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Improving Ocean Management Using Insights from Space

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Abstract

Advancements in space-based ocean observation and computational data processing techniques have demonstrated transformative value for managing living resources, biodiversity, and ecosystems of the ocean. We synthesize advancements in leveraging satellite-derived insights to better understand and manage fishing, an emerging revolution of marine industrialization, ocean hazards, sea surface dynamics, benthic ecosystems, wildlife via electronic tracking, and direct observations of ocean megafauna. We consider how diverse space-based data sources can be better coupled to modernize and improve ocean management. We also highlight examples of how data from space can be developed into tools that can aid marine decision-makers managing subjects from whales to algae. Thoughtful and prospective engagement with such technologies from those inside and outside the marine remote sensing community is, however, essential to ensure that these tools meet their full potential to strengthen the effectiveness of ocean management.

INTRODUCTION

Trends in the future of the ocean will influence planetary biodiversity, global climate, and human well-being. In future decades, the ocean appears poised to be deeply affected by accelerating and diversifying human use of marine resources and habitats, the rapid advance of climate change, increasing overexploitation, pollution, and other stressors (Doney et al. 2012, McCauley et al. 2015). And yet, in this period in which many ocean processes appear to be changing at unprecedented rates, marine science is also rapidly developing new methods to track and manage this change at unparalleled accuracy and unmatched scale. Many of these improvements derive from recent advancements in our capability to observe the ocean from space. Here, we endeavor to review progress in space-based ocean sensing for biodiversity and ecosystem management.

Many factors together suggest that space-based observation can and should play an increasingly prominent and transformative role in ocean management. This rapidly developing potential derives from the fast-expanding density of satellite constellations (**Figure 1**), as well as the increasing diversity of space-based sensing modalities (e.g., optical, radar, and thermal). Sustained expansion of this space observation network seems most likely to continue given dramatic observed and projected reductions in launch costs for low-Earth-orbit satellites (Adilov et al. 2022) and the overall pace of innovation in the space industry. Astounding advances have been made in the spatial resolution and temporal frequency of the data that have become increasingly accessible to civilian scientists owing to the explosive growth in satellite constellations capable of observing the ocean—e.g., optical sensing products with resolutions of ≤30 cm (e.g., from Maxar Technologies; **https://www.maxar.com**) and capabilities for certain products that, in theory, could now image priority locations in the ocean every day. New and future hyperspectral satellite missions, such as NASA's Plankton, Aerosol, Cloud, Ocean Ecosystem (PACE) mission, will increase both the taxonomic resolution visualized from space and the capacity to disentangle complex optical signals along continental margins, thus enhancing the value of satellite remote sensing to coastal managers. These technological advancements are well timed as they coincide with a recent surge in national, regional, and global efforts to synthesize outputs from these kinds of advanced marine remote observations, such as the United Nations Decade of Ocean Science for Sustainable Development, the Global Ocean Observing System Essential Ocean Variables program, and the Group on Earth Observations Essential Biodiversity Variables program.

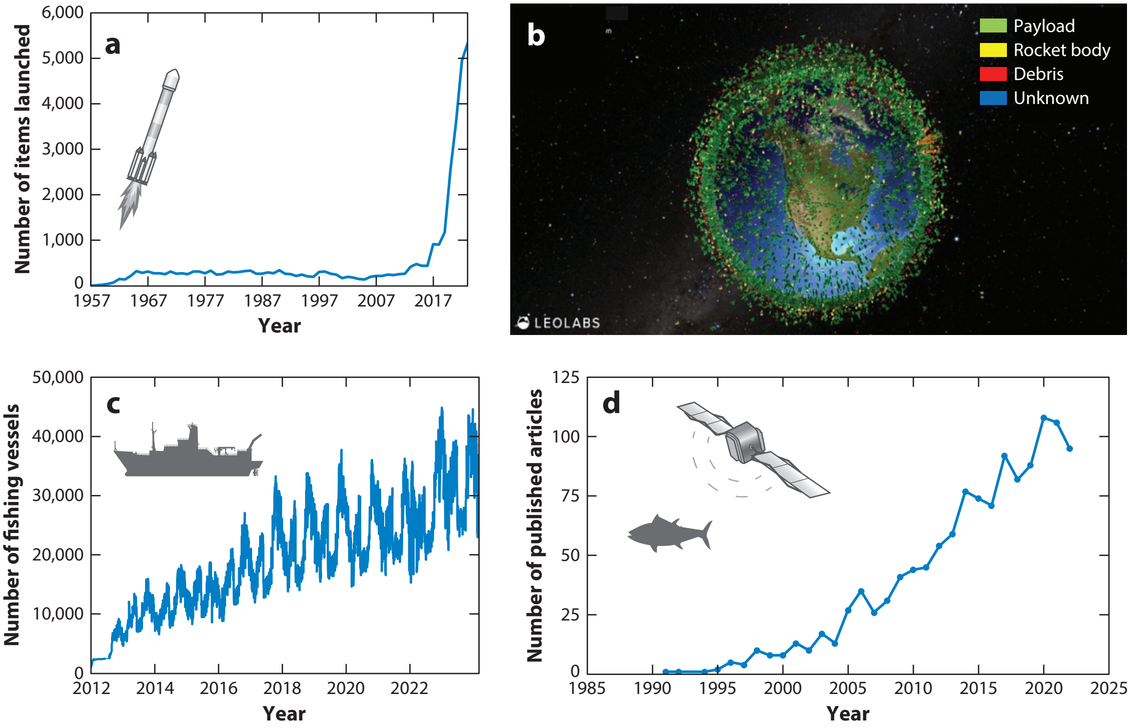

Figure 1

(*a*) Increases in the number of objects (e.g., satellites) launched into space each year, showing the dramatic surge in launches since 2017 (UN Off. Outer Space Aff. 2024). (*b*) Visualization of the density and diversity of low-Earth-orbit satellites, which have vastly increased ocean sensing capabilities. Image by LeoLabs (**https://leolabs.space**). (*c*) Increases in the number of fishing vessels broadcasting AIS per day. (*d*) Increases in the number of published studies each year involving satellite-enabled electronic tracking tags for marine research applications show their increasing utilization. The data are from a Web of Science search using the terms "satellite," "tag," and "marine." Abbreviation: AIS, Automatic Identification System.

The use of remote sensing products has a deep history in the pure ocean science community (e.g., physical and biological oceanography), and thorough reviews have been published that consider aspects such as emerging techniques for sensing the ocean biosphere (Purkis & Chirayath 2022), how such methods can support biodiversity observation networks (Kavanaugh et al. 2021), and advancements in the remote study of particular marine domains (e.g., nearshore or sea surface environments) (Phillips 1988, Holman & Haller 2013). We build on these efforts and specifically focus in this review on data sources and applications that are directly relevant to the management of marine ecosystems, biodiversity, and resources. We attempt to consider not only developments in sensing platforms and emerging data streams but also advancements in artificial intelligence (AI) and other computational techniques. Such analytical methods have the potential to unlock and interpret the vast volumes of new remotely sensed ocean data, making them more practically useful and immediately available to managers. We restrict our consideration throughout to insights for ocean management originating only from satellite platforms (i.e., excluding all other forms of aerial sensing).

This review focuses on nine different domains where space-based insights can be applied for marine management: (*a*) new techniques for monitoring fishing and other oceangoing vessels, (*b*) advancements in measuring non-vessel-based marine industry, (*c*) advancements in ocean hazard management, (*d*) improvements in sensing of the ocean surface, (*e*) advancements in monitoring benthic ecosystems, (*f*) advancements in our ability to electronically track marine animals from space, (*g*) expansions in our ability to directly observe animals and other wildlife from space, (*h*) frontier developments in our ability to build more accurate predictions for marine management using insights from space, and (*i*) best practices for making tools that use data from space practically useful for ocean managers.

ADVANCEMENTS IN VESSEL DETECTION

Historically, a challenge in ocean management has been to optimize fishing for the benefit of people and biodiversity. Fishing removes approximately 80 million tons (FAO 2022) or more (Pauly & Zeller 2016) of wild seafood from the ocean each year, providing billions of people with critical nutrition (Golden et al. 2016) and hundreds of millions with employment. It has also dramatically altered marine ecosystems across the planet, with the biomass of non-mesopelagic fish having been cut by half as a result (Bar-On et al. 2018).

