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Characteristics of animal movement and environmental data for dynamic ocean management: Insights and guidance

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Abstract
Dynamic ocean management (DOM) is a critical approach for protecting highly migratory species amid environmental variability and change. We conducted an adapted systematic review to assess how animal movement and environmental data are used in DOM applications, identifying key data traits, barriers, and research priorities. Animal tag data inform initial assessments of species distributions, development of habitat models, near real-time model inputs, and iterative model evaluation for dynamic management. In documented examples, effective translation of scientific insights into dynamic management products has resulted from early communication between researchers and stakeholders, integration of environmental and fisheries-dependent data into advanced habitat modeling approaches, and reformatting of outputs for interdisciplinary needs. However, challenges persist around data gaps, science-policy translation, and technical capacity limitations. Our findings highlight the importance of intentional, collaborative data collection, translation, and sharing to enable dynamic, climate-resilient management of migratory species. We demonstrate DOM's adaptability and provide guidance for researchers and practitioners to contribute and use impactful data that informs responsive management decision-making.

KEYWORDS
animal telemetry, climate-ready management, dynamic ocean management, flexible management, highly migratory species, mobile marine management

1 | INTRODUCTION

Marine highly migratory species (HMS) regularly travel long distances, often crossing domestic and international boundaries. They can serve as crucial indicators of ecosystem health and offer significant cultural and economic benefits to communities worldwide, but their protection is challenging (Robinson et al., 2009). Given their wide spatial ranges and regular migrations, they are subject to inconsistent levels of management and a myriad of threats (Block et al., 2011; Dunn et al., 2016; Harrison et al., 2018; Pinsky et al., 2018; Santos et al., 2024). Understanding HMS movement patterns in response to changing oceanographic conditions and adapting their protective measures appropriately are research priorities (Hazen et al., 2013; Queiroz et al., 2019). In addition to the direct conservation benefits of HMS populations, adequate management of marine species remains ecologically beneficial to the ecosystems they inhabit and economically imperative for fisheries and ecotourism (Hammerschlag et al., 2019).

Many HMS are undergoing declines in relative abundance or have shown recent declines with no evidence of rebuilding (Lynch et al., 2018). Accordingly, determining the drivers of decline and adopting actions to mitigate the collapse of marine HMS is critical. However, there is a highly documented "science-management knowledge gap" in the animal movement field, which points to a failure in adequately translating movement data into relevant conservation policies. The number of studies that track and monitor marine animal movements is increasing, with many using these data to produce suitable habitat and space use models; however, only a small portion of the data has been successfully translated to inform identifiable conservation efforts to protect species at risk (Hays et al., 2019; Hussey et al., 2015). Barriers to translating tracking data into conservation policies largely revolve around the lack of effective communication and collaboration between researchers, stakeholders, policymakers, and end-users throughout the research and dissemination process (Hays et al., 2019; McGowan et al., 2017). The cumulative and growing threats confronting HMS necessitate a logical and well-planned approach to data collection to adequately support accurate space-use models and informed management decisions (McGowan et al., 2017; Queiroz et al., 2019).

Marine biodiversity is already shifting in response to climate change, with this trend expected to intensify over the next century (Perry et al., 2005; Poloczanska et al., 2013). While many of these shifts are predicted to occur toward the poles (Morley et al., 2018; Smith et al., 2023), factors such as oxygen availability and thermal stress may also influence the relocation of marine biota throughout the water column or inshore/offshore (Horodysky et al., 2016). Climate-driven shifts can result in the creation or expansion of fishing opportunities in some locations while simultaneously reducing established fisheries in others, affecting both vulnerable HMS and human users (Braun, Lezama-Ochoa, et al., 2023; Smith et al., 2023). For example, distribution shifts could result in less overlap between fishing activity and targeted species, exposing fishing-dependent communities to an increased risk of economic loss (Rogers et al., 2019). Alternatively, climate-induced shifts in environmental variables and prey distributions can result in stronger overlaps between high fishing effort and HMS distributions or result in HMS moving out of protected areas, thereby exposing them to higher threats from fishing (Abrahms, 2021; Hammerschlag et al., 2022; Samhouri et al., 2021; Santora et al., 2020; Santos et al., 2024). Further, increases or decreases in overlap between target and bycatch species (Lezama-Ochoa et al., 2024) and/or predator and prey densities (Hazen et al., 2018) can also occur. Such shifts may lead to misalignment with existing static spatial management zones (e.g., time or area closures) or spatially explicit regulations, as has recently been demonstrated in tiger shark migrations in the Atlantic Ocean under warming (Hammerschlag et al., 2022).

A practice that can benefit HMS, especially under climate change, is dynamic management. This approach allows for boundaries of protected areas to be updated automatically, spatially and temporally, in response to changing conditions and often offers a better balance between economic and ecological objectives (Maxwell et al., 2015). In marine systems, dynamic ocean management (DOM) is increasing in interest for use by researchers, marine users, and other stakeholder groups and has demonstrated success in generating ecological, social, and economic benefits across different sectors (Dunn et al., 2016; Hazen et al., 2018; Lewison et al., 2015; Welch et al., 2019). DOM is informed by multiple types of near real-time data on physical and biological variables as well as human users (e.g., fishers) data and management priorities (Lewison et al., 2015; Maxwell et al., 2012). Previous studies have demonstrated that successful DOM requires sustainable and consistent data streams, a high level of collaboration among stakeholders, and the optimal integration and synthesis of data (Lewison et al., 2015). Here, we examine and characterize data streams used or needed in DOM applications to determine how data from tagged marine animals can be collected and shared to support dynamic management applications, with an emphasis on climate-resilient HMS management.

The goal of this study is to characterize animal movement and environmental data streams used in DOM and identify pathways and needs for incorporating these data to inform climate-resilient approaches (Figure 1). Through an adapted systematic review of DOM applications and summaries, we explore opportunities, barriers, and future directions, with a focus on integrating animal tracking data. We also briefly examine animal-borne sensor data, an emerging ocean observation frontier (Harcourt et al., 2019). By characterizing DOM data

