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It is past time to use ecosystem models tactically to support ecosystem-based fisheries management: Case studies using Ecopath with Ecosim in an operational management context

J. Kevin Craig[1] | Jason S. Link[2]

[1]National Marine Fisheries Service, Southeast Fisheries Science Center, Beaufort Laboratory, Beaufort, North Carolina, USA

[2]National Marine Fisheries Service, Woods Hole, Massachusetts, USA

Correspondence
J. Kevin Craig, National Marine Fisheries Service, Southeast Fisheries Science Center, Beaufort Laboratory, 101 Pivers Island Road, Beaufort, NC 28516, USA.
Email: kevin.craig@noaa.gov

Abstract

The implementation of ecosystem management requires ecosystem modelling within the context of a natural resource management process. Ecopath with Ecosim (EwE) is the most widely used modelling platform for investigating the dynamics of marine ecosystems, but has played a limited role in fisheries management and in multi-sector resource decision-making. We review 10 case studies that demonstrate the use of EwE to support operational resource management. EwE models are being used to inform tactical decision-making in fisheries and other ocean use sectors, as well as to identify key trade-offs, develop appropriate policy objectives, and reconcile conflicting legislative mandates in a variety of ecosystems. We suggest the following criteria to enhance the use of EwE and other ecosystem models in operational resource management: (1) a clear management objective that can be addressed through modelling; (2) an important trade-off and a receptive policy context amenable to trade-off evaluation; (3) an accessible and well-documented model that follows best practices; (4) early and iterative engagement among scientists, stakeholders, and managers; (5) integration within a collaborative management process; (6) a multi-model approach; and (7) a rigorous review process. Our review suggests that existing management frameworks are as much or more of a limitation to the operational use of EwE than technical issues related to data availability and model uncertainty. Ecosystem models are increasingly needed to facilitate more effective and transparent decision-making. We assert that the requisite conditions currently exist for enhanced strategic and tactical use of EwE to support fisheries and natural resource management.

KEYWORDS
ecosystem approaches to fisheries, EwE, operational models for management, resource decision-making, strategic and tactical advice, trade-off analysis

1 | INTRODUCTION

A central tenet of ecosystem management is identifying trade-offs among multiple ecosystem goods and services and the attendant consequences of those trade-offs for biological, economic, and social objectives (Fogarty, 2014; Hilborn, 2011; Larkin, 1996; Link, 2010a; Link & Marshak, 2019; McLeod & Leslie, 2009; Pikitch et al., 2004). Failure to consider trade-offs can lead to unintended management outcomes, unrealistic expectations among stakeholders, and further degradation of marine ecosystems (Andersen et al., 2015;

Holsman et al., 2020; Karnauskas et al., 2021; Siple et al., 2019). A broader consideration of the interactions among ecological dynamics, socio-economic factors, and governance systems is needed to facilitate more effective resource management and decision-making (Arkema et al., 2006; Dickey-Collas, 2014; Harvey et al., 2017; Levin et al., 2009; Marshall et al., 2018; Stephenson et al., 2017). In response to these concerns, an ecosystem approach to marine resource management is a stated goal of many nations (U.S. Ecosystem-Based Fisheries Management Road Map, NOAA, 2016; European Union (EU) Common Fisheries Policy, Jennings & Rice, 2011; EU Marine Strategy Framework Directive (MSFD), Ramírez-Monsalve et al., 2016; Australia's Ocean Policy, Vince et al., 2015; Canadian Oceans Act, Jessen, 2011), with articulated principles and best practices for developing ecosystem approaches now codified by many intergovernmental organizations (FAO, Garcia et al., 2003; IUCN, Rodríguez et al., 2015; UNEP, Ferreira et al., 2022; ICES, Ballesteros et al., 2018; PICES, Kim et al., 2014).

Ecosystem approaches vary along a continuum from single species management with ecosystem considerations to holistic, ecosystem-based management (Dolan et al., 2016; Link & Browman, 2014). On one end of the spectrum, single species fisheries management is focused on single stocks with no explicit ecosystem considerations, though ecosystem processes often can be implicitly incorporated (Burgess et al., 2017; Methot, 2009; Plagányi & Butterworth, 2004). The ecosystem approach to fisheries (EAF) maintains a focus on single stocks but includes explicit consideration of one or more ecosystem processes, such as oceanographic effects on recruitment (Tolimieri et al., 2018) and predator effects on natural mortality (Dorn & Barnes, 2022; see also Marshall et al., 2019). Similar to EAF, ecosystem-based fisheries management (EBFM) focuses solely on fisheries, but considers the entirety of the natural resource system (e.g., multiple target and bycatch species and their predators and prey), including multispecies interactions and environmental drivers that influence the broader community or ecosystem (Hollowed et al., 2000; Karp et al., 2023; Link, 2018; Plagányi et al., 2014). Ecosystem-based management (EBM) is a holistic approach that extends beyond fisheries to include the objectives and trade-offs associated with multiple ocean use sectors (e.g., petroleum extraction, aquaculture, renewable energy; Arkema et al., 2006; Ruckelshaus et al., 2008; Long et al., 2015). The common underlying principle of these approaches is that effective resource management increasingly requires consideration of a more comprehensive range of biological, socio-economic, and institutional factors related to human use of the ocean.

The practical implementation of ecosystem approaches to management almost always requires some form of ecosystem modelling within the context of a natural resource management process (Collie et al., 2016; Espinoza-Tenorio et al., 2012; Fulton et al., 2011; Hollowed et al., 2011; Lehuta et al., 2016; Pascoe et al., 2017; Plagányi et al., 2014; Townsend et al., 2019). Decision-makers rely on the outputs from models to (1) understand the past, current, and potential future state of living marine resources, (2) evaluate the likely outcome of alternative policy options, (3) explore trade-offs that arise from ecological processes, management interventions, or among stakeholders, and (4) develop strategic and tactical resource management advice. Ecosystem models include a range of qualitative and quantitative representations of all or selected parts of an ecosystem and typically include effects such as environmental variability, species interactions, and socio-economic factors.

We refer to models that are used to support and inform resource management as 'operational models'. Operational models are characterized by (1) use of established methodological approaches and best practices during model development, (2) regular use of the model to provide information in support of a resource management process, (3) use of the most recently available data that has been quality-controlled, archived, and is easily accessible, (4) model outputs that can inform actionable choices from a defined set of alternatives, and (5) ideally, evaluation of trade-offs among ecological, socio-economic, and policy objectives. Operational models are also regularly updated using established procedures and their outputs are familiar to decision-makers. For example, the International Council for the Exploration of the Sea (ICES) develops 'key runs' using reviewed EwE models that are routinely updated and used to inform ecosystem status, stock status, and resource allocation decisions (ICES, 2019).

Ecosystem models can be used to provide both strategic and tactical management advice as well as provide the context within which management decisions are considered. Strategic and tactical applications are two different but related aspects of the operational use of ecosystem models (Collie et al., 2016; Gavaris, 2009; Plagányi et al., 2014). Strategic model applications are related to decisions about *what* will or can be done to achieve specific goals and objectives, while tactical model applications are related to *how* the specific strategy will be implemented, usually via short-term decisions that can be adjusted on a regular basis (Gavaris, 2009). Strategic applications are typically focused on relatively long time scales (e.g., 5–20 years) while tactical applications are focused on relatively short time scales (e.g., 1–5 years). For example, a strategic decision has been made in many jurisdictions to maintain fishing mortality at levels that will support the long-term maximum sustainable yield (MSY) from a stock, while a tactical decision is the short-term adjustments to catch limits needed to maintain this fishing mortality rate. While the use of ecosystem models in an operational resource management context is increasing, they have generally played a limited role in the decision-making process for most fisheries and ecosystems (Cowan et al., 2012; Karp et al., 2023; Skern-Mauritzen et al., 2016).

Ecosystem models that focus on food webs attempt to understand how trophic interactions affect the flow of matter and energy among different species and functional groups in aquatic ecosystems (Belgrano et al., 2005). Ecopath with Ecosim (EwE) is the most widely used food web modelling approach in marine ecosystems (Christensen & Walters, 2004; Colléter et al., 2015; Pauly et al., 2000; Polovina, 1984; Steenbeek et al., 2016; Walters et al., 1997). Ecospace is a spatial representation of EwE that allows for the movement of represented groups (Steenbeek et al., 2021; Walters et al., 1999). EwE explicitly incorporates trophic interactions among multiple species and functional groups, while the broader food web is simultaneously constrained by the conservation of mass. As a result, EwE can be used to evaluate the effects of bottom-up (Piroddi et al., 2021), top-down (Christensen & Pauly, 2004), and middle-out (Lamb et al., 2019) processes on various components of the ecosystem. These characteristics make EwE particularly useful for quantifying trade-offs that arise from natural or anthropogenic perturbations or management interventions, disentangling direct and indirect effects that are mediated through food web interactions, and assessing the cumulative impacts of multiple anthropogenic stressors on marine ecosystems (Christensen & Pauly, 2004; Coll et al., 2015; Villasante et al., 2016). As such, EwE models can help decision-makers understand the range of possible ecosystem responses and trade-offs that can occur due to human activities. EwE also has a large and collaborative user community with hundreds of models constructed to address an increasing array of issues (Colléter et al., 2013, 2015), multiple symposia and syntheses to document and evaluate technical advances and model uses (Christensen & Pauly, 2004; Coll et al., 2015; Villasante et al., 2016), free and easily accessible software with tested applications, modular subroutines, technical support (www.ecopath.org), and diagnostic and best practices protocols (Ainsworth & Walters, 2015; Heymans et al., 2016; Lassalle et al., 2014; Link, 2010b; Steenbeek et al., 2018). Hence, EwE is well-positioned for operational use in fisheries and in natural resource management in general.