Over the last 10 years, new GPS and satellite technologies have made it possible to monitor the movements of most large fishing vessels (>24 m) and some smaller ones in near real time (Kroodsma et al. 2018, Taconet et al. 2019). In addition, the locations of medium and large (>12 m) fishing vessels can now be ascertained from freely available satellite imagery, allowing global estimates of the distributions of this activity (Paolo et al. 2024), and future work will reveal activities of some smaller vessels. These technologies show great promise, especially when combined, to track large-scale fishing activity and even estimate catch in some cases (Park et al. 2020), but understanding the potential of these new technologies requires understanding the strengths and limitations of each.

The two main technologies for tracking the movements of fishing vessels are vessel monitoring systems (VMSs) and the Automatic Identification System (AIS). VMSs are used on industrial fishing vessels to track their locations through encrypted GPS signals sent to satellites. These systems are crucial for regulation and compliance. Positions are broadcast every few minutes to hours, but access to the data in many cases is limited by regional authorities (McCauley et al. 2016). Although 10 countries now publicly share VMS data, most data have to be accessed via national regulators. In contrast, AIS was designed for safety at sea, and large fishing and nonfishing vessels use it to broadcast their positions every 2–30 seconds so that nearby vessels can see their movements to prevent potential collisions (McCauley et al. 2016). While not designed to track vessels, the messages can be received by satellites, allowing for the tracking of tens of thousands of fishing vessels (Taconet et al. 2019) and hundreds of thousands of nonfishing vessels, data that are increasing every year (**Figure 1**). Machine learning algorithms, such as convolutional neural networks or transformer-based models, can be applied to efficiently synthesize insights from these hundreds of billions of data points to map which vessels are fishing and which are nonfishing, thus generating global maps of industrial fishing activity at hourly and kilometer-level resolution (Kroodsma et al. 2018, Taconet et al. 2019). Satellite and cellular network trackers for smaller vessels have been used to monitor activities of small-scale fishing vessels (<12 m) in some fisheries, but their utility has been limited relative to the number of smaller vessels, and the deployments are not yet globally representative.

Although the vast majority of fishing vessels smaller than 24 m do not broadcast their GPS positions (Taconet et al. 2019), satellite imagery technology has recently allowed mapping at scale of medium-sized vessels (12–24 m) and some smaller vessels. The Visible Infrared Imaging Radiometer Suite (VIIRS) sensor on two satellites that each image the entire Earth every night can detect vessels that fish with lights, but they are limited by clouds and have a resolution of 750 m. It has been used to map the activity of the squid fleet (Seto et al. 2023) and other fisheries (Hsu et al. 2019) and has been combined with AIS data to detect illegal fishing (Park et al. 2020).

Synthetic aperture radar (SAR) can penetrate clouds and detect vessels in all weather conditions. Freely available imagery from the European Space Agency's Sentinel-1 constellation allows detection of the majority of vessels larger than 15 m every 1–12 days in the majority of coastal waters, where the vast majority of industrial activity takes place (Paolo et al. 2024). Privately available satellite radar can complement the European Space Agency's public imagery and has options for higher resolutions to see smaller vessels or cover areas far from the coast, but cost is often limiting (Kroodsma et al. 2022). Similarly, daytime optical imagery can show vessels but is limited by clouds. Sentinel-2 imagery has further improved image resolution (i.e., to 10 m) and application capabilities (Beukema et al. 2023). Higher-resolution proprietary systems, such as the Planet system, image coastal waters daily with a constellation of more than 100 satellites and have great potential to image medium-sized vessels at scale. Much-higher-resolution imagery (≤1 m) can show the smallest boats but cannot monitor large areas of ocean with regular revisit times. Other, more prospective space-based sensing (e.g., radio frequency data) may have promise in further filling in insight gaps. A fortunate aspect for monitoring fishing vessels with imagery is that higher-resolution imagery, while rarely tasked over the open ocean, is often available closer to shore, where smaller vessels are more likely to operate.

These technologies can be combined to infer what types of vessels are operating, but imagery is often limited to detecting the presence and type of vessels and not their identities, while GPS tracking is limited to detecting movements. Impacts on ecosystems must be inferred. For example, risk to seabirds from longlines can be inferred based on the timing of when vessels appear to be setting their hooks, but the actual bycatch of seabirds must be estimated from onboard observation (Kroodsma et al. 2023). Activities of nonbroadcasting fleets detected in imagery can often be inferred from the activities of nearby vessels that are broadcasting their GPS positions (Kroodsma et al. 2022), but on-the-water information is usually critical to verify this inference (Park et al. 2020). Machine learning models trained on oceanographic data and AIS vessel tracks can begin to build predictions about potential legal and illegal fishing (Welch et al. 2022). Small-scale vessels, which have been estimated to be responsible for between 25% (Pauly & Zeller 2016) and 40% (Harper et al. 2023) of global catch, rarely carry GPS devices and are difficult to see in all but the highest-resolution imagery, and future work will be needed to map their activity.

Collectively, insight from this space-based sensing of fishing vessels has been valuable in myriad ways to marine managers—for example, by identifying risks of overlap between fishers and sharks (White et al. 2017), informing management on the high seas (Dunn et al. 2018), addressing issues of equity and slavery in fisheries (McCauley et al. 2018, McDonald et al. 2021), and estimating the amount of seabed that has been disturbed by bottom trawling and carbon dioxide released by trawling (Seto et al. 2023, Atwood et al. 2024). One challenge of using these space-based data is that some of the data are proprietary or costly. However, in recent years, the availability of VMSs and AIS has increased (Taconet et al. 2019), and some of the most useful satellites are run by the European Space Agency or NASA and provide their imagery free of charge.

Nonfishing vessel traffic can also be tracked using similar satellite technologies. Nonfishing traffic of larger vessels in fact outnumbers fishing boats and is growing (Paolo et al. 2024), and nonfishing vessels will likely play a larger role in future impacts to marine life (McCauley et al. 2015). In contrast to fishing vessels, the vast majority of medium to large nonfishing vessels broadcast their GPS positions over AIS (Paolo et al. 2024), and although satellite imagery can augment tracking these boats, AIS data can be used to identify their movements and potential impacts. Such data are being used to estimate vessel noise globally (Duarte et al. 2021, McCauley 2023), reduce risk of collisions of shipping vessels with marine megafauna (Womersley et al. 2022), and protect cetaceans (Bedriñana-Romano et al. 2021). Sand mining and dredging can also be estimated at scale through AIS (UNEP & GRID-Geneva 2024), which can threaten coastal ecosystems (Jouffray et al. 2023),

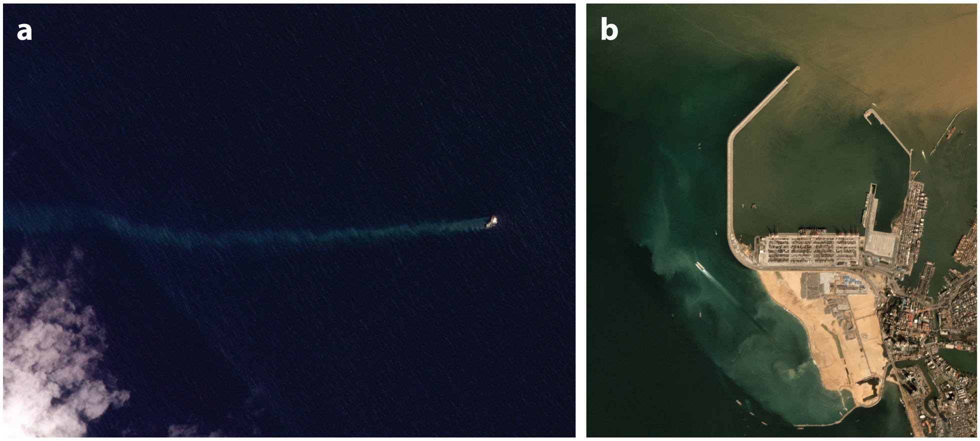

Figure 2

Examples of how optical satellite imaging can be applied to quantitative research and monitoring of a variety of habitat-modifying marine activities. (*a*) Marine mining activities, such as diamond mining operations in Namibia, which excavate and process up to 60 t of seafloor sediment per hour (Schneider 2020), can surface sediment plumes that can be more than approximately 8 km long and are visible from space. Image reproduced with permission from Planet; copyright 2024 Planet Labs PBC. (*b*) Dredging and coastal sand mining operations, such as this operation in Colombo, Sri Lanka, can impact biodiversity and regional ecosystem resilience. Image reproduced with permission from Planet; copyright 2017 Planet Labs PBC.

and satellite imagery can also reveal the extent of sediment released from this activity (**Figure 2**). A significant new area of growing concern is deep-sea and coastal seabed mining. Although satellites cannot detect what is happening on the seafloor, the activities of ocean mining vessels can be monitored (UCSB 2024), and mining effluent plumes released at the surface can be detected and their sizes measured (**Figure 2**).