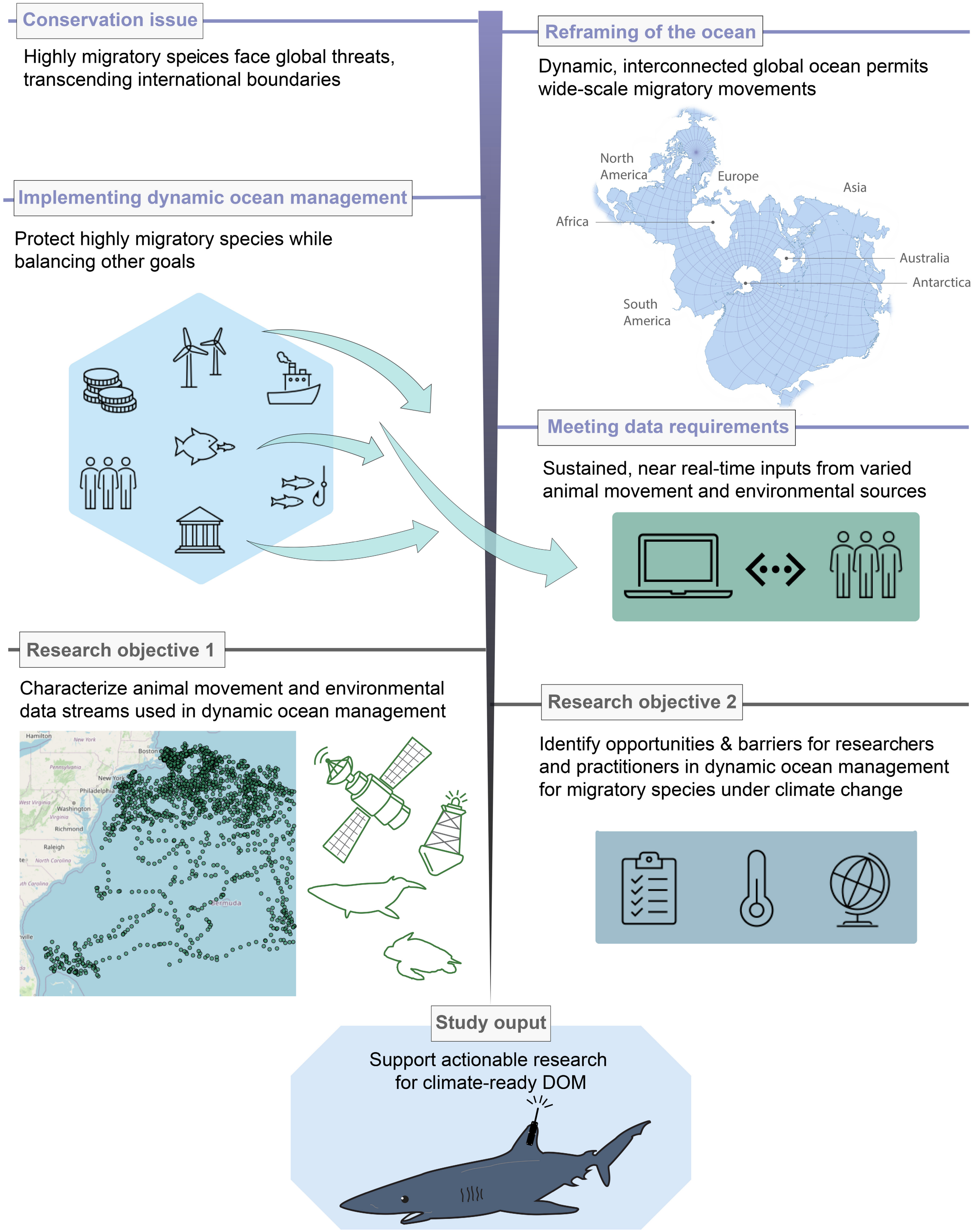

FIGURE 1 Framing the use of dynamic ocean management and its data streams in this study. The study's goals and expected outcomes are listed in the context of DOM, focusing on leveraging specific data streams to support the conservation of highly migratory species in a changing global ocean.

integration, models, and needs, we aim to elucidate factors shaping researcher contributions to usable and accessible data for decision-makers. Additionally, we provide considerations for practitioners to enhance their understanding of how these data streams are collected and can be incorporated into DOM frameworks. This review provides key insights to guide tagging studies toward impactful support of dynamic, climate-ready management.

2 | METHODS

The methods employed in this study included an adapted systematic review and subsequent content analysis. Relevant literature was identified and retrieved from various sources and screened for eligibility using predetermined inclusion and exclusion criteria. Subsequently, articles underwent content extraction, in which data were organized and coded using predefined categories to identify enabling factors and gaps in incorporating animal tracking, environmental, and animal borne ocean sensors (ABOS) data in DOM. Topic modeling allowed themes to emerge across extracted data, and statistical approaches were used to summarize trends across the literature.

2.1 | Literature review

A broad literature search was conducted using Harzing's Publish or Perish to identify relevant articles from Google Scholar and Web of Science in October 2022 (Harzing, 2007). Our search encompassed articles published between 2000 and 2022, and search terms used included a combination of 19 keyword terms (Figure 2). Publish or

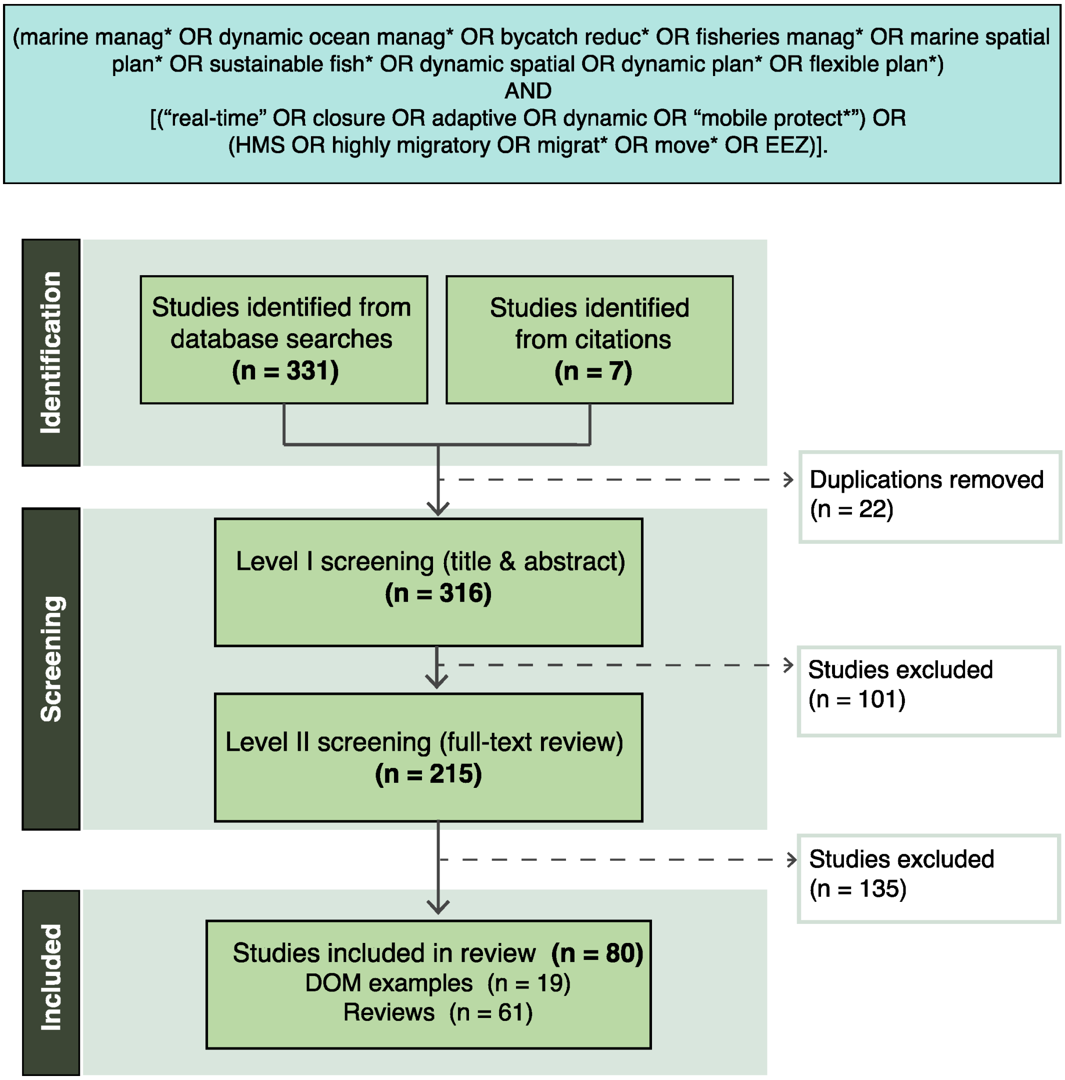

FIGURE 2 Keyword search terms and Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) guide. Flowchart outlining article collection, filtering, and screening prior to data extraction.

Perish determined the articles (up to 400 total, 200 articles/database) having the most impact on research related to the search terms. We conducted a multi-level screening process to identify relevant publications within the search output using Covidence (Veritas Health Innovation, Melbourne, Australia, www.covidence.org), a web-based collaboration software platform, using the workflow outlined in Figure 2.

Importantly, preliminary searches revealed that known instances of "dynamic ocean management" were not always associated with that specific term in the literature. Here, we defined DOM following Maxwell et al.'s study (Maxwell et al., 2015): "*Management that changes rapidly in space and time in response to the shifting nature of the ocean and its users based on the integration of new biological, oceanographic, social and/or economic data in near real-time*." Other terms used recently in the literature to refer to DOM include "mobile marine protected area," "dynamic spatial planning," "flexible marine planning," and simply "dynamic management" among others (Bakker, 2022). We retained examples of DOM that fit our broad criteria of the definition, as listed above.

Level I excluded articles if none of the selected keywords (Table S1) appeared in the title or abstract, the document was inaccessible, or the paper was a presentation or an informal document. Level II retained (1) documented DOM applications (proposed, planned, experimental, or operational) and (2) review or summary papers that provided substantial information on DOM or similar practices defined by different terms. Our inclusion criteria required that each article met at least one of the following requirements. For these requirements across examples of DOM, the article needed to describe (a) in-practice or proposed dynamic management for a marine HMS, (b) methods of (near) real-time data stream incorporation to support HMS management, (c) dynamic management tools or models (new or applied) in marine systems, (d) the collection or use of animal-borne sensor data in marine management, or (e) an update to a previously published instance of DOM for HMS. Review papers (a) provided definitions of DOM or related terms, (b) described additional DOM examples from the literature, (c) identified gaps or barriers in applying DOM, or (d) discussed outcomes from previous application(s) of DOM.