In this paper, we review selected case studies where an Ecopath, Ecosim, or Ecospace (hereafter 'EwE') model has been developed within an operational context to inform fisheries or multi-sector resource management. Prior reviews of EwE models have focused on use of the model over decadal time scales (Colléter et al., 2015), applications in ecosystems of particular interest (Coll & Libralato, 2012; Woodstock & Zhang, 2022), technical aspects of the model (Plagányi & Butterworth, 2004), applications to particular species groups (e.g., predatory fishes, Christensen et al., 2003; jellyfishes, Lamb et al., 2019; forage fishes, Pikitch et al., 2014), and the development of management-relevant outputs (Heymans et al., 2014). The advantages and limitations of EwE as an operational tool to support fisheries and multi-sector resource management have rarely been considered. Our premise is that developing a functional model is only one step required for operational use, and so we emphasize issues beyond the technical aspects of model development, testing, and validation (Plagányi & Butterworth, 2004). While we focus on EwE models because the platform has many characteristics amenable to operational use, our conclusions are relevant to other types of ecosystem models as well. Our primary assertion is that the requisite conditions for enhanced operational use of EwE and other ecosystem models exists, and we recommend explicit criteria to facilitate the use of these models to support fisheries and natural resource management.

2 | CASE STUDIES

We describe 10 case studies where an EwE model is being used to inform a fisheries or multi-sector resource management issue. The case studies are mostly taken from the primary literature and based on ecosystems in North America and Europe, though we include one case study from a developing region and one based on gray literature. We sought examples that were developed within the context of different levels of ecosystem management (EAF, EBFM, EBM; Dolan et al., 2016) and that addressed a broad range of issues, including fisheries management, pollution and habitat, multi-sector use of marine ecosystems, and conflicting policy objectives or legislative mandates. The case studies are ordered along a continuum from EAF (2 examples) to EBFM (4 examples) to EBM (4 examples). For each cases study, we provide a brief synopsis of the management issue, how EwE models are informing the issue, and notable outcomes, lessons learned, and challenges. Given the central role that trade-offs play in resource management, we also note the type of trade-off that motivated each case study.

2.1 | Ecosystem approaches to fisheries

2.1.1 | Forage fisheries—Trade-offs in the management of Atlantic Menhaden

The management issue—Atlantic Menhaden (*Brevoortia tyrannus*, Clupeidae; hereafter 'Menhaden') is an important forage species along the US Atlantic seaboard that is the target of a large industrial fishery (Ahrenholz et al., 1987). The Atlantic States Marine Fisheries Commission (ASMFC) has the dual objectives to simultaneously support the directed commercial fishery for Menhaden and to sustainably manage several recreationally harvested piscivores that depend on Menhaden for food, including Striped Bass (*Morone saxatilis*, Moronidae), Weakfish (*Cynoscion regalis*, Sciaenidae), and Bluefish (*Pomatomus saltatrix*, Pomatomidae) (Anstead et al., 2021). Trade-offs in the management of forage species to simultaneously support directed fisheries and important piscivores is a concern in a number of marine ecosystems (Essington & Munch, 2014; Hilborn et al., 2017; Pikitch et al., 2014; Siple et al., 2019; Tyrell et al., 2011).

How are EwE Models informing the issue? An EwE model of intermediate complexity for ecosystem assessments (MICE, Chagaris et al., 2020) was developed from an existing, more complex EwE model (Buchheister et al., 2017) as part of a multi-model approach to provide quantitative information on the trade-off between fishery removals of Menhaden and biomass of recreationally harvested piscivores, particularly Striped Bass (Drew et al., 2021). The MICE EwE model was ultimately chosen to provide tactical management advice because it adequately captured the relationship between Striped Bass biomass and Menhaden fishing mortality, gave qualitatively similar results to the other models (full EwE, multi-species statistical catch-at-age, and two surplus production models; Drew et al., 2021), and was relatively efficient to run and evaluate. The ecological reference point (ERP) from the MICE EwE model was the Menhaden fishing mortality rate (F) that maintained striped bass biomass (B) at the target level when Striped Bass was fished at their target F and all other species were fished at status quo levels (Chagaris et al., 2020). This ERP (i.e., Menhaden F) was then fed back into a single species catch-at-age model to generate catch advice for Menhaden that would simultaneously provide sufficient forage to support predator populations while also supporting the Menhaden fishery.

Outcomes, lessons learned, and challenges: The catch advice based on the ERP from the MICE EwE model was adopted by the ASMFC for the 2021 and 2022 fishing seasons (ASMFC, 2022). The use of EwE to provide tactical fisheries management advice was facilitated by the existence of a clear trade-off (Table 1), explicitly defined management objectives, an engaged stakeholder community, and a well-defined management process (Anstead et al., 2021; Drew et al., 2021; Howell et al., 2021). The approach leveraged the ability of EwE to account for direct and indirect trophic interactions and the ability of the single-species catch-at-age model to account for the details of Menhaden population dynamics (e.g., recruitment variability, fleet selectivity). By focusing on two species, the EwE model outputs could be presented in terms that were familiar within the existing management framework (Menhaden F and Striped Bass B). The consideration of five structurally different models using a common set of data was particularly beneficial during the review process and facilitated confidence in the model results among stakeholders. However, the time and resources required to develop and review multiple ecosystem models was a challenge (~5 years), despite a long-history of coastwide management during which Menhaden's role as a forage fish was well known (Anstead et al., 2021). Tailoring the model to a specific purpose (i.e., quantifying trade-offs between Menhaden F and Striped Bass B) facilitated its use for tactical management advice but may have limited a more comprehensive exploration of other trade-offs or indirect effects, and it was assumed that conditions favourable for Striped Bass would also be favourable to other piscivores of concern (e.g., Weakfish, Bluefish). Further, while management of Menhaden and several recreationally harvested piscivores are under the purview of the ASMFC, species-specific regulations are still determined by separate species management boards. As a result, the extent to which the assumptions under which the ERP was developed (i.e., sustainable harvest of Striped Bass and status quo harvest of other species) will be met through effective management of other relevant species is not yet known.

2.1.2 | Informing sustainable fishing rates—The Irish Sea groundfish fishery

The management issue—Article 13 of the EU Reformed Common Fisheries Policy (CFP) calls for the implementation of ecosystem approaches to fisheries management in EU waters (Prellezo & Curtin, 2015). Several commercially important fish stocks in the Irish Sea have declined in recent years (Herring, *Clupea harengus*, Clupeidae; Cod, *Gadus morhua*, Gadidae; whiting, *Merlangius merlangus*, Gadidae; *Nephrops norvegicus*, Nephropidae), and stakeholders have expressed concern regarding the lack of recovery despite reductions in fishing effort (Bentley et al., 2020, 2021). Changes in temperature, phytoplankton, and secondary productivity (e.g., large

TABLE 1 Key trade-offs addressed for each of the 10 case studies.

Level of EM	Case study	Key trade-offs
EAF	Forage Fisheries—Trade-offs in the Management of Atlantic Menhaden	• Direct commercial harvest versus forage fish to support recreationally important piscivores
	Informing Sustainable Fishing Rates—The Irish Sea Groundfish Fishery	• Maximizing yield and associated food production versus impaired reproductive potential of individual commercially harvested stocks
EBFM	Mixed Species Fisheries—Is MSY Achievable?	• Maximizing yield and associated food production versus overfishing less productive stocks within a multispecies complex
	Discarding—The EU Landing Obligation	• Discards to support human uses (e.g., industrial fish meal) versus support for marine scavenger populations, some of which are protected species • Current yield in the form of landed discards versus potential future yield of returned discards that survive and grow to a larger, more valuable size • Fisher costs of processing discards versus revenues and employment in fish meal processing and other economic activities that use otherwise discarded fish
	Reconciling Single and Multispecies Models—The Northeast Groundfish Assessment Review	• Maximizing single species yield versus ecosystem overfishing
	Limited Data, Models, and Governance—The African Great Lakes	• Maximizing fishery economic value versus food security versus employment opportunities • Maximizing fishery objectives versus preserving ecosystem structure and productive capacity
	Fishing, Habitat, and Climate Effects on Coral Reef Ecosystem Services	• Land-based human activities versus maintaining the integrity of coral reefs • Anthropogenic activities that increase temperatures versus preservation of coral reef habitats • Non-extractive use of coral reef ecosystems (e.g., recreational diving) versus extractive use (e.g., commercial and recreational fishing)
EBM	Wetland Restoration—Mississippi River Sediment Diversions	• Restoring wetlands versus support of habitat-dependent estuarine species and fisheries
	Good Environmental Status (GES)—Reconciling Fisheries and Ecosystem Policy	• Maximizing long-term sustainable yield of all commercially exploited stocks versus maintaining ecosystem integrity and ecosystem services to support other human activities
	Marine Spatial Planning—Offshore Wind Farms (OWFs)	• Energy production versus fisher access to marine waters • Energy production versus negative effects on species of conservation concern (i.e., marine mammals, birds) • Fishing access restrictions versus enhanced productivity from 'reef' and 'reserve' effects

Note: See text for definitions.

Abbreviations: EAF, ecosystem approach to fisheries; EBFM, ecosystem-based fisheries management; EBM, ecosystem-based management; EM, ecosystem management.

zooplankton) may be limiting the recruitment of several species and slowing their response to management actions intended to reduce fishing mortality. Scientific advice on harvest rates consistent with MSY is provided by ICES based on single-species stock assessments and consists of a range around a target F_{msy} intended to result in no more than a 5% reduction in long-term yield ('pretty good yield;' Hilborn, 2010; Rindorf et al., 2017). Despite this flexibility in quota setting, there are currently no guidelines for how to choose a target *F* within this range.