SENSING OF OTHER ANTHROPOGENIC ACTIVITY AND INFRASTRUCTURE

The past few decades have seen massive growth in other diverse forms of ocean industry. This recent rapid expansion in sectors such as offshore oil and gas, aquaculture, marine energy, desalinization, and seabed mining has been termed by some as the onset of the marine industrial revolution or blue acceleration (Jouffray et al. 2020, Posner et al. 2020). There has been considerable interest from marine managers in the pace and the specific locations of this growth, as well as the tracking of externalities created from these industries, as these new habitat-altering industries could have an outsized impact on biodiversity and marine ecosystem services (McCauley et al. 2015).

Radar and optical imagery can now image this infrastructure and track such industry activity over time (Dong et al. 2022, Paolo et al. 2024). Combining this imagery with vessel tracking makes it possible to see how fishing activity responds to these industries and to estimate the total activity associated with them (Paolo et al. 2024). This includes, for example, tracking growth in marine energy installations, both for oil and for offshore wind. Although oil structures are found in more countries' waters than wind turbines, wind energy is growing rapidly, and in the past five years the number of wind turbines in the ocean has surpassed the number of oil structures (Paolo et al. 2024). Energy structures change local ecosystems by increasing local vessel traffic, serving as artificial reefs (Claisse et al. 2014), and attracting some types of fishing while preventing other types (Paolo et al. 2024). Marine aquaculture farms can also be detected from space, using similar imagery and methods (Fu et al. 2021). This is also an important sector given its rapid growth and potential interactions with biodiversity. Desalination infrastructure has similarly expanded rapidly. Current and future advances in remote sensing may open up pathways for studying the propagation of brine discharges and exploring hypotheses regarding potential biological and oceanographic impacts from this brine (Zhao et al. 2017). As with vessels, satellite imagery is generally limited to detecting where and when this infrastructure is located, although some important aspects of behavior (e.g., gas flaring from offshore oil or gas; Liu et al. 2023) are visible. Inferring their impacts on ecosystems generally requires bringing in information from other sources.

ADVANCEMENTS IN OCEAN DISASTER AND HAZARD DETECTION AND MANAGEMENT

New developments in both sensor technology and algorithms/data products have advanced our capacity to monitor many types of recurrent marine hazards from space to help managers with mitigation efforts. Such tools can also be used to assess the impacts of natural disasters (e.g., hurricanes) on both natural and built (e.g., the aforementioned marine infrastructure) assets to guide recovery efforts (Marlier et al. 2022), a charge that is likely to become even more important as climate change alters the frequency and intensity of such disasters. Hazard management from space includes more time-sensitive observation of acute issues [e.g., oil spills and harmful algal blooms (HABs)] as well as the perennial need to observe chronic hazards [e.g., plastic pollution, nutrient pollution, and associated hypoxia (low-oxygen dead zones)].

HABs are blooms that cause detrimental impacts on the environment, marine animals, human beings, and the economy (Anderson et al. 2014). Although increased occurrences of HABs have been reported around the world, it is often difficult to discern whether that is due to the observer effect (i.e., more observations in response to HAB events could lead to more reported HABs) (Anderson et al. 2021). Satellite remote sensing provides synoptic and frequent measurements to avoid this observer effect, but the lack of reliable algorithms to differentiate HABs from other blooms or discolored waters (e.g., caused by river discharge) has previously hindered the interpretation of satellite imagery. Several recent works have shed light on new ways to address this difficulty. For example, although it is still not possible to discern whether a bloom is harmful or not, a new classification scheme has been developed and applied to long-term Moderate Resolution Imaging Spectroradiometer (MODIS) data to quantify bloom occurrence frequency in global coastal oceans in a statistically meaningful way (Dai et al. 2023). AI, specifically via deep learning, has provided a growing alternative but complementary approach for detecting HABs (e.g., *Karenia brevis* in the eastern Gulf of Mexico) (Yao et al. 2023). Furthermore, remote sensing data products have been incorporated in ecological predictive approaches to predict toxicity (Anderson et al. 2016). Integration of HAB occurrences and wind anomalies has helped managers and decision-makers directly evaluate respiratory risks and design early-warning systems for mitigation [e.g., Stumpf et al. 2022 (for the Gulf of Mexico) and the California Harmful Algae Risk Mapping effort (**https://calhabmap.org/hab-forecast**)].

Similar types of advancements in oil spill detection have been made. The combined strength of computing power, large data volume, and customized algorithms led to the creation of the first-ever map of the global distribution of oil slicks from both natural sources and human activities (Dong et al. 2022). This study found that the contribution from human activities was one order of magnitude higher than that from the natural sources. The second advancement was the ability to classify and quantify oil spills using optical remote sensing (Jiao et al. 2023), which moved beyond the traditional presence/absence detection because it offered more spectral bands to distinguish thick oil emulsions from thin oil slicks (Hu et al. 2021). Such insight is particularly useful for marine managers attempting to target actionable oil (e.g., booming).

Plastic pollution also threatens marine life, yet attempts to detect marine plastics from space began only recently. The small size and difficulty in differentiating floating plastics from other targets (e.g., organic debris) made such efforts challenging (Hu 2021). Nevertheless, several case studies have shown preliminary success in detecting marine litter (including plastics) using primarily high-resolution sensors (e.g., Rußwurm et al. 2023). Detections have focused mainly on waters downstream of river discharge and after heavy rains or hurricanes. Although these studies are based on retrospective analysis, future approaches may help identify hotspots and emission sources in a cost-effective way. Considering that future satellite sensors will have the hyperspectral capacity to possibly fingerprint plastics (Castagna et al. 2023), our detection capabilities for plastics are only expected to improve.

Hypoxia refers to low-oxygen bottom waters (often termed dead zones because less mobile animals cannot survive), which can damage important commercial fisheries (Smith et al. 2014), among other hazardous impacts. Recent advances have shown the advantage of combining remotely sensed surface blooms and ocean warming to predict bottom hypoxia location and size (Li et al. 2023), and in situ–based observing networks have led to investigations of hypoxia in global lakes (Jane et al. 2021). The knowledge of the linkages between hypoxia and the timing and amount of fertilizer use in coastal regions can help improve management via regulations. For example, in the Gulf of Mexico, this knowledge helped the Mississippi River/Gulf of Mexico Watershed Nutrient Task Force prioritize actions to reduce the size of the dead zone along the Louisiana coast.

For all marine hazards above, the use of commercial CubeSat constellations is expected to grow rapidly in the coming years. These satellites can often provide near-daily revisits in coastal waters at very high resolution (VHR) (e.g., ∼3 m from Planet's Dove and SuperDove sensors). Although the number of spectral bands is often limited, they show unprecedented capacity in detecting and quantifying HABs and oil spills (Schaeffer et al. 2022, Yao et al. 2024). Such information, especially when provided almost daily, could be game changing for managers (e.g., when making water discharge decisions).

ADVANCEMENTS IN MONITORING MARINE PRIMARY PRODUCERS AT OR ABOVE THE OCEAN SURFACE

Great strides have been made in recent years in advancing our capacity to study vital marine primary producer communities at the ocean surface—e.g., phytoplankton functional types (such as diatoms, dinoflagellates, or green algae), phytoplankton community composition (assemblages of phytoplankton functional types), macroalgae, intertidal wetlands, or kelp—using satellite tools. While traditional methods for measuring phytoplankton from space are based on a simple index of chlorophyll *a* pigment concentrations in global data products made available by space agencies, recent efforts have emphasized the remote detection of phytoplankton functional types or phytoplankton community composition through phytoplankton pigments, scattering, or size composition. These efforts have used approaches based on abundance, ecology, or spectra (Mouw et al. 2017, Kramer et al. 2022). Global monthly maps of the four major phytoplankton functional types, based on multisensor merged ocean color data, are now regularly generated (Xi et al. 2020). The recent hyperspectral PACE mission will provide new opportunities in mapping phytoplankton community composition at the global scale (Cetinić et al. 2024). Furthermore, active remote sensing systems such as satellite-based lidar can supplement these optical approaches for monitoring phytoplankton biomass (Hostetler et al. 2018). Lidar-based measurements of subsurface particulate backscatter can be used to estimate phytoplankton biomass (Behrenfeld et al. 2013, 2017). These systems can collect data during day and night and are less sensitive to sun angle and other atmospheric conditions. As a result, they can be particularly valuable in regions where a large sun angle or lack of sunlight limits optical measurements. These traditional and new ocean data products are widely relevant to managers, such as those involved in ecosystem-based fisheries management and those studying interactions between climate change and phytoplankton (Sathyendranath et al. 2023 and references therein).