Papers were excluded if they contained only a brief mention of DOM or similar term with little context or follow-up or did not detail data streams characteristics in sufficient detail to be coded (examples only). For both levels of screening, two coders independently reviewed articles in a blinded manner. If the coders screened an article differently, discrepancies were discussed until consensus was reached. Only articles that both coders agreed met the inclusion criteria were retained for extraction. Coders exercised discretion in conducting bibliographical research, including forward and backward citation analysis with the collected studies.

2.2 | Content extraction and analysis

Coders addressed a set of questions to extract data from articles (Table 1). In Covidence, each retained article was coded using an extraction template, first categorizing the record as either a DOM example or review article and then proceeding with associated questions for each type of article. Relevant text and information from articles were extracted for category-specific questions (Table S2).

For DOM examples, questions were grouped into three broad categories: program characteristics, data stream specifics (for animal movement and environmental streams), and animal-borne sensor data. The sources and types of data were noted and summarized, with the goal of further examining how this information is used to support evidence-based management measures. Within the animal movement data stream, we further examined the use of animal-borne sensors in DOM, if applicable. To identify DOM opportunities and barriers, review articles were coded using a separate template outlining their overall goals, methods, and conclusions. Data from reviews were extracted with specific emphasis on dynamic management, HMS, ABOS, and climate change.

TABLE 1 Question categories guiding data extraction and coding for articles retained after Level 1 and 2 screening.

Type of paper	Question area	Data categories extracted
DOM examples	Program characteristics	Developmental stage, program goal, inputs, frequency, outcomes, climate-readiness
	Data stream specifics	Sources and types, temporal and spatial scales, sample size, data translation process
DOM examples and reviews	Role of animal-borne sensors	ABOS data, incorporation process where applicable
Reviews	Findings: DOM, HMS, resilience	Goal, DOM definition and context, climate change and HMS in management, needs, and gaps

Note: General categories of questions that served as a coding guide for collected literature. All sub-categories and specific questions are listed in Table S2.

Quantitative and qualitative data characteristics were further analyzed to determine different groupings and emerging themes using manual and automated topic modeling. Topic modeling algorithms allow for more abstract themes to be pinpointed, by analyzing text input and identifying patterns of word co-occurrence to uncover thematic structure and topics. Text cleaning and correlated topic models (CTM) were conducted in R Statistical Software (v.4.2.2; R Core Team 2022) using the *text mining* and *revtools* packages (Feinerer & Hornik, 2023; Westgate, 2019). CTM models were used as they can capture complex relationships between topics and assume that topics share an underlying correlation structure, allowing increased flexibility in identifying patterns and selection of relevant data for discussion (Blei & Lafferty, 2006). Overarching themes and patterns were identified within the data, supplementing those initially pinpointed by coders during extraction. CTM models were run with 10,000 iterations; each iteration involved a series of steps where the algorithm updates the topic proportions for each document, the topic assignments for each word in each document, and the model parameters (e.g., topic-word distribution and hyperparameters) (Westgate, 2019). Descriptive statistics on the retained articles and the correlational structures among quantitative descriptors and classifiers were calculated where relevant.

3 | RESULTS

In total, 80 publications were retained, with 19 examples of DOM and 61 reviews. Of these articles, 49% were published after 2015, while the other 51% spanned 15 years prior (2000–2015). The majority (74%) of articles mentioned climate change and variability directly at least once, while another ~11% mentioned potential impacts of change indirectly (e.g., referring to an example). Only 12 articles made no reference to climate change or its effects on the management issue considered.

3.1 | Examples of DOM

Most DOM examples focused on the Atlantic and Pacific Oceans (84%), particularly United States waters (Figure 3). Developmental stages included operational ($N = 6$), experimental ($N = 4$), and proposed ($N = 9$). Of these examples, 10 emphasized the need for DOM to be climate resilient while 9 did not. Diverse goals aimed to reduce species interactions, mitigate bycatch, avoid life stages, enable recovery, and mitigate climate impacts on fauna and stakeholders (Figure 3). Among operational and experimental cases ($N = 10$), 7 demonstrated success in meeting objectives, while 3 showed promise but needed further testing, data, or validation. Nearly all ($N = 16$) emphasized socioeconomic data streams, with 10 specifically tailoring their output to stakeholder needs.

Examples identified several challenges faced in dynamic management approaches and outlined needs to improve their management output products. Most pointed toward requiring more data, for both animal ($N = 11$) and environment ($N = 9$) data streams and underlined technical know-how and or capacity needs ($N = 11$). Some examples ($N = 6$) mentioned delays in receiving data to generate technical output, while another 4 stressed the need to improve manager/fisher confidence in DOM products. Lastly, 3 examples emphasized the need for improved data sharing and collaboration. Next steps in operationalizing or improving operational DOM models were also provided in many studies. These included the addition of more variables in the DOM model, further model validation, increased spatial resolution, increased spatial coverage of product, forecasting for the DOM model, and more tagging efforts (Figure 4).

3.2 | Animal spatial data

Among the 19 examples of DOM analyzed, 10 incorporated species distribution (SDM) or habitat preference models, comprising 7 newly developed and 3 pre-existing models (Figure 4). Many instances drew from multiple data sources to inform animal distribution, with over half (57%) relying on fisheries-dependent data such as logbooks and observer program data. Satellite tags were utilized in 6 examples, while other technology-based platforms, including acoustic tags and echo sounders on moored buoys, were employed in 5 instances. Various animal tracking devices were deployed, including GPS, satellite, acoustic, and archival tags, with the Argos satellite positioning tags being the most prevalent. The potential for inclusion of animal-borne sensor data was examined further among the 9 examples that used tag data and reported the tag model: 2 studies did use tags with temperature sensing abilities, while 4 did, but these data were not mentioned at all in the study. Only 1 study stated that their tags measured temperature data but that they were not utilized in the study. Finally, 2 articles, both studying southern bluefin tuna, mentioned and used the temperature data available from the tag, highlighting the importance of this to their study goals (Hobday et al., 2010; Hobday & Hartmann, 2006).