How are EwE Models informing the issue? An EwE model of the Irish Sea ecosystem was used to determine a target *F* within the specified range around F_{msy} that took ecosystem considerations into account (F_{eco}, Bentley et al., 2021). The EwE model was used to identify important correlates of fishery yield in the system, from which either new empirical times series (e.g., temperature, zooplankton biomass) or EwE-generated indicator time series (e.g., predation mortality, trophic indices) were developed (Bentley et al., 2020). The status of these time series in the terminal year of the model relative to their long-term mean was then used to scale F_{msy} up or down within the specified bounds determined from the single-species assessment model. Stock status, reference points, and target F_{msy} ranges are still computed from the single-species assessment model. Indicators identified or taken directly from the EwE model are then used to re-scale the target *F* within the acceptable range to be more precautionary when ecosystem conditions are poor while allowing higher fish mortality when ecosystem conditions are good (F_{eco}).

Outcome, lessons learned, and challenges: Use of the Irish Sea EwE model to provide tactical fisheries management advice was facilitated by a specific question related to a pending management decision (i.e., what target *F* to choose within a prescribed range), an invested stakeholder and management community that worked together to co-produce relevant knowledge and information (Bentley, Hines, Borrett, Serpetti, Hernandez-Milian, et al., 2019; Bentley, Serpetti, Fox, Heymans, & Reid, 2019), and a vetted and reviewed EwE model developed according to best practices (Bentley et al., 2020, 2021; Bentley, Hines, Borrett, Serpetti, Fox, et al., 2019). At least six stakeholder workshops were conducted, and model review occurred at multiple levels, including informal review through the workshop process, peer-reviewed publications, and formal review through the ICES Working Group on Multispecies Assessment Methods (WGSAM) (Bentley et al., 2021; ICES, 2019). Similar to the Menhaden case study, multiple distinct ecosystem models have been developed for the Irish Sea (cited in Bentley et al., 2021), providing the opportunity to address structural model uncertainty, but only the EwE model has been approved for catch advice. Also similar to Menhaden, because the Irish Sea EwE model was used to modify outputs from single-species models, significant modifications to the existing assessment and management process were not required, which facilitated the incorporation of ecosystem information into tactical management advice (Howell et al., 2021). However, the need to conform to the existing management framework also limited the use of the model to a fairly narrow scope (i.e., setting target *F* levels within a pre-specified range for four key species). Also, the approach as currently designed cannot be used for data-limited stocks or those without F_{msy} ranges from single species assessments (Bentley et al., 2021). Further, the use of an indicator-based approach to inform short-term management advice is challenging due to uncertainty in whether the EwE model adequately captures the current and historical states of the Irish Sea ecosystem, potential alternative functional relationship (i.e., other than linear) between particular indicators and stock productivity, and lack of a standardized approach for combining and weighting indicators (Bentley et al., 2021; Thorpe et al., 2021).

2.2 | Ecosystem-based fisheries management

2.2.1 | Mixed-species fisheries and discarding

The management issue: The reformed CFP policy for EU fisheries has highlighted trade-offs (Table 1) around two issues relevant to fisheries that harvest multiples species and size classes: (1) the feasibility of obtaining single-species MSY simultaneously for all harvested stocks in a complex (i.e., the mixed-species fishery problem; Fulton et al., 2022; May et al., 1979; Worm et al., 2009) and (2) a requirement to land all species subject to catch limits or minimum size limits (i.e., the Landing Obligation (LO) or discard ban; Catchpole et al., 2017; Christou et al., 2019; Guillen et al., 2018). In the case of mixed-species fisheries, the trade-off is between maximizing food production and the economic benefits to the fishery while avoiding overfishing thresholds for all species in a mixed-species complex. In the case of discards, trade-offs (Table 1) have been identified between (1) processing costs to fishers versus the additional revenue from the sale of previously discarded fish, (2) the current harvest of undersized individuals versus the future harvest of surviving discards at a larger, more valuable size, and (3) the trophic subsidy that discards provide for scavenger populations, some of which are species of conservation concern (e.g., marine birds, dolphins), versus societal values regarding resource use and waste (Celić et al., 2018; Guillen et al., 2018; Onofri & Maynou, 2020).

2.2.2 | Mixed-species fisheries—Is MSY achievable?

How are EwE Models informing the issue? EwE models are being used to evaluate the sustainability of mixed-species fisheries in the North Sea (Heymans et al., 2011; Mackinson et al., 2009, 2018; Stäbler et al., 2016, 2019) and off the west coast of Scotland (Alexander et al., 2015; Baudron et al., 2019). Similar to other north temperature ecosystems (Kempf et al., 2016; Lucey et al., 2012; Mueter & Megrey, 2006), the general conclusion from these models is that simultaneously achieving MSY from single-species stock assessments for all species in a mixed-species fishery is not possible due to trade-offs among different fleets or among species that are linked by trophic and bycatch interactions. For example, an EwE model that explored trade-offs among demersal fish and shrimp trawl fleets in the southern North Sea that harvest predators (European Cod), prey (Brown Shrimp, *Crangon crangon*, Crangonidae), and both adults and juveniles (as bycatch) of the same species (e.g., flatfishes; European Plaice, *Pleuronectes platessa*, Pleuronectidae; Common Sole, *Solea solea*, Soleidae) concluded that alternative fishing regimes could sustainably harvest only 30% of the single-species MSYs simultaneously for each stock (Stäbler et al., 2016). Significant effort reductions (i.e., 20%–50%) may be required for some fleets in order to achieve sustainable harvest rates for all species (Mackinson et al., 2009; Stäbler et al., 2019). EwE models have also been used to evaluate how both environmental (marine mammal predation, changes in primary productivity; Stäbler et al., 2019) and economic (fishery subsidies, Heymans et al., 2011) factors external to the harvesting system alter sustainable yields from mixed-species fisheries, and to prioritize alternative management actions (Mackinson et al., 2018). For example, a management strategy evaluation (MSE) that used an EwE model of the North Sea as an operating model indicated that alternative regulatory options related to discarding had much larger consequences for meeting fishery objectives compared to other management decisions (e.g., choice of target *F* within the range of pretty good yield, recovery time frames). Alternative approaches to managing discards also had large consequences for species of conservation concern. This information is being used to identify key issues that are critical to meeting the objectives of the proposed North Sea multi-annual plan for North Sea demersal fisheries (Mackinson et al., 2018).

2.2.3 | Discarding—The EU Landing Obligation

How are EwE Models informing the issue? EwE models are being used to evaluate the consequences of the LO policy to limit discards both for fisheries and for the broader ecosystem (Celić et al., 2018; Moutopoulos et al., 2013, 2018; Pennino et al., 2020). For some systems, results from EwE and other food web models (Angelini et al., 2016) suggest that the LO will have negative or only modest effects on commercially harvested species due to compensatory trophic interactions, the removal of biomass that otherwise would be recycled within the system, and the limited reliance of some economically important species on discards as a food resource (Celić et al., 2018; Moutopoulos et al., 2013, 2018). An EwE model of the Adriatic Sea suggested the additional revenues generated from the sale of undersized or nontarget species for fishmeal was unlikely to compensate for the increased processing and infrastructure costs to fishers from landing small fish with limited marketability, so that the net economic effect on the fishery may be negative (Celić et al., 2018). However, linked EwE and species distribution models suggest more significant positive and negative effects of limiting discards that differ across species (Pennino et al., 2020). Whether the LO has net positive or negative effects may also differ between fisheries that are regulated by effort controls compared to those regulated by catch limits due to different incentives for selective harvesting (Celić et al., 2018; Mackinson et al., 2018). EwE models also suggest the effects of the LO will depend on the status of the relevant populations, with overfished species benefiting more from reductions in fishing effort than in discarding, whereas limiting discards has greater effects for species where landed catch is near sustainable levels (Mackinson et al., 2018; Moutopoulos et al., 2018). A general result that has emerged from EwE models of multiple ecosystems is the potential negative effects of limiting discards on scavenger populations, particularly marine birds but also marine mammals and sea turtles, that have come to rely on discards as a food resource (Celić et al., 2018; Fondo et al., 2015; Mackinson et al., 2018; Moutopoulos et al., 2018).

Outcomes, lessons learned, and challenges: EwE models of fishery systems with multiple target and bycatch species are helping to diagnose the trade-offs among fleets and harvested populations that result from the direct and indirect effects of fishing and trophic interactions. These models are also helping to determine whether current management practices are consistent with sustainable harvest objectives, identify the most consequential regulatory options, and determine whether particular policies are likely to meet stakeholder expectations. The general conclusion that fishery objectives based on single species approaches are unlikely to be met in systems with strong predation and bycatch interactions among species harvested by multiple fleets is not surprising. However, the EwE results are providing specific guidance in particular ecosystems as to the species and fisheries most at risk, the extent to which sustainable yields from single-species models may be overestimated, and the economic implications associated with different harvesting practices. This information is being used to evaluate and refine fishery management plans and discards plans, which should improve future decision-making (Damalas, 2015; Mackinson et al., 2018; Pennino et al., 2020). However, EwE results of fishery systems are sensitive to the amount and quality of diet data and information on the behavioural responses of fishing fleets to changing economic and regulatory incentives, both of which are often assumed static in time (Mackinson et al., 2018; Romagnoni et al., 2015). Heterogenous spatial and temporal patterns in fishing effort, catch, and discarding can be difficult to adequately capture with EwE. Hence, while EwE is useful for diagnosing when existing or proposed fishery policies may not have intended effects and for identifying particular ecological and fishery trade-offs, complementary tools may be needed to develop specific technical or regulatory solutions to mixed-species fisheries and discarding issues.