Various kinds of floating macroalgae have been reported in global oceans, of which the major types are *Sargassum fluitans* and *Sargassum natans* in the Atlantic Ocean (Wang et al. 2019), *Sargassum horneri* in the East China Sea, and *Ulva prolifera* in the Yellow Sea (Qi et al. 2022). Although macroalgae fix carbon through photosynthesis and therefore play a role in carbon sequestration, excessive amounts of macroalgae in coastal waters or on beaches can be a significant burden on coastal environments, human health, and local economies (Zhou et al. 2015, Rodríguez-Martínez et al. 2019). These emergent macroalgae blooms are related to climate variability, ocean and atmospheric processes, and human activities (aquaculture and fertilizer use; Qi et al. 2022). Existing satellite-based monitoring systems, such as the Sargassum Watch System (Hu et al. 2016) (**Figure 3*f***), are based on new algorithms to detect and quantify floating macroalgae (Hu et al. 2023), which have been used widely by managers and others to prepare for inundation events and mitigate the adverse impacts. The recent PACE mission as well as future hyperspectral satellite missions [e.g., Geostationary Littoral Imaging and Monitoring Radiometer (GLIMR) and Surface Biology and Geology (SBG)] will improve our capacity to monitor and forecast these macroalgae blooms, thus enhancing management activities.

Intertidal Wetlands

Coastal intertidal wetlands (e.g., mangroves and salt marshes) are ecologically important ecosystems that have declined dramatically in recent decades due to coastal development such as urbanization, agriculture, and aquaculture. For example, between the early 1980s and early 2000s, at least 35% of the world's mangrove forests were lost (Valiela et al. 2001). Satellite imagery is valuable for monitoring these losses. There is a long history of using multispectral, hyperspectral, radar, and lidar data to map the extent and structure of intertidal mangrove and salt marsh vegetation (e.g., Pham et al. 2019). Vegetated wetlands are relatively easy to identify due to their high near-infrared reflectance, but in some settings it can be difficult to distinguish intertidal and upland vegetation. In mangrove ecosystems, space-based lidar and radar have been valuable tools for estimating height and aboveground biomass (Simard et al. 2019, Hu et al. 2020). Due to the maturity of these methods, several new satellite-based maps of global salt marsh extent (Mcowen et al. 2017) and global mangrove extent and height (Giri et al. 2011, Bunting et al. 2022) have been recently developed. Improved monitoring and data access have proved to be extremely valuable for conservation of coastal wetlands and are among the cited factors contributing to recent declines in mangrove deforestation rates (Friess et al. 2020).

Floating Kelp Canopy

Kelp forests, found on shallow rocky reefs along approximately 25% of the world's coastlines, are another incredibly productive and valuable ecosystem (Wernberg et al. 2019). Some of the largest kelp species form exposed floating canopies that are relatively easy to distinguish using multispectral satellite imagery. As the availability of moderate- to high-resolution multispectral satellite imagery has increased, so have efforts to map and monitor these ecosystems. Long-term data are particularly valuable because the high natural background variability of kelp forest abundance makes it difficult to detect impacts of long-term processes such as climate change (Bell et al. 2020). Multispectral imagery from satellites such as Landsat and Sentinel-2 has been used

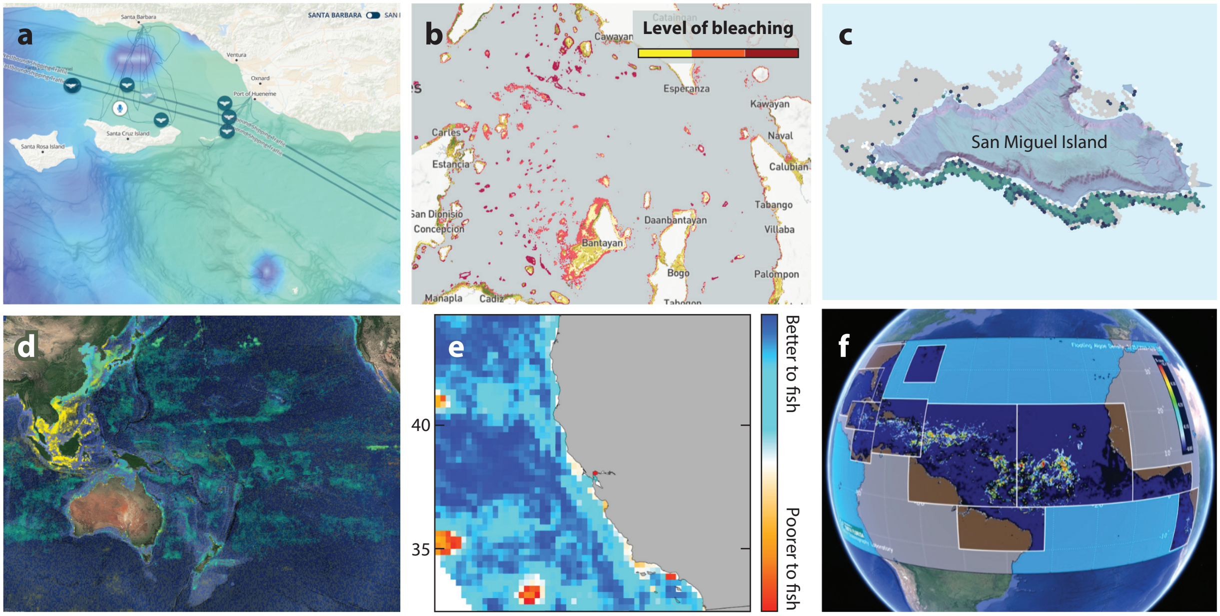

Figure 3

Views from six representative tools that operationalize satellite-derived data in service of marine managers. (*a*) Whale Safe (**https://whalesafe.com**) leverages insights from AIS satellite ship tracking data and a blue whale habitat model that relies on satellite-derived oceanographic data and satellite tracking data of whales—all combined with other in situ data sources—to help marine shipping companies to avoid lethal collisions with endangered whales. (*b*) The Allen Coral Atlas (**https://allencoralatlas.org**) leverages underwater physical algorithms, machine learning, high-resolution Planet Dove, and Sentinel-2 MSI satellite imagery to map the world's coral reefs and monitor their threats to provide data for coastal ecosystems conservation. (*c*) Kelpwatch.org (**https://kelpwatch.org**) visualizes and analyzes maps of kelp canopy extent derived from multispectral Landsat imagery to help scientists and managers track trends in kelp abundance, identify threats to kelp forests, and manage kelp harvest. (*d*) Global Fishing Watch (**https://globalfishingwatch.org**) tracks the activity of hundreds of thousands of fishing and nonfishing vessels using vessel GPS data and global feeds of satellite imagery and combines this information with other data layers for marine managers. (*e*) EcoCast (**https://coastwatch.pfeg.noaa.gov/ecocast**) integrates remotely sensed environmental data with five species distributional models to assess opportunities for fishing with low bycatch risk (*blue*) and places to avoid with high bycatch risk (*red*). (*f*) A sample *Sargassum* density map (March 25–31, 2023) from the Sargassum Watch System (**https://optics.marine.usf.edu/projects/saws.html**) shows widespread *Sargassum* from west Africa to the Caribbean Sea and Gulf of Mexico and includes maps that are updated daily in near real time with Google Earth compatibility and are divided into subregions (*white lines*) to facilitate regional mitigation efforts. Abbreviations: AIS, Automatic Identification System; MSI, MultiSpectral Instrument.

to monitor long-term changes in kelp forest abundance along the west coast of North America (Bell et al. 2023) and the coasts of sub-Antarctic islands (Mora et al. 2021, Houskeeper et al. 2022), New Zealand (Tait et al. 2021), and southern Australia (Butler et al. 2020). More recently, high-resolution (∼3 m) multispectral CubeSat imagery has been used to monitor small, nearshore kelp beds that cannot be detected from imagery with 10–30-m resolution (Cavanaugh et al. 2023). These and other forms of kelp forest remote sensing have applied value for managing kelp forest harvest; designing, managing, and monitoring marine protected areas; guiding kelp forest restoration; and detecting climate change impacts on kelp (Cavanaugh et al. 2021).