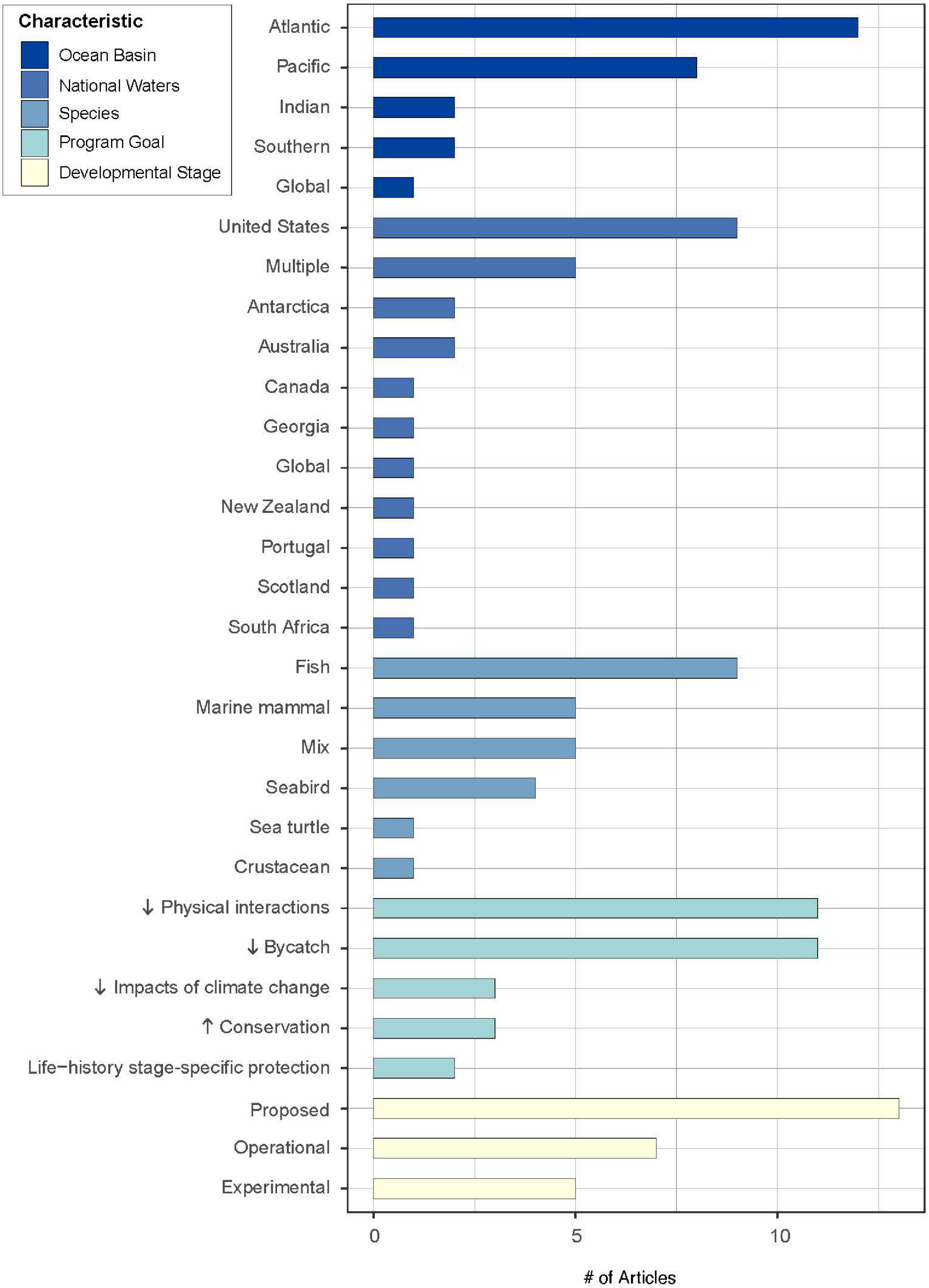

FIGURE 3 Frequency of general characteristics among published examples of dynamic ocean management.

The process of translating animal movement data for use in DOM depended on the number of data streams, scale, and output format. However, several shared steps emerged (Figure 4). Key factors shaping the translation process were the number and format of data streams, scaling, and output design. Generally, data collection and compilation integrated various sources like tags, surveys, and fisher logs. Data pre-processing included cleaning and quality control. In multi-species examples, layers were weighted and combined (e.g., Hazen et al., 2018). Interpolation and modeling (e.g., SDM) with environmental variables or fishing effort were used to estimate distribution patterns and habitat suitability. These models were then validated and implemented to create

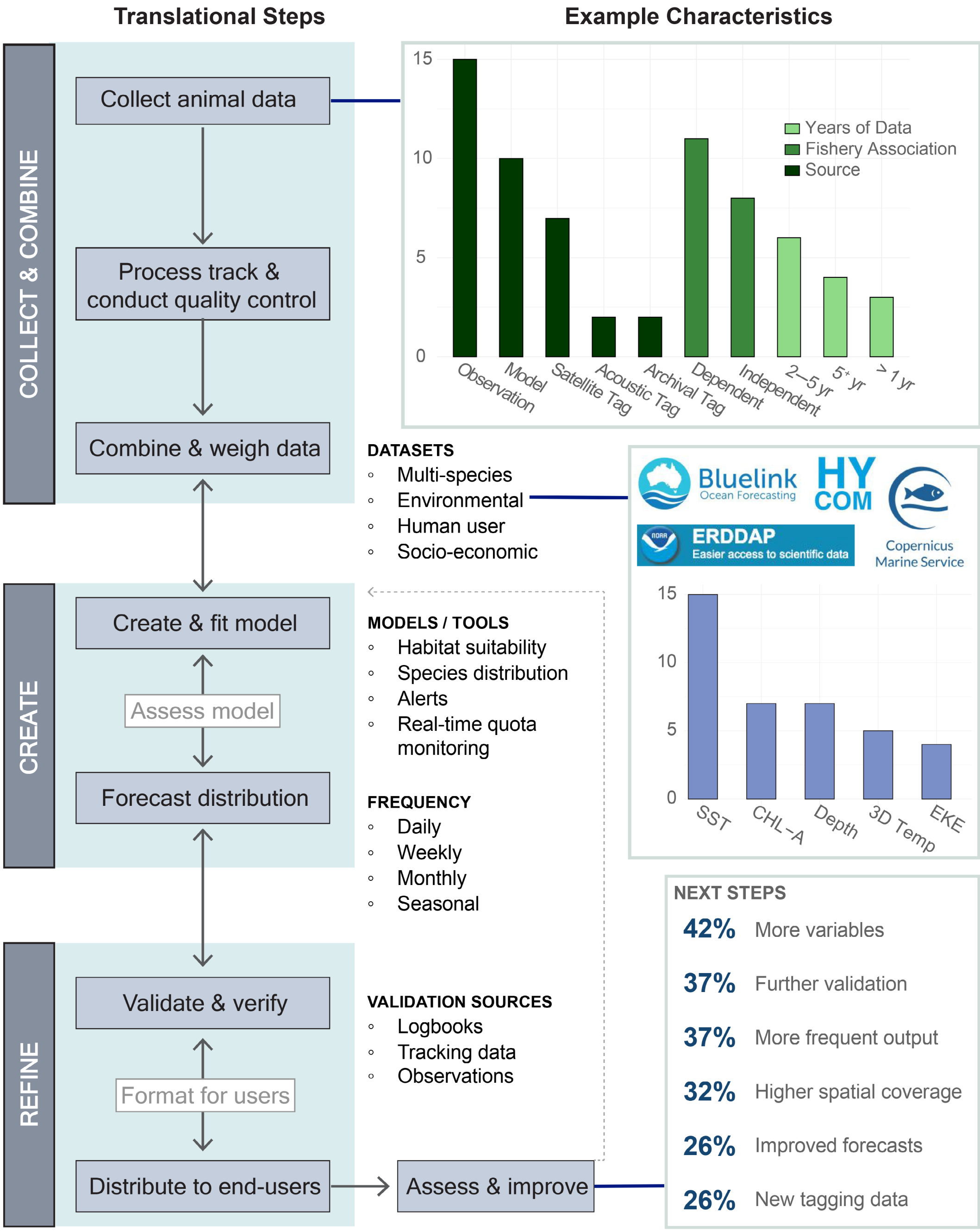

FIGURE 4 Summary of common steps involved in translating animal movement to use in dynamic ocean management (left) and corresponding characteristics of DOM examples (right). Steps are listed in a general order based on patterns recorded in DOM examples, though not all steps occur in this order or are applicable to each case of DOM. Steps with double-sided arrows between them represent that these steps are iterative and are likely to repeat several times based on new data incorporation or feedback of end users. The most common environmental variables used in examples include sea surface temperature (SST), chlorophyll-a (CHL-A), depth of water, temperature at depth (3D temp), and eddy kinetic energy (EKE).

present and near-real-time predictive maps. A common final step in operational DOM is ensuring that data and code are in a usable format for the next users (e.g., ensuring SDM is usable for those developing DOM model) or the ultimate end-users (distributional maps for fishers).

3.3 | Environmental data

Many studies ($N = 15$) used remotely sensed or blended environmental data products, alone or in combination with other sources. Most were accessed from NOAA's Environmental Research Division Data Access Program

(ERDDAP) (https://www.ncei.noaa.gov/products/weather-climate-models/using-erddap) or EU Copernicus Marine Environment Monitoring Service (CMEMS) (https://marine.copernicus.eu/). The remaining 4 examples did not include or report on the environmental data streams used. There were 21 different environmental variables used in the examples. The most common were sea surface temperature ($N = 15$), chlorophyll-a ($N = 7$), depth ($N = 7$), and temperature at depth ($N = 5$) (Figure 4).