2.2.4 | Reconciling single and multispecies models—The US Northeast Groundfish Assessment Review

The management issue: The northwest Atlantic has supported some of the most productive commercial fisheries in the world for centuries (Link et al., 2011). Several groundfish species off the US Northeast shelf collapsed in the early 1990s and despite increasingly stringent management, many species have experienced limited recovery (Brodziak et al., 2008; Fogarty & Murawski, 1998; Hilborn & Litzinger, 2009). Multiple stakeholder groups have expressed concern as to whether the ecosystem can support the sustainable harvest of the managed groundfish stocks at their biological reference points determined from single-species stock assessments. In 2007, the NOAA Northeast Fisheries Science Center (NEFSC) convened a regional scientific review process called the Groundfish Assessment and Review Meeting (GARM III) to provide benchmark stock assessments for 19 groundfish stocks managed by the New England Fishery Management Council. Consideration of ecosystem processes, in particular whether the overall productivity of the Northeast shelf ecosystem is sufficient to support the estimated harvest levels, was a specific term of reference for the review.

How are EwE Models informing the issue? The regional review was conducted via a series of technical workshops that synthesized the available information on biological reference points for nearly all fishery species (landed and bycatch) in the Northeast shelf ecosystem (Overholtz, Link, et al., 2008). The results suggested that biomass of the 19 groundfish species was 59% of the combined B_{msy} target level, indicating the complex was overfished. To put these results within a broader ecosystem context, an Ecopath model of the Northeast shelf was developed to identify ecological constraints on the system and determine how biomass would be re-distributed among trophically-linked, harvested groups under various fishing scenarios (Link et al., 2006; Link, Overholtz, et al., 2008). The Ecopath model was part of a multi-model approach that included aggregate (Overholtz, Fogarty, et al., 2008) and multispecies (Link, Gamble, et al., 2008) surplus production models and a bottom-up, trophic transfer model (Fogarty et al., 2008). While the details differed among the models, the overall fishery yield indicated by the ecosystem models was less than the summed single species reference points, as has been found in other north temperate marine ecosystems (Fogarty et al., 2012; Lucey et al., 2012; Mueter & Megrey, 2006). This led to a reconsideration of some parameters in the single-species assessments to better align the results with those from the ecosystem models, which enhanced the acceptance of the resulting catch advice by managers and stakeholders (NEFSC, 2008). A key conclusion from the ecosystem models was that pelagic stocks should be managed at a higher biomass than suggested by single-species assessments, and that a second layer of management consideration for the groundfish stocks that addresses the system-level productivity of the Northeast shelf is warranted.

Outcomes, lessons learned, and challenges: The consideration of single species and ecosystem models within the same review framework, as during GARM III, illustrates the utility of simultaneously developing and evaluating multiple models with different underlying assumptions (NEFSC, 2008). The use of standardized data inputs and explicit model comparisons led to a better understanding of the strengths and limitations of the different models. The ecosystem models resulted in general management recommendations as well as information that improved the single-species stock assessments. Periodic evaluation of ecosystem models within a resource management process can provide a check on some of the primary assumptions of single-species models (e.g., stationary, Chen et al., 2022), even if they are not used directly to generate catch advice. This case study also illustrates the importance of a formal review process characterized by thorough documentation, transparency, and independent review panels (NEFSC, 2008; see also Kaplan & Marshall, 2016). The GARM III process included four, 1-week workshops, four review panels, 18 reviewers, and thousands of pages of documentation. Because the ecosystem models were developed for a time period when many stocks were already depleted, the ecological limits to fishery yields inferred from the ecosystem models were not an immediate management concern. However, there was a recognition that consideration of these limits would be increasingly important as stocks rebuild (NEFSC, 2008). More formal comparison of the ecosystem models and the single-species assessment models in terms of actual fishery management performance (e.g., using MSE; Gaichas et al., 2017; Lucey et al., 2021) would help further assess the utility of these models for providing management advice.

2.2.5 | Limited data, models, and governance—The African Great Lakes

The management issue: African inland lakes are a critical source of food, income, and employment for that region's population, directly or indirectly employing 4–5 million people, accounting for a third of the continent's fishery production, and providing a third of the total animal protein for landlocked African countries (Funge-Smith & Bennett, 2019; Kolding et al., 2019). Lake Victoria is the largest of the African inland lakes, both in terms of size and fishery production, and generates approximately one million tons of fish annually (Natugonza et al., 2022). The introduction of piscivorous Nile perch in the 1950s, which was intended to increase the economic value of Lake Victoria's fisheries, led to significant declines in native haplochromine cichlids (previously about 500 species), which also supported significant subsistence fisheries in the three bordering countries (Uganda, Tanzania, and Kenya). The catchment basin for Lake Victoria has one of the highest population densities in Africa (~500 people per km^2), and fishing is one of the few sources of livelihood for local communities (Ogutu-Ohwayo et al., 2020). There is a need to better understand the trade-offs among economic (fisheries profits), social (employment), and conservation (ecosystem structure and resilience) objectives in order to develop effective fisheries policies, though limited resources to support data collection, modelling, and fisheries governance and enforcement have hindered resource management efforts (Musinguzi et al., 2017).

How are EwE Models informing the issue? A systematic evaluation of prior ecosystem modelling efforts in the region led to an updated EwE model for Lake Victoria (Natugonza et al., 2016, 2019, 2020a, 2020b). The model was tuned using time series of survey and landings data, calibrated using standard approaches (i.e., vulnerability parameters and the diet composition matrix), and subject to multiple model diagnostics (Heymans et al., 2016), including PREBAL (Link, 2010a, 2010b), pedigree analysis (Christensen & Walters, 2004), and skill assessment (Olsen et al., 2016). The model and associated documentation is also readily available (https://doi.org/10.6084/m9.figshare.7306820.v4). The EwE model and a recently developed Atlantis model (Nyamweya et al., 2016, 2017) were used to evaluate alternative fisheries policies with an emphasis on the trade-offs among economic, social, and conservation objectives (Natugonza et al., 2020b), as described in the Lake Victoria Management Plan III (2016–2020) (LVFO, 2022). Projected future outcomes of alternative fishery policies for Nile Perch and haplochromine fishes were qualitatively similar between EwE and Atlantis for the major harvested groups and indicated a need for reductions in fishing effort. Further, the models suggested that maximizing fishery profits was more compatible with maintaining ecosystem structure of Lake Victoria than maximizing catch or employment in the fishing sector. Given that fishing is open access and alternative livelihood opportunities are limited in the region, effort reductions could impose high social costs, an issue that is exacerbated by illegal fishing and limited enforcement. A synthesis of multiple Ecopath models for Lake Victoria indicated that recent enforcement of minimum size limits, the predominant tactical management measure, is causing the overharvest of large-bodied species and the underharvest of small-bodied species ('unbalanced harvest', Garcia et al., 2012; Natugonza et al., 2022). More balanced harvest across trophic levels could produce food resources to support an additional 8 million people compared to current harvest patterns (Kolding et al., 2019), but would require a significant reconsideration of the objectives and current regulatory practices for the fishery.

Outcomes, lessons learned, and challenges: The Lake Victoria case study demonstrates that rigorous development of ecosystem models to inform strategic policy decisions and tactical regulatory measures is feasible for developing regions with limited data. The Lake Victoria

EwE model was constructed based on a synthesis and extension of prior models for the system, made efficient use of the most recently available data, was subject to multiple model diagnostics, explored policy trade-offs, was compared to a structurally different model (i.e., Atlantis), and is transparent and easily accessible. By revealing trade-offs among economic, social, and conservation objectives (Table 1), the model is serving as an important decision support tool to aid long-term strategic planning for the region. The synthesis of multiple Ecopath models also raises questions about the efficacy of current regulatory practices (i.e., minimum size limits) for maximizing food security, which should ultimately lead to a better alignment between tactical management regulations and the strategic objectives for the fishery. However, data limitations remain a significant issue, given the limited historical time series and diet data, particularly for non-harvested groups (Natugonza et al., 2019, 2020a). In addition, while there was active engagement with other scientists during model development, engagement with managers and other stakeholders occurred mostly after the models had already been published. As a result, stakeholder considerations were only incorporated indirectly into the model through the Lake Victoria fishery management plan development process, which is highly consultative in nature (Lake Victoria Fisheries Organization, 2022). Direct engagement with the stakeholder community as well as a formal review process (beyond peer-reviewed publications) would enhance the utility of the model for informing tactical management decisions.

2.3 | Ecosystem-based management

2.3.1 | Fishing, habitat, and climate effects on coral reef ecosystem services

The management issue: In the United States, coral reef ecosystems are protected and managed under multiple legislative mandates, including the Coastal Zone Management Act, the Magnuson-Stevens Fishery Conservation and Management Act, the Endangered Species Act, and the Coral Reef Conservation Act (Foran et al., 2016). Many coral reef ecosystems are degraded due to a combination of land-based pollution (i.e., nutrients and sedimentation), fishing, and increasing temperatures that lead to coral damage and disease (Ateweberhan et al., 2013; Sully et al., 2019; Tebbett et al., 2021) and altered fish and invertebrate communities (Strona et al., 2021). Nearshore reef ecosystems of the Hawaiian Archipelago exemplify many of these stressors. For example, coral cover and reef fish populations on fringing coral reefs off Hawai'i Island declined by 35% and 50%, respectively, from 1980 to 2007, and reef fish landings decreased by 20% despite increasingly stringent fishing regulations (Weijerman, Gove, et al., 2018). Wastewater inputs to coastal waters have increased due to a growing local population with greater access to the coast. Elevated ocean temperatures in 2015 led to a severe bleaching event on Puako, a fringing reef on the west coast of Hawai'i Island, that resulted in the loss of nearly half of the reef's live corals. In 2016, a pledge by the governor of Hawai'i to effectively manage 30% of the coastline by 2030 (DAR, 2022) catalyzed a state-led, multi-year planning effort to identify a suite of fishery and land-based management options that would maintain the capacity of the fringing reefs to support dive tourism and fishing, while also improving reef resilience to climate change (Weijerman, Gove, et al., 2018).

