving towards dynamic marine protected areas. Most dynamic management scenarios produce continuous risk surfaces, e.g., bycatch risk in EcoCast or shipstrike risk in WhaleWatch [91]. Moving towards binary open/closed areas is a logical next step. Doing this in a dynamic capacity, however, will require exploring trade-offs between protection levels and opportunity cost across time and ensuring that the locations of closed areas do not change drastically from day to day.

Secondly, Marxan is part of a family of decision support tools designed for conservation planning, and it would be worthwhile to explore how other tools such as Zonation, C-Plan, and prioritizr perform in a dynamic capacity.

Want to learn more?

- Tune in for an upcoming OCTO webinar *EcoCast: A dynamic ocean management tool to reduce bycatch and support sustainable fisheries* [92] on October 31
- Watch an animation of how EcoCast and Marxan results change over time [93]

Were you on holiday/in the field during July and August? Catch up on The Skimmer! [94]

In case you missed it, last month's issue of The Skimmer featured original articles:

- **Expanding our view of voices that matter: New perspectives on ocean stakeholders.** [95] As economies, technologies, and climate shift, it is critical to reexamine our views of who ocean stakeholders are, their relative importance, and how we engage them. Read fascinating new perspectives on ocean stakeholders [95].

- **An end to harmful fisheries subsidies may be coming soon – and that could help a marine ecosystem near you** [96]. Every year, national governments collectively provide an estimated US$20 billion to their domestic fishing industries in ways that hurt marine ecosystems and many coastal communities. Learn about harmful fisheries subsidies and global efforts to eliminate them [96].

Printer-friendly version [97] PDF version [98]

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