The environmental data incorporated into DOM models varied based on management needs and technological capabilities. Relevant variables were chosen based on their known or anticipated impact on species occurrence. However, not all variables were applicable or accessible depending on management objectives and location. Environmental data underwent quality control and, in some instances, projection onto a standardized grid to aid interpretation and modeling. Mirroring the stages of animal data translation (Figure 4), models were compared, validated, and verified to ensure clear outputs for end users in near real-time. For instance, new environmental data inputs could prompt re-interpolation of final fishing or non-fishing locations, with updated maps provided to fishers at regular intervals (Howell et al., 2015). Notably, some DOM examples either lacked environmental data entirely or failed to elaborate on its utilization, hindering further stream characterization.

3.4 | Reviews

Of the 61 articles included in reviews, the majority (54%) examined multiple management types, or a management type closely related to DOM (e.g., adaptive management), while 10 articles mainly focused on DOM. The remaining 18 papers reviewed several elements critical to DOM,

TABLE 2 Themes and associated challenges, needs, and solutions identified in management from review articles.

Challenges	Need and/or solution
Static MPAs cannot fully protect HMS	Tailor seasonal or dynamic protections Improve tracking and prediction of dynamic features attracting HMS
Adequate reserve design	Improve data-driven spatial understanding of users (animal and human) and trade-offs Consider smaller, dynamic reserves to protect critical life-stages
International threats to HMS	Increase understanding of connectivity Protect migratory corridors Enhance international cooperation (policy-enabled)
Lack of data for adjustments	Increase collaborations and capacities: data collection, standardization, sharing, and analytical abilities Incorporate more local knowledge and experience
Adequate climate-resilient fisheries policies and governance	Adopt adaptive/dynamic and integrative management practices Improve understanding of perturbations and effects Boost inclusion of stakeholder needs Pinpoint and remove political barriers
Shifts in distributions: animals	Increase and optimize tracking to monitor and predict shifts More international collaboration, data sharing, promotion of public resources Relevant experimental/lab studies
Shifts in distribution: human users	Increase monitoring and predictions of fishing and recreational activity, shipping routes, etc. Use DOM tools to monitor and get input from users
Shifts in ocean currents and processes	Increase observations, especially at depth Strengthen forecast models Improve modeling of currents and ocean processes
Lack of real-time, short-term data	Increase technical capacity for data collection, sharing, analyses Incorporate more local knowledge of system
Potential fisheries collapse, income loss	Increase redundancies and buffer areas Strengthen link between biological and economic models Dynamic management

Note: Challenges, needs, and solutions associated with management that is climate-ready or that supports HMS were either assigned iteratively during extraction or emerged later as during topic modeling.

such as fisheries resilience under climate change, management of HMS, use of tracking data in conservation, and human impacts on marine predators. Migratory species were the sole focus of 9 review articles, while another 76% of reviews focused on a mix of both migratory and non-migratory species. Of these review articles, 8% ($N = 5$) did not refer to migratory species. Many reviews discussed the need for flexibility in management practices, the importance of regular review, integrated multi-scale stakeholder participation, and consideration of socio-economic factors in practice. Challenges, needs, and solutions under the specific context of management in support of HMS and under climate change identified in topic modeling were summarized (Table 2).

DOM was referred to favorably in 63% of reviews (i.e., mentioned as a potential solution to a given problem, at a minimum). 18 articles explicitly suggested DOM as a solution, while another 13 referred to incorporating more flexible and real-time data to address management issues. 18 articles had no mention of DOM or the practice of flexible management at all, while 4 articles cited examples of DOM but did not discuss them further. More than a third of the articles ($N = 23$) made no reference to the use of animal tracking data, while all others mentioned its utility in management for different uses at least once. Only 5 reviews specifically referenced the use of ABOS.

4 | DISCUSSION

Intentionally designed and coordinated animal tagging studies can collect and integrate data to complement and strengthen dynamic management approaches. Sustainable, data-driven dynamic management of highly migratory species requires multi-sector collaboration enabled by technological capacity and infrastructure for developing and maintaining models. Here, we reflect on shared themes across articles and outline researcher and practitioner opportunities to contribute to climate-resilient dynamic ocean management, summarizing key needs, gaps, and pathways.

4.1 | DOM definition and study limitations

The term "dynamic ocean management" was used more regularly after 2014, after the publication of several influential DOM defining articles (Lewison et al., 2015; Maxwell et al., 2015). However, the practice of dynamically managing marine resources itself has been implemented much earlier. While not formally referred to as "dynamic management" at the time, extractive human users of the marine environment have been dynamically altering their behavior (e.g., shifting fishing effort) to suit changing environments over centuries (Berkes et al., 2000; Cinner & McClanahan, 2006; Farchadi et al., 2024). Still, the number of articles reviewed may have been reduced by the lack of consistent term use to define DOM instances and limiting records to those published in English. DOM approaches that use tag data as well as a reflection of being in the comparative "early stages" of DOM adoption and standardization of terms, similar to other newer marine research fields as they gained popularity (e.g., marine protected areas). We interpret this as a key finding: currently, DOM applications are few compared to the general interest in the topic, as exemplified by the dominant number of review articles identified in the review procedure. This finding is important for understanding the current state of DOM research, suggesting that while there is significant interest and theoretical exploration in the field, there is a delay in practical implementation and empirical studies. Growing, focused efforts on applying and adopting DOM to address real-world scenarios will help bridge this gap. This will advance the field from predominantly theoretical discussions to practical, actionable strategies that can effectively manage marine resources.

Additionally, some coastal areas that are hotspots for HMS may have good tracking data available, but the environmental data products required for implementing these approaches may not have the appropriate spatial resolution, both in the present and for future projections. A lack of high-resolution environmental data and downscaling models in certain regions could hinder the accurate implementation of DOM-based approaches for HMS occurring there (Pozo Buil et al., 2021).

Successful operational and experimental DOM examples are characterized by a strong balance between economic interests and conservation goals, often heavily reliant on strong communication among parties and compliance. Nearly all examples highlight the importance of including socio-economic data in their models. Further analysis of these data streams is not undertaken in this study, though these factors emerged frequently during the extraction of retained articles, often in reference to outstanding DOM needs as well as to barriers in effective HMS management.

4.2 | Data requirements

Articles highlight the need for timely, consistent, and high-resolution data on animal movements, environmental variables, and human activities to inform effective dynamic management. The importance of understanding

HMS movements within the global ocean is stressed, which underlines the utility of tagging data and DOM applications for this purpose (Table 2). Animal tagging studies conducted with the intention of informing conservation must recognize the spatiotemporal dynamism of all system components: animals, environments, human users, and policies; instances of successful DOM integrate varied sources that reflect this.

Common sources of animal movement data are SDMs, direct application of tagging data, and fisheries-dependent data (e.g., logbooks, observer data) (Figure 4). Importantly, fisheries-dependent sources are used in 71% of cases where DOM achieves the stated goal. This utility supports previous findings that show that use of fishery-dependent data improves identification of temporal relationships between the probability of species presence and environmental variables (Pennino et al., 2016). Even if not used in generating the initial DOM product, fisheries observations and logbooks can be used to validate predicted occurrences of species of concern (Breece et al., 2021). The high utilization of fisheries-dependent data may be attributed to its relatively easy access and comprehensive information compared to costlier fishery-independent data, particularly for species in remote areas. However, it is essential to acknowledge potential biases associated with preferential sampling or fishermen behavior when validating models with these datasets. Very few reviewed examples utilize "real-time" animal movement data, with most relying on models informed by previously collected animal movement data. The application of real-time tag data in DOM remains an important next step for research and management (Figure 4). Still, we recognize that movement data are involved in only some DOM approaches, and several other datasets and types are used in successful DOM applications, many of which are not yet present in the published literature (e.g., reducing fishing pressure on striped bass in Chesapeake Bay during periods of intense heat) (Oestreich et al., 2020).