How are EwE Models informing the issue? EwE models are being used to evaluate alternative management strategies related to maintaining or enhancing dive tourism, recreational and commercial fishing opportunities, and land-based run-off while also enhancing the capacity of coral reefs to recover from perturbations, such as temperature-induced bleaching events (Weijerman et al., 2021; Weijerman, Gove, et al., 2018). Medium-term (15–30 years) forecasts of alternative management interventions, including different fishing practices (i.e., traps, lines, spears, and nets), the implementation of marine protected areas (MPAs), and decreases in land-based pollution, found that no single strategy clearly outperformed all others, but that current management underperformed all of the other scenarios. Fishing only with line gear in combination with nutrient and sediment reductions led to the most balanced trade-off among the economic value of the fishery, tourism, and reef resilience, though other management strategies, such as limiting harvest of herbivorous fishes and no-take MPAs, led to viable though different trade-offs. Further, the EwE model indicated that the loss of coral cover due to projected increases in bleaching events could be partially mitigated by reductions in land-based nutrients, suggesting that local watershed management actions could offset some of the anticipated effects of climate change on coral reef ecosystems (Weijerman, Gove, et al., 2018).

Outcomes, lessons learned, and challenges: In the case of Hawai'i coral reefs, EwE models are serving as decision-support tools to clarify the trade-offs associated with alternative fishing and land-based management interventions while accounting for the effects of climate change. An important result of the EwE models is that status quo management is not a viable strategy and that both marine- and land-based approaches are needed to preserve or restore the multiple ecosystem services provided by coral reefs. Further, a defined set of management alternatives led to different types of trade-offs, which highlighted a need to better characterize the social and economic objectives of stakeholders (Weijerman et al., 2021). Alternative models addressing similar issues have been developed for Hawai'i coral reef ecosystems (HiReefSIM, Weijerman, Veazey, et al., 2018; Atlantis, Weijerman, 2020), but have not yet been integrated into a multi-model approach. Multiple planning and model development workshops have been critical for enhancing communication with stakeholders, clarifying ecological, economic, and social objectives, and increasing familiarity with the outputs of ecosystem models (Weijerman et al., 2019, 2021). However, given the diversity of stakeholder interests and multiple management authorities (local, state, and federal), formalizing a model evaluation and review process has been challenging. Similarly, the multi-jurisdictional nature of the issues affecting coral reef ecosystems has led to a complex and highly decentralized decision-making process regarding the management measures suggested by the ecosystem models that is currently ongoing.

2.3.2 | Wetland restoration—Mississippi River sediment diversions

The management issue: The Mississippi River delta region of southern Louisiana is one of the largest and most economically important coastal systems in North America, encompassing over 25,000 km^2 of freshwater and coastal wetlands (Day et al., 2009). During the 1900s, about a quarter (>5000 km^2) of the coastal wetlands in this region were lost due to changes in hydrology associated with channelization of the Mississippi River, along with land subsidence from sea level rise and petroleum extraction (Reed et al., 2020). The Coastal Protection and Restoration Authority (CPRA) was formed to organize state and federal management agencies with mandates related to coastal wetlands, nearshore fisheries, and habitat restoration in the region (CPRA, 2017). A multi-agency project development team was assembled to evaluate a suite of river diversion projects designed to redirect water, sediments, and nutrients back to the deltaic plain in order to rebuild coastal wetland habitat. The potential consequences of the proposed diversions for recreationally and commercially important fisheries in the nearshore coastal zone are of particular concern.

How are EwE Models informing the issue? Because the Mississippi watershed drains 54% of the conterminous US, ecosystem models capable of linking terrestrial, aquatic, and marine ecosystems are needed to evaluate the potential efficacy of sediment diversions and the attendant consequences for marine and fishery resources. EwE models have been developed to provide a coupling of watershed dynamics and river flow to the biomass and spatial distribution of important coastal fish and shellfish species in estuaries along the Louisiana coast (de Mutsert et al., 2012, 2017, 2021). The results suggest that river diversions will lead to the re-distribution of important harvested species (e.g., Brown Shrimp, *Farfantepenaeus aztecus*, Penaeidae; White Shrimp, *Litopenaeus setiferus*, Penaeidae; Gulf Menhaden, *Brevoortia patronus*, Clupeidae; Red Drum, *Sciaenops ocellatus*, Sciaenidae; Spotted Seatrout, *Cynoscion nebulosus*, Sciaenidae) within estuarine ecosystems, but will have only modest effects (both positive and negative) on total species biomass. Spatial patterns in biomass associated with river diversions differ considerably among species and across different estuaries, highlighting the importance of local and species-specific responses to changing salinity and other factors. Simulations of multiple planned restoration activities that also incorporate long-term projected sea-level rise (SLR) suggest that some potential beneficial effects of sediment diversions on coastal fishery species may be offset by future increases in SLR (de Mutsert et al., 2021). Systematic comparison of the EwE model and a structurally different food web model (Comprehensive Aquatic Systems Model, CASM; Bartell et al., 2020) led to a broader understanding of the structure and energy flow of the estuarine food web as well as a common set of indicators that can be used across models to evaluate food web responses to coastal restoration activities (Lewis et al., 2021).

Outcomes, lessons learned, and challenges: The large-scale restoration of wetland habitat in coastal Louisiana demonstrates the use of EwE models to inform restoration planning within the context of a long-term, complex policy-making process with multiple management authorities, legislative mandates, and stakeholder interests. The ecosystem modelling efforts to support decision-making regarding sediment diversions and other restoration activities have evolved over more than a decade and required long-term collaborations among scientists, managers, and stakeholders within a multi-agency project development, evaluation, and review process. The EwE model, along with multiple other models, helped to inform the decision to further consider two specific river diversion projects (Middle Barataria Bay and Middle Breton Sound) among the multiple projects that were initially proposed. While different from the tactical decisions common in fisheries, this case study represents a tactical application of an EwE model in another ocean use sector because it is being used to directly inform actionable decisions regarding alternative management interventions to support wetland restoration. Similar to the Hawai'i coral reefs case study, the EwE model incorporates the projected effects of climate change (i.e., increasing SLR) to better inform manager and stakeholder expectations regarding the long-term consequences of the proposed restoration activities (de Mutsert et al., 2021). However, a number of technical and procedural challenges were encountered in developing the EwE model and integrating it within the policy process. Lack of long-term data, particularly on spatial processes, is a common challenge for parameterizing and validating spatially-explicit EwE models (i.e., Ecospace; Steenbeek et al., 2021). Coordinating the multiple, one-way coupled models needed to link processes in the Mississippi watershed to downstream effects on Louisiana estuaries was a particular technical and collaborative challenge that was compounded by specific management deadlines. Further, ecosystem modelling has little precedent in environmental impact assessment (EIA) and permitting, which is also a challenge for integrating model results into the decision-making process (USACE, 2022).

2.3.3 | Good Environmental Status (GES)—Reconciling fishery and ecosystem policy

The management issue: The overarching goal of the Marine Strategy Framework Directive (MSFD, EC, 2008) is to integrate ecosystem considerations into all relevant policy decisions in EU marine waters by requiring each member state to reach 'Good Environmental Status' (GES; Borja et al., 2013). GES is defined by 11 descriptors, three of which are highly relevant to fisheries (biological diversity, commercially exploited fish and shellfish, and marine food webs). While the most recent reform of the CFP also promotes the incorporation of ecosystem considerations into fisheries management, a primary objective remains to maximize the long-term sustainable yield of all commercially exploited stocks, leading to potential conflicts between the two policies. Approaches to implementing the MSFD (Newton et al., 2015), as well as the extent to which fisheries objectives of the CFP, are consistent with the ecosystem objectives of the MSFD are areas of active research (Elvarsson et al., 2020;

Fock et al., 2011; Kopp et al., 2016; van Hoof, 2015). Meeting the dual goals of these two policies will require both an extension of the existing fisheries assessment process to include consideration of the ecosystem effects of fishing (Baudron et al., 2019; Lynam & Mackinson, 2015; Stäbler et al., 2016) as well as the development of specific ecological indicators and reference points that reflect the GES descriptors (Bourdaud et al., 2016; Fu et al., 2019; Lynam et al., 2016; Piroddi et al., 2015; Tedesco et al., 2016).

How are EwE Models informing the issue? EwE models have been used to identify conflicts and clarify trade-offs between fisheries management objectives and the ecosystem objectives embodied in the GES descriptors (Baudron et al., 2019; Lynam & Mackinson, 2015; Stäbler et al., 2016). While reductions in fishing effort consistent with single-species fishing mortality targets lead to improvements in some EwE-derived indicators of GES (e.g., biodiversity, food web structure; Lynam & Mackinson, 2015), trade-offs between fishery and ecosystem objectives may still occur even when fishing is sustainable. For example, fishing effort scenarios that simultaneously achieved MSY for three southern North Sea demersal fleets (beam, shrimp, and demersal trawl fisheries) resulted in trade-offs with multiple GES indicators (e.g., abundance of large fish, biomass of target species; Stäbler et al., 2016, see also Uusitalo et al., 2022). An EwE model of the west coast of Scotland indicated that fishery recovery scenarios for multiple depleted demersal stocks had positive effects on most GES descriptors (e.g., biomass, diversity, size, and trophic status), but under the best fishery management scenario, conflicts remained between biodiversity and food web indicators (Baudron et al., 2019), suggesting it may not be possible to maximize multiple GES descriptors simultaneously. In contrast, an EwE model of the Baltic Sea indicated that reducing Cod fishing mortality to sustainable levels had relatively small effects on biomass, biodiversity, and food web indicators (Lassen et al., 2013).