ADVANCEMENTS IN MONITORING BENTHIC MARINE ECOSYSTEMS

Historically, satellite sensing of the ocean was confined largely to measuring attributes of the ocean surface discussed above. New methods are now unlocking more capacity to measure key features below the ocean's surface. The coastal ecosystems near the interface of land and ocean encompass some of the world's most biodiverse marine regions and habitats (e.g., coral reefs and seagrass), which contribute resources and services (e.g., seafood, tourism, and flood protection) that benefit millions of people. These shallow-water ecosystems have also experienced substantial recent declines across various dimensions (Li et al. 2019). As pressures on these systems escalate (e.g., terrestrial pollution and coastal development; Carlson et al. 2021), it is even more important to leverage satellite sensing to collect precise and current spatially explicit information about these biomes.

Coral Reefs

Conventional, manually collected field surveys of coral reefs generate detailed information, but their applicability is limited to small geographical areas (Roelfsema et al. 2018). Satellite remote sensing technology offers a solution for consistently mapping and monitoring coral reef benthic habitats across extensive geographical areas (Li et al. 2020). Most contemporary scientific and management initiatives have relied on a single coral reef map, the World Atlas of Coral Reefs (UNEP-WCMC et al. 2021). Originally a compilation of digitized reef maps, the World Atlas later drew from Landsat 7 satellite imagery that estimated reef extents from space, particularly in distant or hard-to-reach areas (Andréfouët et al. 2006), which led to the creation of the United Nations Environment Programme World Conservation Monitoring Centre (UNEP-WCMC) Global Distribution of Coral Reefs data product (UNEP-WCMC et al. 2021). While this product is immensely useful, its accuracy may vary because the underlying data come from various sources employing different methodologies, and the sampling intensity differs across regions (Li et al. 2020). Researchers have recently resolved some of these challenges, creating globally uniform coral reef maps across three categories—the extent of reef ecosystems, the locations of geomorphic zones, and the composition of benthic habitats—using machine learning algorithms from 1.17 million Dove CubeSat images (between 2018 and 2020, i.e., Allen Coral Reef Atlas 19) (Lyons et al. 2020). In the meantime, effectively distinguishing between live coral and bleached coral covered by algae remains difficult for satellite remote sensing due to constraints in spectral resolutions (Asner et al. 2022). However, multiple existing and forthcoming hyperspectral satellite sensors, such as the Earth Surface Mineral Dust Source Investigation (EMIT), Planet's Tanager, and NASA's SBG, offer the potential to address this issue (Cawse-Nicholson et al. 2021, Joshua et al. 2023).

Seagrass

Seagrasses are another critically important focal ecosystem for space-based sensing, as they efficiently capture and retain significant quantities of carbon in sediment, accounting for approximately 17% of the organic carbon buried in marine sediments annually (Duarte et al. 2005). Studies on mapping seagrasses have concentrated on the utilization of satellite remote sensing, which offers thorough and frequent observations of seagrass habitats. This capability allows for both retrospective analysis and near-real-time monitoring (Bannari et al. 2022, Zhou et al. 2022, Li & Asner 2023). However, state-of-the-art satellite seagrass mapping still has not been conducted at a global scale using consistent data sources and algorithms. Global assessments of seagrass extent from multiple efforts (e.g., UNEP-WCMC datasets, the Global Biodiversity Information Facility, and the Ocean Biogeographic Information System) vary from 177,000 to 600,000 km^2, and certain models predict habitat suitability that could be two or more times the observed extent (McKenzie et al. 2020). New research is needed to develop a consistent and high-resolution global seagrass map.

Bathymetry

Developing an improved understanding of physical features of coastal ecosystems via satellites, such as their bathymetry, is also important to managers because bathymetry shapes biologically relevant processes (e.g., light attenuation and hurricane or typhoon storm surges; Mouw et al. 2015) and is relevant to marine industry (Ashphaq et al. 2021). Optical satellite-derived bathymetry algorithms can be created by applying physical models that describe the transfer of light underwater (Hedley et al. 2018). These algorithms have been largely improved by including deep learning methods, multiple data fusion [e.g., Ice, Cloud, and Land Elevation Satellite 2 (ICESat-2) lidar data], and cloud-based platform computing (Albright & Glennie 2021, Li et al. 2021). The improved algorithms provide fundamental information for multiple shallow coastal satellite applications, including coral reef mapping and monitoring, fish biomass estimation, seagrass mapping, coastal water quality quantification, and benthic complexity estimation (Parrish et al. 2019, Asner et al. 2020, Li & Asner 2023). Moreover, NASA's ICESat-2 green wavelength lidar sensor has shown great promise in combining with multispectral satellite imagery to improve bathymetry estimation results in nearshore waters (Parrish et al. 2019, Ma et al. 2020, Thomas et al. 2021).

ADVANCEMENTS IN SATELLITE-BASED MARINE ANIMAL TELEMETRY

Electronic tagging technologies have permitted scientists to leverage space-based technologies to study free-ranging marine fauna for over four decades. These telemetry tools are on the rise (Watanabe & Papastamatiou 2023) (**Figure 1**). At its core, biologging science involves attaching small electronic tags to animals that store data on behavior and oceanographic variables; when at the surface, they then often utilize radio telemetry to transmit data to satellites in order to determine the animals' positions and relay archived tag data on behavior and oceanography back to researchers. Lessons learned from past research have generated many applied benefits, including identifying the habitat requirements of endangered species (e.g., Schofield et al. 2013), providing insights into marine protected area design (e.g., White et al. 2017), and generating information about spatial and temporal distributions of marine megafauna (e.g., Block et al. 2011, Andrzejaczek et al. 2023). In addition, significant advancements in physiology, behavioral research (such as foraging ecology), and spatial habitat analyses that are directly germane to whole-ecosystem management have been made using these tools (Block et al. 2011, Raymond et al. 2015). Discoveries made using satellite-based tagging have been especially valuable in contexts where focal species range into pelagic and mesopelagic environments and/or too far or too deep to be studied using fixed acoustic receiver arrays.

The first use of satellite telemetry involved tracking a basking shark with a towed Argos transmitting tag for 17 days (Priede 1984). Subsequent studies in the early-to-mid-1990s estimated the positions of tagged individuals (e.g., whale sharks, blue sharks, and blue marlin) using towed and early fin tags, with some success (Eckert & Stewart 2001; B.A. Block, unpublished data). In the mid-1990s, pop-up satellite archival tags were developed, expanding tag deployments to a range of pelagic fishes (e.g., Block et al. 1998). These tags combined archival and Argos satellite technology, recording environmental variables (e.g., pressure, temperature, and ambient light-level data) and estimating position via geolocation algorithms (Teo et al. 2004, Block et al. 2005). This was followed by advancements in positioning algorithms that were enabled using Fastloc GPS tags to rapidly estimate position by acquiring snapshots of the GPS satellite constellation while the animals were at the surface. More accurate estimations of position are obtained, but limitations still exist for uplinking data routinely (most often to Argos) on diving animals in the sea.

Current advances in this field include efforts to continue to improve the spatial accuracy of tagged animal position estimates; prolong tag deployment durations, which are currently limited primarily by the battery; and expand the array of sensors available and the quantity of data transmitted. Future developments will rapidly result in miniaturization of this technology to facilitate deployments on smaller marine species and size classes. Positional data, however, remain the top priority for managers, with accuracy varying across tag types depending on how the user has programmed the tag and how position estimates are generated. Algorithms for light-based geolocation methods have been improving, with newer models and more comparative data. Positional errors vary with latitude, ranging from 50 to hundreds of kilometers for pop-up satellite archival tags, to several kilometers for the Argos system, to several hundred meters for Fastloc transmitters. Currently, data on position, as well as accuracy and the volume of archived data transmitted, are also influenced by the availability of overhead satellites. For instance, there are presently only seven polar-orbiting Argos satellites. The projected increase in the number of operational polar orbiting satellites and the planned addition of two-way communication in the Argos system will potentially result in a dramatic increase in energy efficiency, eliminating the need to duplicate transmissions. The recent expansion of low-Earth-orbit satellite internet connectivity (e.g., Starlink) could also open up opportunities for lower-cost, higher-speed data links that could create interesting opportunities for electronic tagging as well as other marine sensing applications. Use of Iridium and other growing nanosatellite technologies should enhance the capacity to improve position acquisition rapidly and improve the capability of tags transmitting real-time behavioral and oceanographic data.