DOM-incorporated environmental data are primarily datasets available from open-source repositories, such as ERDDAP and CMEMS. A total of 21 different environmental variables are used across examples, selected according to specific ecological and management needs as well as availability for their respective study areas. Many of the environmental datasets have considerably fine spatial (1–20 km) and temporal (1–3 day) scales, especially widely used measures such as sea surface temperature and chlorophyll-a. Comparisons of skill with additional datasets is particularly important for operational DOM as increasing the number of products and sensors can result in more downtime for the tool (Hazen et al., 2017; Welch et al., 2018). Modeled ocean products have been suggested as a solution for this issue (Abrahms et al., 2019; Brodie et al., 2018). Data were often reprojected to match the resolution of the coarsest dataset, which ultimately determined the resolution of the final output in some cases, demonstrating the importance of enhanced high-resolution observing to measure a wider range of variables. Indeed, increased availability of high-resolution environmental data was identified as a need in many DOM examples. Incorporating downscaled, high-resolution environmental data that resolves local processes is crucial for improving regional habitat use models and projections, as demonstrated by a study that downscaled global climate models to capture fine-scale upwelling and biogeochemical dynamics in the California Current System (Pozo Buil et al., 2021).

In some instances, HMS (e.g., tuna, billfish) will aggregate in distinct groups and biogeographic classifications can be used for managing them within an ecosystem approach, if they reflect large enough regions for transboundary management (Todorovic et al., 2019). Moreover, a diverse management portfolio has been proposed, using a suite of adaptive, dynamic, and static approaches to address the varying scales of changing environmental conditions (Holsman et al., 2019). Enhanced observational methods allowing for high-resolution measurements at depth can help predict shifts in ocean processes, impacting some HMS with known associations to dynamic oceanographic features.

4.3 | Recommendations for the researcher

Overall, advancing dynamic management requires a multidimensional strategy focused on generating and translating timely, relevant data, expanding technical capacities, validating and adding value to decision-support tools, and strengthening collaborative processes. Targeting these interconnected needs would galvanize the uptake and impact of DOM for conservation.

4.3.1 | New data: Intentional design and co-production

Analysis of DOM examples revealed that additional data acquisition remains a strong need. More than half of examples underscored the need for more animal movement data, but fewer than half of them explicitly advocated for additional tagging data (Figure 4). This disparity demonstrates a crucial insight: while tagging data have traditionally served as a cornerstone of ecological research, they often do not constitute the sole solution for attaining the needed movement data for management efforts. Therefore, for novel tagging efforts to be relevant to management, it is imperative to discern whether such data are indeed required by managers or if the requisite information could be obtained from alternative sources, such as fisheries-derived datasets, local ecological knowledge, or existing tag data. For rare marine species, new fisheries-independent tracking data may be particularly important to collect, as they may provide one of the only reliable sources of movement information to inform dynamic management approaches (Hartog et al., 2011; Hazen et al., 2013). Integrating these tracking datasets with other data streams allows the delineation of important habitat areas and migratory corridors that can guide the implementation of appropriately timed and located management measures (Sequeira et al., 2019). If new tagging data are needed, researchers should consider prospects for early engagement with end-users. For instance, Australia's Eastern Tuna and Billfish Fishery (ETBF) management system collaborated with researchers deliberately to capitalize on existing tagging operations to gain more information on southern bluefin tuna (Hobday et al., 2010). Understanding and identifying such opportunities involves early engagement of researchers with DOM managers and the fishing community to craft specific research goals and approaches that will ultimately be useful to stakeholders.

High-quality co-production in dynamic management must be context-based (Norström et al., 2020). No one-size-fits-all approach exists; co-production must be iterative and tailored to the species, place, time, and users. Indeed, building capacity for co-production, collaboration, and co-operative partnerships is key to actionable knowledge practices (Clark et al., 2016) and to DOM's credibility, relevance, and success (Lewison et al., 2015). Marine users whose livelihoods depend on understanding ocean dynamics and their effects on catches are among the first to detect changes in the marine system. As such, marine fishing vessels can often act as ocean observing frontiers, taking early notice of changing stock dynamics and environmental variability (Bradley et al., 2019).

While co-production is often crucial to the DOM process, it can be very time intensive. Therefore, co-production may only occur during targeted engagement at vital stages like defining questions and interpreting outputs with local knowledge (Goethel et al., 2022). Time may also be ultimately saved by actively pursuing data sharing standards and common management frameworks that will facilitate future scaling of dynamic ocean management efforts. Development of open data policies, metadata protocols, and best practice guidelines for integrating data streams and engaging stakeholders is needed and may help streamline the initial steps in Figure 4 (Hazen et al., 2018; Sequeira et al., 2021). This balanced approach leveraging diverse data sources through standards and strategic co-production can strengthen DOM's robustness and applicability for conserving migratory species (Crear et al., 2021; Lewison et al., 2015).

4.3.2 | Collected data: Compiling, collaboration, and translation

Framing animal movement alongside the choice of environmental variables is a crucial step that facilitates the transition toward dynamic ocean management, bridging the gap between ecologists, researchers, marine users, and practitioners (Figure 4). Tag data were integrated with environmental datasets increasingly sourced from online open-access platforms. Considering interannual and interseasonal variability, and their accurate representation in models, is important for creating reliable forecasts and predictions to inform DOM strategies. The integration of tracking and environmental data is facilitated through coding software equipped with dedicated packages, enabling the development of dynamic management tools tailored to specific contexts (e.g., *rerddapXtracto* in R (Mendelssohn, 2019), *erddapy* in Python (Medrano, 2021)). Several existing DOM models have been strengthened by incorporating improved environmental data from wide-scale ocean observing methods (Breece et al., 2021; Hobday et al., 2010; Howell et al., 2015).

Collaboration to combine existing animal movement/occurrence datasets or efforts has demonstrated success, resulting in a more robust dynamic management product. For example, TurtleWatch initially utilized data only from satellite-tagged loggerhead turtles, providing valuable insights into their habitat preferences (Howell et al., 2008). These findings were then complemented by data from fisheries' logbooks, which recorded incidents of turtle bycatch over a 13-year period. Over time, TurtleWatch has expanded its scope, incorporating location estimates of other turtle species and engaging citizen scientists to report turtle encounters (Howell et al., 2015). Recognizing and acknowledging the importance of both streams of occurrence data is of incredible importance in balancing dynamics in collaborative work (Turnhout et al., 2020). Similarly, Whale Alert began with acoustic buoy data detecting nearby right whale calls and has since evolved into a shared platform among network members, benefiting mariners, shipping companies, biologists, and managers alike. End-user input can be invaluable in the selection of final variables included in the DOM model and output, given their familiarity with the marine environment (Kohut et al., 2013). Collaborative efforts among ecologists, data collectors, and end-users in the study area can yield a comprehensive understanding of the system's physical and human dynamics, as well as reveal any observational gaps.

Data translation succeeds through researcher–stakeholder relationships, user-centered design, and interdisciplinary exchange when facilitated by collaborators with suitable capacity (Figure 4). Existing relationships and communication between researchers and end-users can boost data translation and validation. For example, Atlantic sturgeon presence modeled in the Delaware Bay was initially plagued by persistent satellite data loss due to cloud cover over the study area, limiting the usefulness of the species distribution model for commercial fishers and state managers (Breece, 2017). By engaging user groups through meetings and soliciting feedback, researchers tailored the updated product to meet stated needs on resolution, timescales, and length (Breece et al., 2021; Kohut et al., 2013). If the end product confuses or lacks accessibility or usefulness, translation is futile (Welch et al., 2019). While researchers can be reluctant to move into interdisciplinary spaces, marine ecologists can benefit cross-discipline engagement to gain a better understanding of how other data are collected and best practices for working with these datasets. This facilitates movement along in the general translation process (Figure 4).

4.3.3 | Use of animal-borne sensors

Applying ABOS data can effectively synchronize animal movement patterns with spatiotemporal environmental variables, offering valuable inputs for DOM. However, this application remains largely untapped, with only two examples explicitly using tag-derived data (Hobday et al., 2010; Hobday & Hartmann, 2006). In some instances, this application was limited by the constraints of the tag model used. However, many DOM examples used ABOS-equipped tags but did not utilize the environmental data collected despite their potential value. However, the use of ABOS data may not always be applicable to management or study goals. For instance, catch-associated presence data may better represent feeding preferences and species overlap with fishing as compared to continuous tag measurements representing general occurrence (Hobday et al., 2010). Still, ABOS data holds potential to boost ocean–atmosphere monitoring in remote areas and inform DOM through improved forecasting, detecting climate signals, and elucidating high-resolution environmental drivers of movements (Alos et al., 2022; Harcourt et al., 2019; Hussey et al., 2015). Specifically, ABOS data permit understanding of physiological constraints and behavior-specific environmental preferences relevant to conservation and fisheries (Hobday & Hartog, 2014). Furthermore, there are differences in spatial and temporal resolution between the tag's measure of a variable and the corresponding value reported in ocean models, especially if the ocean product is coarse (Hobday et al., 2010). While insufficient alone for forecasts, ABOS could help inform predictive layers in data-assimilative models like regional ocean modeling systems (ROMS) (Shchepetkin & McWilliams, 2005) and help to validate animal distribution patterns (Figure 5). ROMS has been used in recent studies to determine habitat suitability and threat risk for HMS (Abrahms et al., 2019) and to examine habitat compression indices (Schroeder et al., 2022). Careful consideration of when and how to integrate ABOS data in dynamic management products moving forward is important.