Outcomes, lessons learned, and challenges: This case study illustrates the use of EwE models to help reconcile conflicting policy objectives from different legislative mandates (i.e., CFP and MSFD) related to human use of the marine environment. EwE models suggest that fishery management strategies intended to optimize MSY-related objectives can have beneficial, detrimental, or little consequence for achieving ecosystem objectives under the MSFD, highlighting that the nature of this trade-off is specific to the ecosystem and particular GES descriptors of interest. Even so, EwE models indicate that the direct effect of fishery removals and the indirect effects of fishing on the broader food web are both important considerations in assessments of GES. An emerging result from the EwE models is that conflicts between maximizing fishery yields and achieving GES are likely to occur even when fisheries are sustainably managed, highlighting the importance of evaluating trade-offs. EwE models are helping to identify which GES descriptors are most responsive to changes in fishing pressure, as well as specific management interventions to better align fishery and ecosystem objectives. However, identifying appropriate indicators that reflect GES and achieving consensus on standardized approaches for their evaluation is an ongoing challenge (Fu et al., 2019; Heymans et al., 2014; Queirós et al., 2016; Reed et al., 2017; Shannon et al., 2014). There is also considerable uncertainty about how to include MSFD conservation objectives into new or existing management frameworks with explicit protocols for resolving conflicts (van Hoof, 2015).

2.3.4 | Marine spatial planning—Offshore wind farms (OWFs)

The management issue: Marine spatial planning and comprehensive ocean zoning are frameworks to manage the interactive and cumulative effects of multiple ecosystem stressors across ocean use sectors (Alexander & Haward, 2019; Smythe & McCann, 2018, 2019). Renewable energy development through the construction and operation of offshore wind farms (OWFs) is a rapidly expanding sector of ocean use (Esteban & Leary, 2012). OWFs typically require spatial restrictions in the form of fishing exclusion zones, but also induce a 'reserve effect' that increases harvestable biomass via the spillover of fish into areas accessible to fisheries (Punt et al., 2009). OWFs also induce a 'reef effect', whereby colonization of OWF structures by epibenthic and benthic organisms provides an additional food resource for upper trophic levels (Raoux et al., 2017). The construction of OWFs also has consequences for apex predators that are often of conservation concern, such as marine birds (Furness et al., 2013) and marine mammals (Teilmann & Carstensen, 2012). As a result, the construction and operation of OWFs induces trade-offs both within (i.e., fishing restriction vs. fisheries production) and between (i.e., renewal energy vs. fisheries) ocean use sectors and with protected species that occurs within an often-contentious regulatory environment (Lester et al., 2018).

How are EwE Models informing the issue? EwE models are being used in multiple marine ecosystems to evaluate the effects of proposed OWFs on the structure and function of marine food webs, to address trade-offs with marine capture fisheries, and to assess the consequences for species of conservation concern (west coast of France: Halouani et al., 2020; Nogues et al., 2022; Pezy et al., 2020; Raoux et al., 2017, 2019, 2020; The Yellow Sea: Wang et al., 2019; west coast of Scotland: Alexander et al., 2016; Serpetti et al., 2021). For example, an EwE model for the northwest coast of France suggested the increase in biomass from spillover effects around a proposed OWF site would mitigate the negative impact of fishing access restrictions, leading to an increase in localized catch comprised of a higher proportion of more valuable species (Halouani et al., 2020). In contrast, an EwE model of the west coast of Scotland that included both reef and exclusion zone effects concluded the overall effects of OWFs were weak at both local (6.25 km^2) and shelf-wide (110,000 km^2) spatial scales and that increases in fishery productivity around proposed OWFs sites would not necessarily mitigate access restrictions for some fisheries (Alexander et al., 2016). While studies to date vary in spatial scale and the particular trade-offs considered, EwE models of proposed OWFs often indicate negative effects on fisheries and local ecosystems during the construction phase, but no or potential positive effects over longer time scales due to the combined effects of bottom-up and biomass spillover processes.

Outcomes, lessons learned, and challenges: While a consensus on the long-term effects of OWFs has yet to emerge, EwE models are clarifying specific trade-offs related to how OWFs will affect the structure of marine ecosystems, access to fishing grounds, and fishery production. The construction of OWFs typically requires an EIA (Bailey et al., 2014; Leung & Yang, 2012), and the focus of traditional EIA primarily on a few species or groups of conservation concern (birds, marine mammals, and fish) is a recognized issue with respect to OWFs (Wilding et al., 2017). EwE models are complementing and expanding traditional EIA approaches by providing a more holistic assessment of OWF effects on the ecosystem (Pezy et al., 2020). Similar considerations apply to other ocean uses sectors that have an inherent spatial component, such as offshore aquaculture systems (Froehlich et al., 2017) and the construction and decommissioning of oil and gas platforms (Bull & Love, 2019). A particular technical challenge in applying EwE to spatial planning issues is the need for data and methods to parameterize and validate spatially explicit ecosystem models (i.e., Ecospace) that include multiple, scale-dependent processes (Alexander et al., 2016; Bailey et al., 2014; Steenbeek et al., 2021). This is a particular challenge in the case of OWFs because it is unclear how far the ecological and fishery effects extend beyond the immediate OWF site. Similar to the Wetland Restoration case study, there is not a strong precedent for using EwE or other ecosystem models in the permitting process for OWFs, which has limited there use in the EIA process. Similar to other multi-sector resource issues, a formal multi-jurisdictional management and decision-making authority to address multi-sector trade-offs with respect to OWFs is generally lacking. As a result, there is less formal engagement of stakeholders in the model development process and multi-model approaches and formal review of EwE and other ecosystem models for use in EIA and related decision-making is not common.

3 | DISCUSSION

3.1 | Use of EwE within an operational management context

Each of the case studies reviewed here illustrates how an EwE (Ecopath, Ecosim, or Ecospace) model is being used to inform decision-making within an operational resource management context. In the Menhaden and Irish Sea Groundfish examples, EwE models are directly informing tactical fisheries management decisions by providing quantitative information to determine short-term catch levels and target fishing mortality rates that account for the requirements of predators or ecosystem effects on stock productivity. EwE models in the Mixed Species Fishery, EU Landing Obligation, and US Northeast Groundfish Assessment Review examples identified key ecological or economic trade-offs among fisheries, between fisheries and protected species, or highlighted the limits to harvest imposed by the productive capacity of marine ecosystems. The EwE model for Lake Victoria is informing policy decisions regarding alternative fishery management objectives (i.e., optimizing profits, catch, or employment) in a developing region where food security and livelihood opportunities are important social considerations. The EwE model of Hawai'i coral reefs is informing discussions about how to restore or sustain the multiple ecosystem services provided by coral reef habitat in order to meet the goal of effectively managing 30% of the coastline by 2030. The EwE model in the Mississippi River Wetland Restoration example is contributing to near-term decisions about which of several specific river diversion projects to consider for further evaluation within a long-term, multi-agency evaluation and planning process. EwE models in the EU Good Environmental Status (GES) example are informing efforts to reconcile broad fishery (CFP) and ecosystem (MSFD) policy objectives. EwE models in the Offshore Wind Farm (OWF) example are clarifying specific trade-offs related to fisheries access restrictions and associated effects on fish production around proposed OWF sites that are helping to inform environmental impact assessments. Collectively, these case studies illustrate the use and potential for EwE models to inform decision-making in an operational management context across multiple ecosystem types (lakes, estuaries, continental shelves) and across multiple levels of ecosystem management, including single-species, multispecies, and multi-sector resource management.

A common element across the cases studies was the central role that trade-offs played in the development and application of EwE models (Table 1). In each of the examples, there were clear trade-offs across taxa, fisheries, ocean use sectors, or legislative mandates. As the Mixed-Species Fisheries, Landing Obligation, and GES examples illustrate, there are often competing management authorities and legislative mandates whose objectives are difficult to simultaneously achieve or, in some cases, are incompatible. The value of ecosystem models like EwE is that they not only reveal the existence and nature of specific trade-offs, but provide a framework for quantifying the consequences of a defined set of alternative policies or management options, ultimately helping to make better informed and more transparent decisions. Trade-offs are ubiquitous in marine resource management (Table 1). Failure to explicitly identify and evaluate trade-offs can lead to unintended outcomes and more controversial future decisions under a more restrictive set of management options.

3.2 | Factors that enhance the use of ecosystem models to support resource management

The case studies illustrate several common elements that facilitate the use of EwE models in an operational setting to inform resource management decisions (Table 2). Ecosystem models should address a clear policy issue within a defined management context or process (Figure 1, Townsend et al., 2019). This criterion was most clearly satisfied for the case studies that addressed tactical fisheries management decisions, such as setting catch (Menhaden) or fishing mortality (Irish Sea Groundfish) targets, where a structured decision-making process is already established. The Hawai'i Coral

TABLE 2 Criteria that facilitate the use of ecosystem models in an operational management context.

Criteria								
Level of EM	**Case study**	**Clear objectives**	**Important trade-off**	**Best practices**	**Active stakeholder engagement**	**Connected to a management process**	**Multi-model approach**	**Formal review**
EAF	Forage Fisheries—Trade-offs in the Management of Atlantic Menhaden	✓	✓	✓	✓	✓	✓	✓
	Informing Sustainable Fishing Rates—The Irish Sea Groundfish Fishery	✓	✓	✓	✓	✓		✓
EBFM	Mixed Species Fisheries—Is MSY Achievable?	✓	✓	✓	✓	✓		
	Discarding—The EU Landing Obligation	✓	✓	✓		✓		
	Reconciling Single and Multispecies Models—The Northeast Groundfish Assessment Review	✓	✓	✓		✓	✓	✓
	Limited Data, Models, and Governance—The African Great Lakes	✓	✓	✓		✓	✓	
EBM	Fishing, Habitat, and Climate Effects on Coral Reef Ecosystem Services	✓	✓	✓	✓	✓		
	Wetland Restoration—Mississippi River Sediment Diversions	✓	✓	✓	✓	✓	✓	✓
	Good Environmental Status (GES)—Reconciling Fishery and Ecosystem Policy	✓	✓	✓				
	Marine Spatial planning—Offshore Wind Farms (OWFs)	✓	✓	✓				

Note: See text for definitions. Check marks indicate whether the particular criterion was a prominent component of the case study based on the primary literature and should be interpreted as general patterns across the different levels of EM.