Ongoing developments in tag hardware show further promise for tracking a wider range of smaller and deeper-distributed taxa. Such innovations include reductions in tag and battery size (Scarpignato et al. 2016, Holton et al. 2021), integration of solar power (Chan et al. 2016), and increasing memory and sampling frequency (Holton et al. 2021). These developments will advance our understanding of how and why animals move while improving the ability for the animals themselves to become environmental sampling platforms of physical and biological oceanographic processes (Roquet et al. 2017).

Although hardware (e.g., tag and satellite) developments have arguably led past progress, software developments now hold great promise for further transformations. It has not usually been possible, for example, to send the large quantity of data that can be produced by tag sensors via satellite, making tag recovery critical. However, several developments in data processing have led to ways to summarize this high-resolution data in informative packets for transmission (e.g., Skubel et al. 2020).

Linking multispecies datasets is increasingly being facilitated by shared movement data repositories (e.g., the Ocean Tracking Network, Tagging of Pacific Pelagics, Movebank, and the BirdLife Seabird Tracking Database) and will facilitate application of these data to management. For instance, tracking data from many species have been used to help identify multispecies seabird hotspots and important bird areas (Davies et al. 2021). Coupling tracking datasets with other remotely sensed data, as well as with coupled biologger data and/or other individual data, opens additional frontiers. Deep learning–assisted platforms have recently been developed that allow for better comparisons of complex movement data across groups (Maekawa et al. 2020). New statistical tools and theory for identifying resource tracking (e.g., using optimal movement theory) will help us utilize these multiple data streams to gain new insights on why animals migrate. Meanwhile, integrating new types of satellite data (e.g., geomagnetic data) may also help us understand how animals migrate.

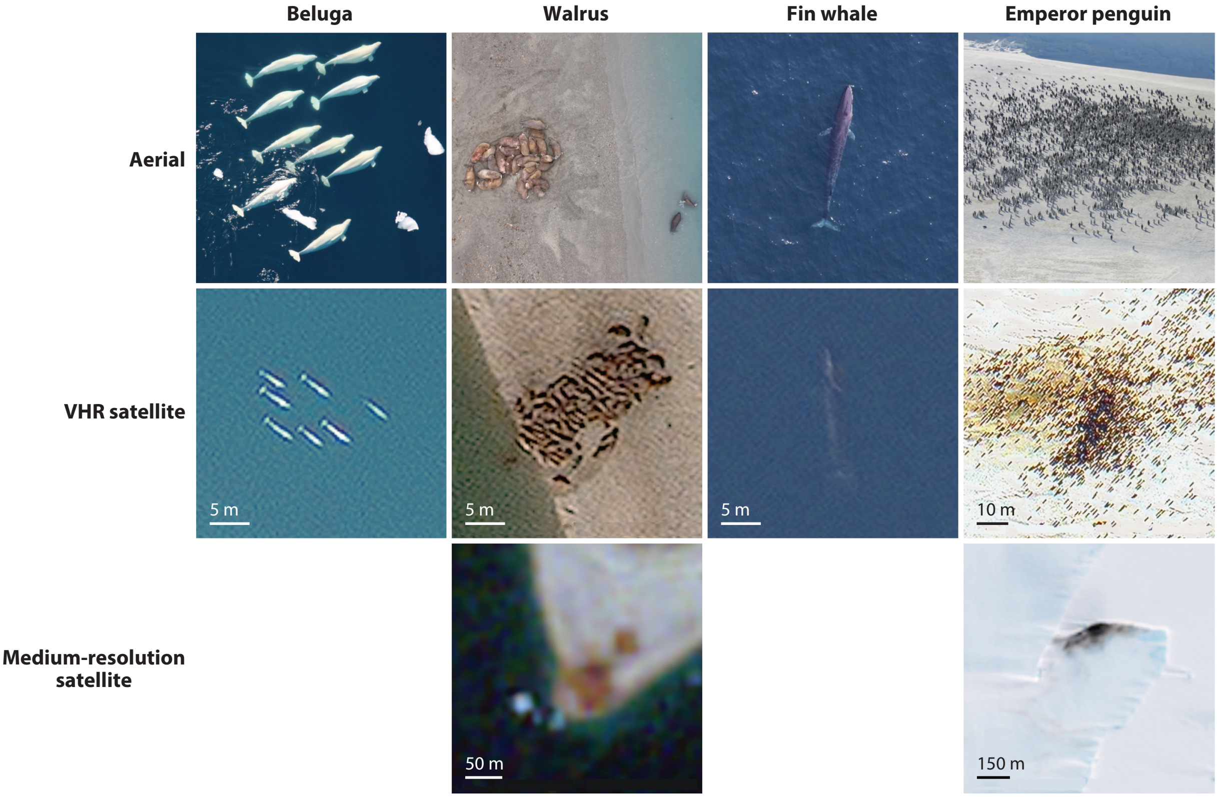

Figure 4

Four examples of marine fauna seen from space in VHR and medium-resolution optical satellite imagery: beluga (*Delphinapterus leucas*), walrus (*Odobenus rosmarus*), fin whale (*Balaenoptera physalus*), and emperor penguin (*Aptenodytes forsteri*). Aerial imagery is also presented for comparison with the satellite imagery. Abbreviation: VHR, very high resolution. Beluga aerial image by the National Marine Fisheries Service/Alaska Fisheries Science Center/National Marine Mammal Laboratory (National Marine Fisheries Service permit number 782-1719) (public domain); walrus aerial image by Hannah Cubaynes; fin whale aerial image by the Northeast Fisheries Science Center (Marine Mammal Protection Act permit number 17355) (public domain); emperor penguin aerial image by Robin Cristofari. Medium-resolution satellite images reproduced from the European Space Agency; copyright 2024 European Space Agency. VHR satellite images reproduced with permission from Maxar Technologies; copyright 2024 Maxar Technologies.

ADVANCEMENTS IN THE DIRECT OBSERVATION OF ORGANISMS FROM SPACE

Satellite imagery is emerging as a new potential tool to monitor marine fauna more frequently and noninvasively, especially in remote regions (Fischbach & Douglas 2021, Lynch 2023). Various types of satellite sensors (e.g., optical, radar, and thermal) and spatial resolution (e.g., medium resolution to VHR; **Figure 4**) can be used to monitor wildlife directly (Cubaynes 2020, Khan et al. 2023). Medium-resolution optical satellite imagery (10–30 m, e.g., Sentinel-2) can usefully detect large aggregations of animals on land, such as penguin colonies—including discovering new colonies (Fretwell & Trathan 2009, Lynch & Schwaller 2014)—and walrus (*Odobenus rosmarus*) haul-out groups (Fischbach & Douglas 2021).

There are many applications where presence/absence information about target organisms is helpful (e.g., improving data for species distribution modeling or understanding the phenology of marine migrations). But the increased density of satellite constellations, increased resolution, and reduced costs (for remote regions) are also opening up abilities to do abundance measurements (e.g., counting entire populations of pinnipeds; LaRue et al. 2021) and assess population trends over time. Estimating abundance is expected to be more feasible in contexts where marine animals gather on land but much more complicated—although not necessarily impossible—for fully aquatic marine species (e.g., whales; Belanger et al. 2024). The ability to discern and count individual animals requires VHR optical satellite imagery (<1 m, e.g., WorldView-3) and comes with limitations on the sizes of the studied species. Marine species counted from space include cetaceans (Cubaynes et al. 2019, Charry et al. 2021, Clarke et al. 2021), pinnipeds (Fudala & Bialik 2022, Laborie et al. 2023), seabirds (LaRue et al. 2014, Bowler et al. 2020), and polar bears (LaRue & Stapleton 2018) (**Figure 4**). A growing number of studies have been able to use VHR imagery to provide population size, density, and abundance estimates (e.g., LaRue et al. 2014, Laborie et al. 2023). Because satellites capture images continuously for years, researchers can perform image differencing and detect changes over time. For instance, the seasonality of walrus presence at one of their terrestrial haul-out sites could be monitored (Fischbach & Douglas 2021).

Observing behaviors will be more difficult and not always feasible. Attempts have been made for belugas (*Delphinapterus leucas*), where the general behaviors of groups but not individuals have been determined (i.e., traveling or foraging) (Fretwell et al. 2023). Feeding behavior has been observed for some cetaceans, such as bubble net feeding by humpback whales (*Megaptera novaeangliae*) (P.J. Clarke, personal communication) and mud ring feeding by bottlenose dolphins (*Tursiops truncatus*) (Ramos et al. 2022).