4.3.4 | Technology: Enabler and barrier

Increasing technical expertise and capacity was noted by many examples as an ongoing need and enabling factor for effective development and application of dynamic management tools. As noted in the above sections, technical know-how is critical throughout the translational process (Figure 4). Over half of the examples used species distribution models to predict species occurrences. In building and validating distribution models, trade-offs between model and technical complexity, number of data inputs, and interpretability should be carefully considered (Crowder & Norse, 2008). The type of movement data available for the species of interest will help guide the building of appropriate, robust SDMs (Braun, Arostegui, et al., 2023).

While more complex dynamic management models may provide better predictive performance, they can also be more difficult to interpret, lead to more opportunities for data gaps and failures in operationalization, delays, or failures, and require additional technical know-how and analytical abilities. Mature DOM operational models should have built-in protocols for when near real-time data sources are not available in time for product release (Welch et al., 2019). In contrast, simpler models may be more interpretable and have less risk of data delays but may not capture the full complexity and predictability of the system being studied (Lewison et al., 2015). Additionally, ecosystem models can be employed as a complementary tool to further investigate the implications of DOM-based SDM outputs, providing a more comprehensive understanding of the ecological dynamics and interactions within the studied system. Importantly, the technical capacity of end-users to interpret and utilize model outputs should also be evaluated, including timely

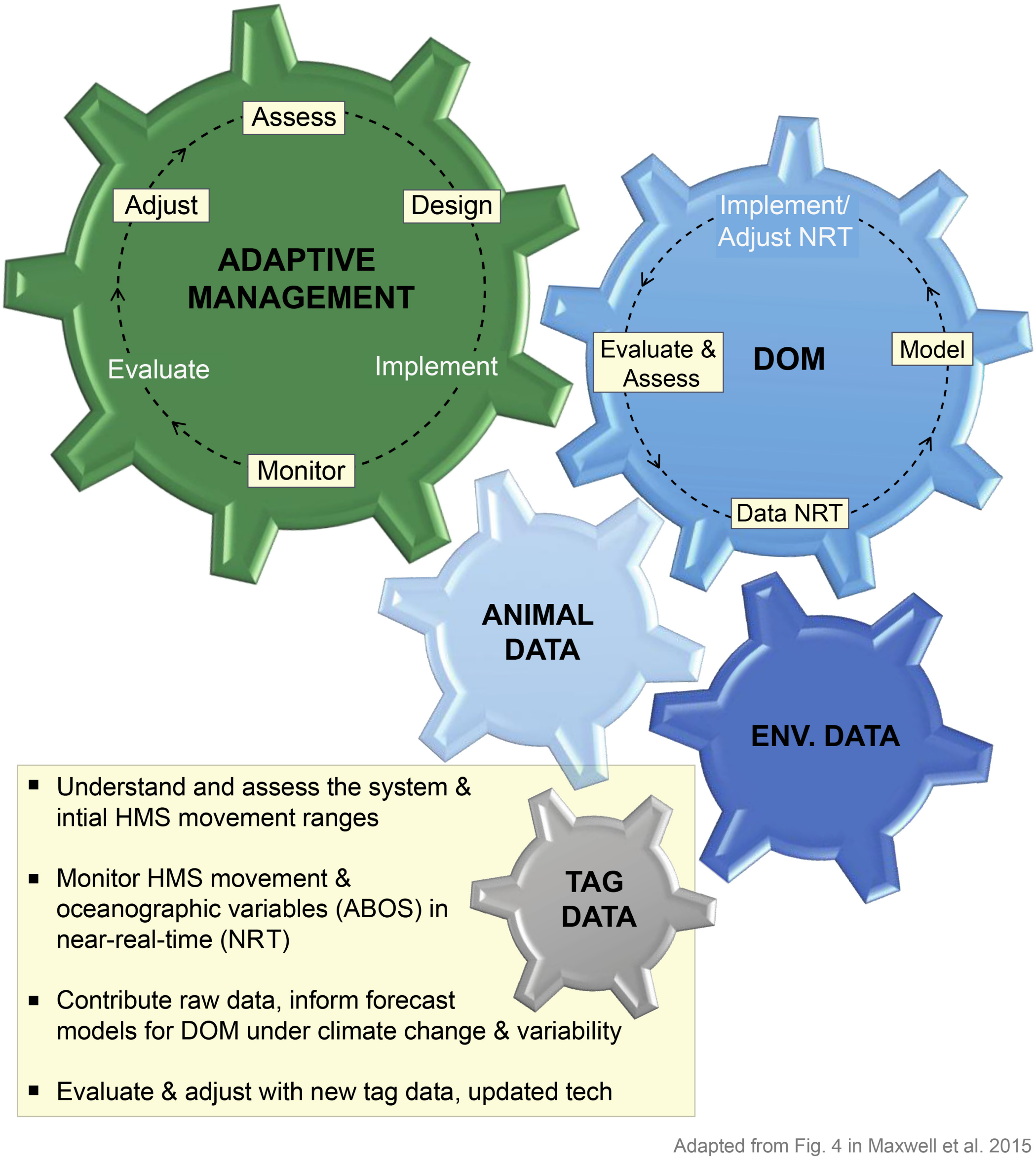

FIGURE 5 Opportunities for contributing tag data to adaptive management, DOM, and its data streams. Elements required by adaptive management and DOM in which tag data can be especially valuable and utilized are highlighted in light yellow.

access to receive any technological output (e.g., cell phone, internet connection, etc.).

4.4 | Pathways for the practitioner

While intentional design and co-production are discussed above, both are essential for practitioners to consider as well. Engaging in co-production involves the collaborative development of management strategies and tools with scientists, managers, and stakeholders, ensuring that the outputs are practical and relevant. Analysis of DOM examples has revealed that additional data acquisition remains a strong need (Figure 4); therefore, practitioners may be well-suited in some instances to help guide researchers toward filling data gaps.

4.4.1 | Climate resilience of dynamic management efforts

Many articles stress that management must be responsive to climate change and its impacts and capable of incorporating real-time, small-scale changes that can amount to large-scale spatial shifts (Table 2, Figure 3). Key challenges include the lag in fisheries adapting to the shifting distributions of target species and their prey because of logistical constraints, social structures, management bodies, and political boundaries. This lag can result in both conservation concerns and economic losses (Table 2). Studies exploring interactive and cumulative effects of climate change and other stressors in ecosystems could help predict individual HMS responses in situ (Lewison et al., 2014; Turschwell et al., 2022). Further, targeted sampling at distributional fringes could allow earlier detection of climate-driven range shifts in HMS or their prey (Goethel et al., 2022). In addition to tagging data, alternative methods such as citizen science/public sightings, eDNA, or remote underwater video can be employed to detect early emergence or absence of an HMS species in a given area (McDonnell et al., 2020).

Just over half ($N = 10$) of DOM examples mentioned climate resilience of management strategies, while 9 did not, highlighting a growing but incomplete integration of climate-resilience and readiness considerations in marine management systems. Management systems could be enhanced in this area by implementing adaptive monitoring, expanding temporal or spatial scale of measurements, and increasing internal capacity to adapt strategies quickly based on emerging climate effects (Table 2 and Figure 5). Additionally, while climate change adaptation is crucial, other immediate concerns such as market changes, input costs, labor availability, community attitudes, and conservation policies often take precedence for fishers and marine managers (Creighton et al., 2016). Still, it would be valuable for practitioners to incorporate near-term forecasts and climate change projections into their marine management practices to effectively protect marine species in rapidly changing environments.