Abbreviations: EAF, ecosystem approach to fisheries; EBFM, ecosystem-based fisheries management; EBM, ecosystem-based management; EM, ecosystem management.

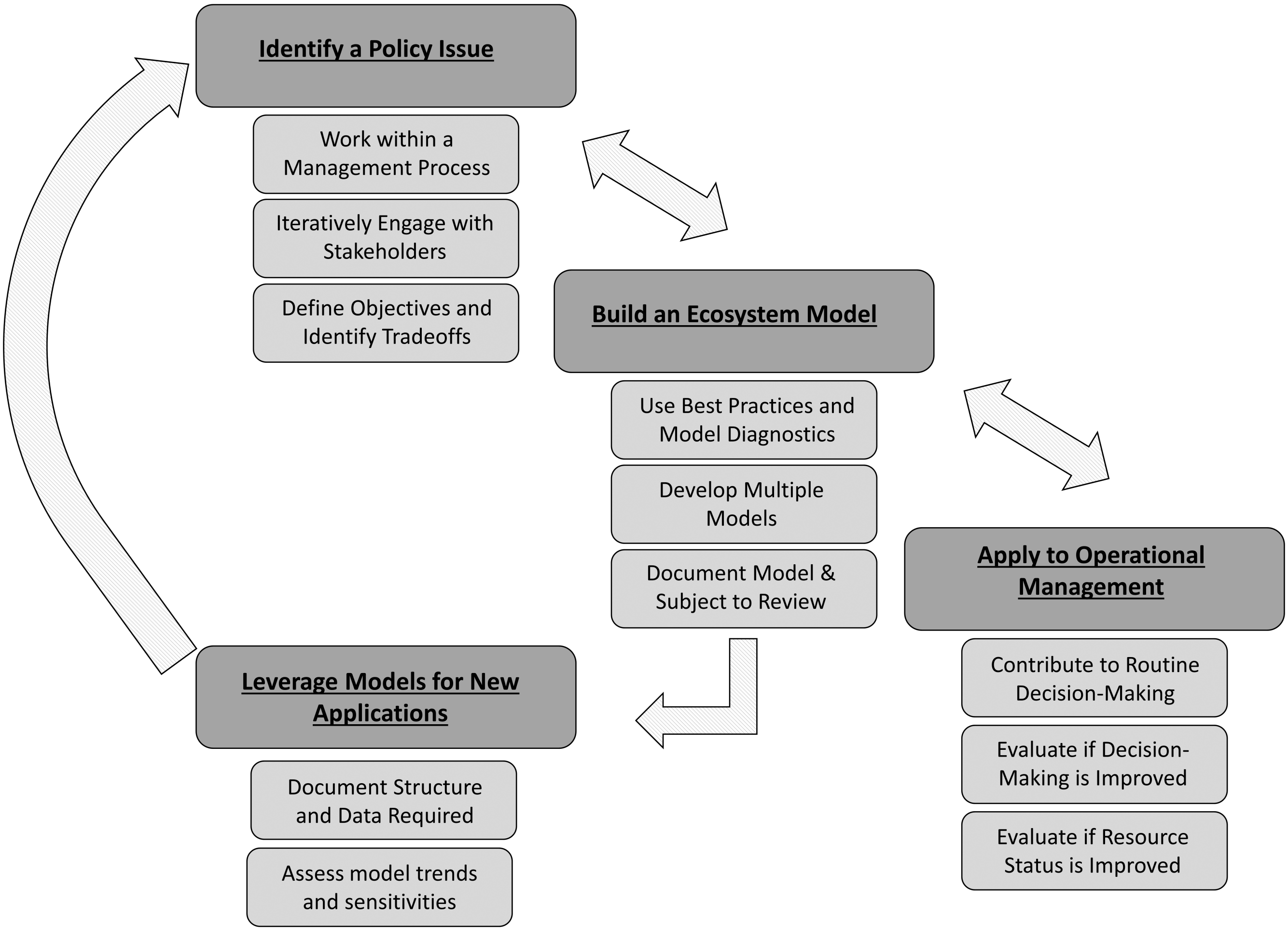

FIGURE 1 Conceptual diagram of steps to facilitate the use of ecosystem models in operational resource management: (1) identify a policy issue (upper left), (2) model development (middle), (3) operational use to support resource management (bottom right), and (4) application to new policy issues (bottom left). Light-shaded boxes indicate specific activities related to the above dark-shaded box. Double-headed arrows indicate steps where iterative two-way communication among modelers, managers, and stakeholders is particularly important.

Reef and Wetland Restoration examples involve broad management authorities that consist of multiple agencies and stakeholder groups where the decision-making process is more complex compared to the fisheries management examples. Some case studies are addressing important policy issues but are less connected to a formal management process due to limited governance (African Great Lakes) or precedent for the use of ecosystem models (Offshore Wind Farms), or relatively new policy mandates for which management processes and operational criteria are not yet well-defined (GES example). The main point is that for EwE models to inform operational decision-making, they need to be developed and used within a management framework, irrespective of the extent to which that framework is formalized or well-established.

Building and documenting an EwE model that both captures the primary processes of interest and can be used to evaluate the management options available to decision makers is critical (Figure 1). All of the case studies used the available data in model development and evaluated multiple diagnostics to ensure the models were a reasonable representation of the structure and dynamics of the relevant ecosystem. A number of treatises on 'best practices' and recommendations for the development of EwE models (Ainsworth & Walters, 2015; Heymans et al., 2016; Link, 2010a, 2010b; Plagányi & Butterworth, 2004), and ecosystem models in general (AORA, 2018; Collie et al., 2016; FAO, 2008; Geary et al., 2020; Grüss et al., 2017; Rose et al., 2010, 2015; Schmolke et al., 2010) are available to help guide the model development process. The African Great Lakes case study is of particular note as an example of a rigorously developed, well-documented, and accessible EwE model for a region with limited resources to support data collection and model development (Natugonza et al., 2020b).

Early and iterative communication is necessary to facilitate the use of ecosystem models to support resource management (Figure 1, Table 2; Boschetti et al., 2018; Fulton et al., 2011). The Menhaden, Irish Sea Groundfish, Hawai'i Coral Reef, and Louisiana Wetland Restoration case studies in particular involved extensive communication that, in effect, led to the co-production of knowledge among scientists, managers, and stakeholders (Anstead et al., 2021; Bentley et al., 2021; de Mutsert et al., 2021; Weijerman et al., 2021). Early and iterative communication ensures that scientists understand the policy issue, stakeholders understand the capabilities and limitations of the model, the modelling objectives are well-aligned with the policy question and can inform the available management options, and appropriate model outputs are agreed upon (Fulton et al., 2015; Jones & Seara, 2020; Tommasi et al., 2021). Effective communication builds familiarity, credibility, and confidence while also promoting transparency, trust, and an understanding of the political arena in which decisions are made (Djenontin & Meadow, 2018).

Periodic review throughout the model development process and formal external review of final models is typically a prerequisite for use of model results in resource management (Figure 1; Kaplan & Marshall, 2016; Townsend et al., 2008, 2014, 2019). The level of review is generally beyond that required for peer-reviewed publication, and typically involves independent expert panels, extensive documentation, in-person workshops, real-time model runs, and both independent and consensus reviewer reports. Though the extent and formality of external review varied, five of the 10 case studies, and all of those used for tactical decision-making, underwent external review that focused on the utility of the model to support management decisions. The US Northeast Groundfish Assessment Review case study in particular illustrates the extensive level of documentation and review that is often required for the use of models in resource management (NEFSC, 2008).

Five of the 10 case studies developed an EwE model as part of a larger suite of models that included at least one and sometimes up to four other ecosystem models (Table 2). Developing multiple models addresses structural uncertainty (i.e., variability arising from the particular mathematical representation of the system; Walker et al., 2003), and increases the confidence and acceptance of the model results (Reum, Kelble, et al., 2021; Reum, Townsend, et al., 2021). Given the time and resources needed to develop ecosystem models, opportunistically leveraging and adapting existing models to address new questions is also not uncommon (Figure 1). Essington and Plagányi (2014) describe some of the pitfalls of recycling ecosystem models and provide guidelines for adapting existing models to address new questions. Documenting the model structure, spatial and temporal resolution, required data inputs, adequacy of modelled trends, and sensitivity to key parameters can help avoid pitfalls and identify where existing models have further applications, hence, streamlining the model development process.

3.3 | Challenges to the operational use of ecosystem models

Management frameworks, policy considerations, and jurisdictional issues—It is clear from many of the case studies that the management framework often imposes limitations on the operational use of EwE and other ecosystem models, either because it is highly structured with fairly limited opportunity for new information and approaches (e.g., Menhaden and Irish Sea Groundfish), not sufficiently developed to support decision-making based on model outputs (e.g., Landing Obligation and Good Environmental Status), or simply lacks precedent for using ecosystem models (e.g., EIAs for Offshore Wind Farms and Wetland Restoration). This seems to be as much or more of a limitation to operational use than technical issues related to data availability and model uncertainty that are often noted with respect to EwE and other ecosystem models.