The best target species for research using optical satellite imagery are those that contrast well with their environment and are large enough to be observed (LaRue et al. 2017). In cloudy regions, medium-resolution and VHR SAR imagery has proved useful to detect subjects like walruses (Fischbach & Douglas 2021), although its utilization remains nascent. While no recorded wildlife surveys have used thermal satellite imagery, the potential has existed since the launch of the HOTSAT constellation (3.5 m) (SatVu 2024). Advancements of satellite video products (e.g., SkySat) may in the future provide a means of collecting more dynamic information on megafauna behavior.

An important advantage of satellite imagery is the potential for monitoring vast and remote regions. However, review of satellite imagery is mainly done manually, limiting the geographical extent that can be surveyed. Advances in machine learning and other types of AI show promise for increasing processing efficiency (e.g., Bowler et al. 2020, Green et al. 2023). Alternatively, citizen science projects may also help sieve through large amounts of imagery (LaRue et al. 2020).

ADVANCEMENTS IN PREDICTIVE SPECIES DISTRIBUTION MODELING

We regularly rely on satellite-based models to guide decision-making in many facets of social and economic life (e.g., hindcasts, nowcasts, predictions, and storm tracking). Applications of predictions based on satellite inference can be similarly powerful in ocean decision-making. Species distribution models (SDMs), for example, offer the ability to correlate where a species is found as a function of underlying environmental data. These models can then use historical or real-time environmental data to predict habitat suitability. Traditional SDMs have relied on in situ measurements of the environment collected in tandem with visual surveys, mark–recapture surveys, or quadrat sampling (Elith & Leathwick 2009). The introduction of combining electronic tagged individuals with satellite-measured environmental variables has revolutionized our ability not only to fit SDMs but also to predict at broad spatial and fine temporal scales. This has opened the door for real-time models of where species are for use in management (Hazen et al. 2018), marine spatial planning (Welch et al. 2023), and even dynamically moving protected areas for pelagic species (Maxwell et al. 2020).

Hindcasts use a fitted SDM to make predictions based on past data for evaluation of prior ecological states and for management strategy evaluations (Hazen et al. 2018, Welch et al. 2023). Hindcasts have been critical in assessing multiple management decisions—e.g., the sizes and dates of closures of the California Dungeness crab fishery to maintain fiscal yield while also reducing whale entanglement (Welch et al. 2023). The initial hindcasts were just maps of habitat suitability overlaid with human uses to examine risks but have since been expanded to include fisheries livelihoods as well (Welch et al. 2023, Samhouri et al. 2024). Hindcasts can be especially useful in contexts (e.g., fishery closure) where fishing experiments are either too costly or detrimental (Braun et al. 2023).

Nowcasts provide predictive surfaces of current conditions, similar to meteorologist predictions of instantaneous weather. In the ocean, satellite data can be used both to fit SDMs and to predict where a species is most likely to be at risk from anthropogenic pressures, up to a daily time step (Hazen et al. 2017, 2018; Abrahms et al. 2019). While nowcasts have traditionally relied on satellite data for fitting and predicting, ocean models that re-create broad-scale processes or assimilate satellite data can help fill gaps and increase resolution (e.g., Hobday et al. 2011, Abrahms et al. 2019). These models can be valuable for gap fitting and continuity, as changes in satellite type or data hosting can result in breaks in operational workflows.

Forecasts can provide predictions such as those from SDMs at three-day to multiannual timescales (Hobday et al. 2016). On the shortest timescales, internal variability has been used to forecast Atlantic sturgeon distribution up to a week in advance for avoidance by the striped bass fishery (Breece et al. 2021). Seasonal forecasts have usefully predicted the timing of fishery opening dates (e.g., lobster; Mills et al. 2017). Integrating satellite data with forecasts has meant more models coming online and being assessed for their skill (Jacox et al. 2023). Forecasts have shown skill for marine predator indices such as the habitat compression index, which assesses risk for whale entanglement, and the Temperature Observations to Avoid Loggerhead (TOTAL) tool, which indicates when warm waters are at risk for bringing critically endangered loggerhead sea turtles nearshore and at risk from US highly migratory species fisheries (Brodie et al. 2023).

Projections represent timescales from 10 to more than 100 years and often use satellite data for model fitting or hindcast evaluation but use global climate or Earth system models for climate prediction. Projections are important both for long-term marine spatial planning (Hobday et al. 2016) and to assess new risks of human–wildlife conflict under changing global conditions and new needs and opportunities for management as species shift (Pinsky et al. 2018). On the US west coast, global and more recently downscaled Earth system models have been used to predict which marine top predators are most likely to gain or lose habitat, helping provide information for climate change planning (Hazen et al. 2013, Lezama-Ochoa et al. 2024). An increased amount and density of tracking data are necessary for both model validation and ongoing model fitting because species–environment relationships may change.

Remotely sensed satellite data are often used as a proxy for ecological processes. Chlorophyll is often included to represent a higher likelihood of prey availability, while sea surface temperature can have the most direct physiological implications for the predator or their prey and is often the most skillful variable in marine forecasts (Brodie et al. 2023, Jacox et al. 2023). There is no one-size-fits-all best choice of scale and environmental predictors, as the variables chosen, spatial resolution, and temporal frequency may vary based on model application and management need (Scales et al. 2017, Braun et al. 2023).

SDMs are often focused on one or a few species and rely on sufficient species data to fit the models. An important frontier area for predictive modeling from space should include experimental tests that validate the models and seascape-level efforts that capture variability in complex oceanic conditions (e.g., El Niño/Southern Oscillation) and relate them to multiple species and ocean ecosystem processes (Kavanaugh et al. 2016).

OPERATIONALIZING SPACE-BASED INSIGHTS IN TOOLS THAT ARE PRACTICALLY USEFUL FOR MARINE MANAGERS

A real opportunity and historical challenge has been serving up the complex insights emerging from space-based sensing in more accessible formats so that they can be more immediately actionable by marine managers. This last-mile effort often takes the form of developing dashboards or web tools for managers. However, it is important to note that a perennial challenge in such exercises is not only generating dashboards but also relying on the principles of user-centered design to ensure that such tools are genuinely useful to marine habitat and fishery managers. Creating such tools is a costly and time-consuming step in the research process that can take as much effort as the initial scientific study. However, these tools can be difficult to fund and require ongoing maintenance and support (Welch et al. 2019). A wide range of examples are now available that illustrate how space-based insights can be effectively operationalized for marine management. A set of representative examples is shown in **Figure 3**.

When insights from space are operationalized to directly shape real ocean decision-making, it is critically important to acknowledge, if not quantify, the multiple sources of radiometric errors involved when propagating satellite data from data acquisition at the origin sensor (e.g., errors associated with sensor calibrations) all the way through the atmosphere (e.g., errors associated with atmospheric correction) and water surface and column (e.g., errors associated with sun glints, waves, and water attenuation effects) to insight delivery to managers (e.g., errors associated with algorithm choice, modeling approach, and variables selected) (Mobley et al. 2016, Brodie et al. 2022, Hieronymi et al. 2023). Not only should the potential contribution of these many error sources be transparently described in documentation for all management-facing platforms, but they must also be practically interpreted for managers to avoid overinterpretation of the precision of outputs from such programs.

An important frontier consideration in this domain of satellite-powered tool design is coming up with new best practices, founded on open data science principles, for considering common website design platforms and hosting sites, common code libraries, and common operational workflows. Aligning on such frameworks will increase both the accessibility and the stability of these products and reduce the cost of efforts to produce them. Each of these steps is fundamentally a huge lift, which satellite data have already made more possible. The platforms that make these data accessible span government, education, private nongovernmental organizations, and companies as well as corporate interests; thus, common hosting platforms [e.g., the NOAA Environmental Research Division Data Access Program (ERDDAP)] and code libraries (e.g., rERDDAP) for interacting with satellite data have more recently lowered the bar to transition from science to management. That said, changes in satellite data hosting practices or analytical techniques can break existing operational tools, creating roadblocks in operational science tools (Welch et al. 2019). Developing a framework from satellite data to data dissemination that could be more broadly applied and training tools for next-generation users is a critical nexus for increasing the use of satellite data in marine resource management and will rely on a strong collaboration with the fields of computer science and user-centered design.