4.4.2 | Scale and format of predictions

When implementing DOM, practitioners must consider the temporal and spatial scale of predictive outputs as well as working with scientists to format output to optimize their utility in specific areas. For example, daily predictive distributional maps or alerts for single species, such as sturgeon or striped bass, can provide high-resolution, up-to-date information crucial for managing species that are highly mobile or sensitive to episodic environmental events, like marine heatwaves (Breece et al., 2021). Further, multi-species predictive maps, like those produced by EcoCast, integrate data for several species, optimizing fishing locations and times and helping to reduce bycatch (Hazen et al., 2018). Integrated maps were important in this case to reduce efforts on singling out leatherback turtles when fishing or in unintended consequences such as tourism. Additionally, the grid system used by scallop fishermen through the SMAST program offers a simplified approach where daily advisories denote fishing areas with varying levels of bycatch risk for species like yellowtail flounder. This system uses a color-coded grid (red for high, yellow for medium, and green for low bycatch areas) that is easy to interpret and less resource-intensive, ensuring that crucial information is accessible without extensive analysis (Lewison et al., 2015; O'Keefe & DeCelles, 2013). Similar to the issues raised above regarding technology, more complex model outputs can also be more difficult for end-users to interpret, leading to misunderstandings or non-use. Therefore, the format and update frequency should strike a balance between the need for detailed data and the risk of overcomplication, ensuring that the information remains accessible and actionable without requiring excessive technical know-how or analytical abilities. By tailoring the scale and format of predictive outputs to their specific operational context, practitioners can enhance the effectiveness of DOM strategies, ensuring they are both practical and impactful in addressing the complex challenges of marine resource management.

4.4.3 | Challenges in implementation

Optimizing spatial HMS protection presents multifaceted challenges, demanding a balance between conservation priorities and economic interests (Table 2). Ineffective reserve designs may persist due to a lack of updated connectivity information (Hidalgo et al., 2017), emphasizing the importance of integrating connectivity and space use assessments across management stages, from initial evaluations to adaptive adjustments in DOM (Figure 5). For nearshore HMS species, moderately sized reserves offer promise in containing adult movement, with strategic placement along habitat boundaries, like reef edges, enhancing conservation outcomes (Gaines et al., 2010). Many articles emphasize that static MPAs are often not effective enough for HMS with dynamic habitat requirements (Crespo, 2020; Game et al., 2009), underscoring the need for seasonal MPAs and dynamic protected areas. Still, other studies urge that the value of static protective measures should not be ignored and can even be combined with DOM approaches to maximize HMS conservation, particularly in regions where HMS aggregate near static features such as coral reefs, within spawning areas, or those frequented by vulnerable juveniles (Green et al., 2014; Lewison et al., 2015; Norse et al., 2005; Roberts & Sargant, 2002). Technology-based solutions, including animal telemetry, buoy and glider data (Alos et al., 2022; Hussey et al., 2015), and satellite monitoring of vessel activities, offer valuable insights into ongoing shifts in animal and human use of marine areas (Norse et al., 2005). Technological challenges and solutions are elaborated upon in Section 4.3.

Adequate translation of tagging data for interdisciplinary collaborators and/or end-users is critical to its use in DOM but can be challenging. For researchers seeking to ensure the utility of their data, early consideration of, and involvement and input in translational steps (Figure 4), is important. Many spatial ecologists collect and analyze tag data to meet study goals but rarely complete all translational steps required to ensure data can be taken up into management (Hays et al., 2019). Even when tracking findings are published, the accessibility or lack of standardization of these data can be a barrier to their inclusion in other efforts (Hays et al., 2019; Sequeira et al., 2021), pointing to a need for improvement in data collection programs (Table 2). While some researchers may complete an efficient translation of data from start to finish, others may require assistance in doing so or may need to outsource this task entirely.

Building stakeholder trust and confidence in dynamic approaches is a concern, pointing to the need for validation, forecasting capabilities, and processes to facilitate manager and fisher participation (Table 2) (Breece et al., 2021; Hobday et al., 2010; McInnes et al., 2019). In many cases, DOM approaches that are voluntary and co-developed with the fishing community may be as successful at reducing bycatch as mandatory DOM triggered closures (Lewison et al., 2015; O'Keefe & DeCelles, 2013). Enhancing collaboration and communication channels among scientists, managers, and stakeholders is identified as an area for improvement (Crear et al., 2021). Incorporating cross-discipline workshops in the management plans would help with this; these could serve both to share information with fishermen and to validate models with their on-water experience, the latter presenting an opportunity for iterative co-production at a later stage of DOM.

As highlighted in Section 4.3, increased reliance on technology can introduce potential hindrances, such as system failures or lack of access. Indeed, the wider adoption of DOM may be hindered if stakeholders or managers perceive it as unsuitable for their specific situation or overly data-and technology-intensive, often due to preconceptions about what "dynamic management" entails. Fisheries lacking data or technology may face challenges implementing DOM, but delaying action until ideal conditions are met risks missed opportunities and emerging problems (Planque et al., 2010). Local knowledge and participatory co-management hold strong potential to facilitate adjusting management amidst change (Goethel et al., 2022; Johnson & Welch, 2010). With mounting changes, prioritizing local stewardship to collect targeted data with existing resources can directly address management objectives (Goethel et al., 2022). Rather than awaiting comprehensive assessments or perfect dynamic approaches, action can begin by leveraging local expertise through participatory processes to gather key information, guiding incremental improvements.

Transitioning from research demonstration to government adoption of DOM programs is critical, but certain factors can curtail this transition. For instance, research demonstrations often highlight the potential of DOM, but government adoption requires sustained commitment and integration into existing management frameworks. Successful examples include WhaleWatch and NOAA Greater Atlantic Regional Fisheries Office's adaptive slow zone protections for right whales, which have been embraced by government agencies (NOAA, 2020). In contrast, other programs, like certain regional monitoring efforts, have struggled to gain, maintain, or expand similar government support and funding (Breece et al., 2021; Garrison et al., 2022; Koubrak et al., 2021). Further, government agencies often resist DOM due to the need for permanent infrastructure, computing resources, and dedicated analysts. This resistance stems from the competition for resources with traditional monitoring programs. Overcoming this hurdle requires demonstrating the long-term cost-effectiveness and conservation benefits of DOM (Lewison et al., 2015; Welch et al., 2019).

4.5 | Conclusions

Overcoming barriers faced in fisheries management requires new and integrative ways of generating, sharing, and applying knowledge (Moon et al., 2021). Here, we provide guidance and considerations for leveraging dynamic ocean management as an effective tool in the conservation of highly migratory species facing threats from climate change and other global pressures. We find that the success of dynamic management in marine systems is underpinned by the need for data integration, identifying and removing implementation barriers, and facilitating research translation for management uptake. The feasibility and practicality of implementing dynamic management approaches are context-dependent, especially given existing regulatory frameworks and socio-economic constraints in the fishing industry, and therefore dynamic management may not be appropriate to apply in all instances of HMS conservation. However, the availability of the requisite technology is increasing, with novel tools emerging frequently to support data translation, management practices, and climate forecasts (Bakker, 2022).

Ultimately, effectively dynamically managing HMS under climate change will require collaboration between multiple stakeholders as well as the incorporation of management tools and outputs to meet diverse needs (Crear et al., 2021; Hazen et al., 2018; Maureaud et al., 2021). While core ingredients exist, tailored data streams are needed (Lewison et al., 2015). Researchers can intentionally design tagging studies to complement fisheries-dependent and emerging data sources, in support of dynamic management translation and ongoing validation of SDMs and other DOM end-products. Tracking data, especially for rare species, can inform multiple management stages when integrated via communication with stakeholders. Harnessing advancements in animal-borne telemetry and climate forecasting is key to enabling climate-resilient dynamic management models and a more sustainable future for vulnerable highly migratory species.

AUTHOR CONTRIBUTIONS

Study design and conceptualization: All. *Data collection, coding, and analysis*: L. H. M. *Figures design and production*: L. H. M. and K. J. M. *Interpretation*: All. *Original draft*: L. H. M. *Review and editing*: All.

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DATA AVAILABILITY STATEMENT

A list of articles reviewed and extraction templates are included in the Supporting Information.

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SUPPORTING INFORMATION

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