CONCLUSIONS AND RECOMMENDATIONS

The degree to which marine managers make productive use of insights from space has increased significantly in recent years. But this uptake is a small part of the full future potential for such tools to positively influence ocean management. We submit seven emergent synthesis points and recommendations based on trends reviewed above:

1. First, to realize the full potential of putting ocean observation data from space to service to managers, data and research practices must be kept as open as possible. This theme surfaced in all reviewed areas as a means for significantly unlocking progress (e.g., management tool design and cross-integration of multispecies telemetry data). Best practices in open science are easier to apply in use cases involving publicly funded satellite data but can become more complicated in the many contexts reviewed here involving private sector providers. Trends toward increased privatization of satellite constellations mean that this may increasingly become an issue. Eschewing useful proprietary data may not always be the best choice. Solutions for maximizing access may include working with private sector partners to emphasize the necessity of openness in science, increasing the resolution of aggregated insights that can be openly shared, and negotiating improved access agreements for academic and management contexts where data can promote environmental and social sustainability. If costs for basic satellite programs were to decline further, it may be constructive for the ocean community to pool efforts and resources to create their own open sensing programs (such as the MethaneSAT program). Parallel efforts should also be undertaken to unblock public access to higher-resolution satellite data that can benefit ocean management without introducing security risks (e.g., recent US Department of Commerce decisions to reduce access restrictions on higher-resolution optical and SAR data).
2. The next biggest breakthroughs in the application of space data for ocean management seem mostly likely to come from AI advances. As reviewed, a wide variety of AI tools (e.g., convolutional neural networks, deep learning, and computer vision) are already being applied to process patterns from the increasingly voluminous quantities of satellite marine data, but this area seems likely to grow rapidly. Design of these AI tools is one arena in which researchers also have more autonomy to adhere to open science principles, thereby ensuring this growth happens equitably.
3. All space-based marine tools have blind spots. Some of the most useful, complete, and practical applications for marine management involve projects that fill these blind spots by integratively coupling insight from multiple satellite data streams (**Figure 5**). Continued effort should be made to integrate and synthesize across datasets (e.g., by encouraging shared repositories for tracking or imaging datasets) in ways that make these available to data users without specialized expertise.
4. Similarly, there are hard limits on what can be learned about the ocean from space. More work is needed to link data derived from satellites with nonsatellite data sources (e.g., in situ ocean sensor networks, citizen science data, autonomous vehicle and drone sensing, aerial ocean sensing, and numerical models).
5. Some of the most tangible examples of positive change in marine management come from instances where researchers have designed tools to distill simplified guidance from space data (**Figure 3**). This community of academic solution engineers must endeavor to engage user communities beyond traditional, well-established marine managers (e.g., NOAA) and also serve smaller and less wealthy management stakeholders (e.g., managers of community-based marine protected areas, and small-scale fishers in the Global South). Furthermore, elevating the value we assign to the creation of these hyperapplied tools within academic and funding communities will be a critical part of seeing them flourish.
6. There is an especially urgent need for focused application of space data for tracking and managing the impacts of climate change on the ocean (e.g., monitoring coral bleaching and

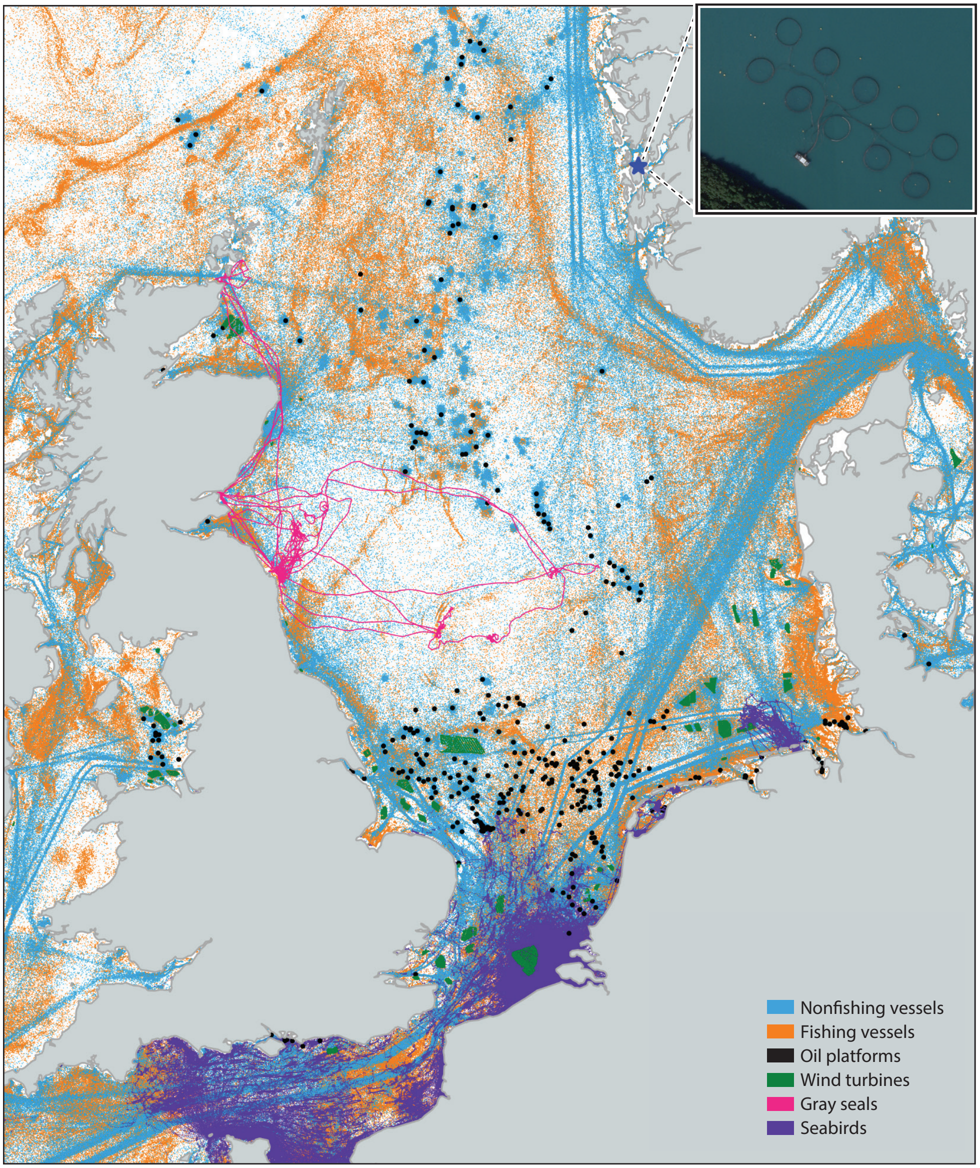

Figure 5

Integration of insights from multiple satellite data sources, which can provide marine managers with a more complete portrait of how anthropogenic activity intersects with marine biodiversity and ecosystems. This map of the North Sea depicts vessel activity [both nonfishing (*light blue*) and fishing (*orange*)]; offshore wind turbines (*green*); offshore oil and gas structures (*black*) (Paolo et al. 2024); satellite tracks of four seabirds [northern gannets (*Morus bassanus*) (Warwick-Evans et al. 2018), lesser black-backed gulls (*Larus fuscus*) (Garthe et al. 2016), herring gulls (*Larus argentatus*) (Stienen et al. 2023), and Eurasian oystercatchers (*Haematopus ostralegus*) (Dokter et al. 2023)] (*purple*) and gray seals (*Halichoerus grypus*) (Michelot & Blackwell 2019) (*pink*); and an optical satellite image of a salmon aquaculture farm (*inset*). Optical satellite image reproduced with permission from Planet; copyright 2022 Planet Labs PBC.

sea ice and tracking macroalgae inundation, using satellite tracking data to monitor long-term species shifts of habitat). This toolkit must diversify beyond traditional applications to address climate threats to marine aquaculture, fisheries, sea level rise, deoxygenation, ocean current regime shifts, animal migration, and beyond.

7. Speed is of the essence for marine managers. A critical area for future growth is in increasing the temporal frequency and reducing the latency with which ocean data collected from space can be dynamically used. Increases in satellite constellation density (**Figure 1**) will help by reducing overpass times. Integration of AI can also further reduce the time it takes for data from space-based sensors to be acquired and made available to managers. A key near-term goal for the marine community should be replicating progress in the terrestrial remote sensing community (e.g., hotspot management of wildfires) for delivering high-frequency, near-real-time insights for the many time-sensitive marine management applications (e.g., detection of illegal fishing).

Data collected from space will never replace the necessity and value of many current and future in situ monitoring practices that form the backbone of many types of marine management (e.g., fisheries catch data and scuba surveys). However, all indications suggest that the rapidly advancing field of space-based ocean observation will significantly improve the accuracy and efficiency of marine management at both local and global scales and will play an increasingly important role in the ways we monitor and manage ocean ecosystems in the future.

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The authors are not aware of any affiliations, memberships, funding, or financial holdings that might be perceived as affecting the objectivity of this review.

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