Integrating ecosystem models within a well-developed management process that does not have a strong history of ecosystem considerations can be challenging. In the Menhaden example, there was a long history of considering predator–prey interactions in assessment and management prior to the formal development of ecosystem models (Anstead et al., 2021). This history, in combination with a common management authority for the species of concern, enhanced the familiarity of stakeholders with the issue, which led to the formulation of clear policy objectives and actionable management options. A somewhat similar situation exists in the Irish Sea Groundfish example, where multiple species are managed based on ICES advice provided to a Council of Fisheries Ministers, and consensus has been growing among stakeholders that significant ecosystem changes influencing the productivity of multiple stocks has occurred (Bentley et al., 2021). The EwE models in these cases were used in combination with existing single-species assessment models to address specific and well-defined questions, which facilitated their use within the existing management frameworks (Howell et al., 2021), but also limited a more comprehensive analysis of trade-offs, and indirect and cumulative effects. Where management systems and associated modelling approaches are well-established, the burden of proof will often be to demonstrate that alternative approaches result in improved management performance. MSE can be helpful in this regard, and the use of EwE (Mackinson et al., 2018) and other multispecies (Trijoulet et al., 2019, 2020) and ecosystem models (Kaplan et al., 2021) to evaluate the performance of alternative management strategies is growing. Even so, single-species and single-sector models will only be useful for answering questions about the status, trends, and trade-offs within a particular species or sector of ocean use (e.g., fishing). Nearly all management decisions involve trade-offs that often extend beyond single species or sectors (Table 1). EwE or other ecosystem models are the best option for identifying, quantifying, and addressing these trade-offs in a direct and transparent manner.

Less formalized management frameworks, characteristic of multi-sector resource issues, may be more amenable to the use of EwE and other ecosystem models. However, stakeholder objectives are often not sufficiently defined and a formal decision-making process to address cross-jurisdictional trade-offs and conflicts rarely exists. For instance, the Hawai'i Coral Reefs example has shown that the status quo is the least desirable option for sustaining the multiple ecosystem services provided by coral reefs (Weijerman, Gove, et al., 2018). However, the set of alternative management options to enact suitable changes is spread across multiple jurisdictions (i.e., fisheries, tourism, land use), which requires a complex decision-making process and significant effort to characterize the specific social and economic objectives of multiple stakeholder groups (Weijerman et al., 2021). A similar situation exists in the Wetlands Restoration example, where proposed sediment diversion projects have implications for land restoration, storm protection, fisheries, and protected species (de Mutsert et al., 2021; USACE, 2022), as well as the other multi-sector (e.g., GES, Offshore Wind Farms) and even within sector (e.g., Landing Obligation) case studies. Lack of clearly defined objectives and a structured management framework for identifying and addressing trade-offs should not be construed as a limitation of ecosystem models to address policy-relevant questions.

To address these challenges, stakeholder objectives, desired or acceptable states of ecosystems, and criteria for making decisions regarding trade-offs need to be as explicit as possible and revisited and increasingly refined over time. As ecosystems change due to natural or anthropogenic factors and as multi-sector resource use of marine systems increases, highly structured management frameworks will need to enhance procedural flexibility and develop protocols to accommodate a broader range of issues and alternative modelling approaches. Less formalized management frameworks will need to sufficiently define stakeholder objectives and develop processes for trade-off evaluation and conflict resolution that quantitative ecosystem models can then address. Addressing these challenges will require balancing the need to provide useful and robust management advice to decision-makers in a familiar and efficient manner, while also allowing for innovation and new sources of information and modelling tools. Useful ecosystem modelling can certainly occur outside of a management framework, but there is a lower probability that it will address stakeholder objectives or significantly influence the decision-making process, and a higher probability that the scope of the model will become too large, which can actually impede its use for management.

Data, uncertainty, and the use of ecosystem models in resource management—A common perception of EwE and ecosystem models in general is that high model complexity, combined with the lack of easily applied procedures to address uncertainty and model performance, limits their utility for tactical management applications (Collie et al., 2016; Fulton et al., 2003; Hyder et al., 2015; Link et al., 2012; Skogen et al., 2021). Limited data to parameterize and validate EwE models is a real concern for many ecosystems, and some model outputs will have a high degree of uncertainty compared to those from single-species or -sector models. While EwE models are not parameterized by fitting to data to the same extent as most single-species models, they are increasingly tuned to historical times series, estimate several model parameters, and are increasingly subject to an array of model diagnostics (Heymans et al., 2016; Lassalle et al., 2014; Link, 2010a, 2010b; Olsen et al., 2016; Scott et al., 2016; Steenbeek et al., 2018, 2021). Methods to assess uncertainty are increasingly applied to EwE (Essington, 2007; Gaichas et al., 2012; Guesnet et al., 2015; Whitehouse & Aydin, 2020) and to other ecosystem models (Bauer et al., 2019; Gårdmark et al., 2013; Spence et al., 2018), and approaches for effective decision-making in the face of uncertainty exist (Garrand et al., 2017). Parameter uncertainty is often the basis for assertions that EwE is not appropriate for tactical management, but should be considered within the context of other types of uncertainty that are relevant to any model for resource management, including implementation and outcome uncertainty, uncertain management objectives, inadequate stakeholder communication, natural variability, and bias-variance trade-offs (Collie et al., 2016; Fulton et al., 2003; Link et al., 2012; Peterman, 2004; Townsend et al., 2017). The Mixed Species Fisheries example is a good illustration of a bias-variance trade-off, where simple (single species) modelling approaches applied to complex (multispecies) fisheries has resulted in overly optimistic management advice. While EwE and other ecosystem models have the potential for high dimensionality, complexity, and associated uncertainty, they can often be structured in a way that balances the desire for increased realism while limiting model uncertainty to levels that are acceptable within a resource management context (Chagaris et al., 2020; Collie et al., 2016; Plagányi et al., 2014).

3.4 | Tactical and strategic model applications

EwE was originally envisioned as a strategic tool to help support fisheries management by screening alternative policy options, conducting scenario analyses, and identifying management approaches that are robust to uncertainty (Walters et al., 1997), and these applications remain an important use. However, the increasing capability of EwE to explore model fits to data and the development of model diagnostics and best practices have made the platform more amenable to tactical applications. There is also a need to broaden the consideration of what constitutes a tactical application of ecosystem models to support resource management decisions. For example, there are many tactical decisions in fisheries beyond setting annual catch limits that could be informed by EwE, such as determining when and where to implement annual spawning season and other closures, setting opening dates for fisheries, and identifying areas and times where bycatch interactions should be monitored or limited. The key point is that strategic and tactical decisions are related, both are aspects of the operational use of models to support resource management, both are critical for effective decision-making, and both can benefit from the use of EwE and other ecosystem models.

EwE models are helping to inform tactical decisions in ocean use sectors in addition to fisheries, as illustrated by the Offshore Wind Farms and Wetland Restoration case studies. The strategic decisions to pursue offshore wind farms (to support renewable energy production) and sediment diversions (to support wetland restoration) have already been made. Which sediment diversion projects to pursue and how best to operate gated diversion structures (i.e., timing, duration, and magnitude of water releases) to support wetland restoration while minimizing impacts to key fishery species is a tactical decision. Similarly, the specific siting of wind farms and the logistics of their operation while minimizing impacts to fisheries and protected species is a tactical decision. In the Hawaiʻi Coral Reefs example, the EwE model identified limiting nutrient and sediment runoff as important for preserving reef-dependent fisheries (a strategic application), but could also be used to inform specific nutrient reduction targets and evaluate the efficacy of associated regulatory measures, such as the operation of septic systems or remediation measures, to meet those targets (a tactical application). Other case studies illustrate the potential for EwE models to inform tactical decision-making, even if they are not the primary model on which short-term management advice is based. For example, the Mixed Species Fisheries and US Northeast Groundfish Assessment Review case studies evaluate the feasibility of obtaining sustainable yields estimated from single-species models from a multispecies complex, and, hence, are helping to evaluate and refine the management advice based on current single-species assessment approaches. The use of EwE to retrospectively evaluate current policies, as these particular examples illustrate, is a first step toward the use of ecosystem models to provide tactical management advice (Mackinson et al., 2018).

4 | SUMMARY AND CONCLUSIONS

Our primary assertion is that the requisite conditions for enhanced operational use of EwE to support and inform resource management decisions exists, and these models can contribute to both strategic and tactical management decisions (Fulton et al., 2018; Karp et al., 2023; Lehuta et al., 2016). Based on the case studies presented here, the successful use of EwE in an operational resource management context requires: (1) a well-defined management objective that can be addressed through modelling, (2) a clear trade-off and a management process receptive to the evaluation of trade-offs, (3) an accessible and well-documented model that follows best practices, (4) early and iterative engagement among scientists, stakeholders, and managers, (5) a model development process that is collaborative, interactive, and iterative in nature, (6) a multi-model approach, and (7) a rigorous and tailored review process. Many of these elements have been recognized with respect to multispecies and ecosystem models in general (Anstead et al., 2021; Bentley et al., 2021; Karp et al., 2023; Reum, Kelble, et al., 2021; Reum, Townsend, et al., 2021; Townsend et al., 2019), but the case studies reviewed here demonstrate their particular application with respect to a suite of recent EwE models that span a broad range of ecosystem management approaches (i.e., EAF, EBFM, EBM). EwE and ecosystem models in general are particularly useful for identifying and quantitatively evaluating trade-offs, which are a near universal feature of marine resource management. Hence, EwE and other ecosystem models should be routinely used in concert with existing approaches to provide more robust decision-making support.

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CONFLICT OF INTEREST STATEMENT

The authors declare no competing interests.

DATA AVAILABILITY STATEMENT

Data sharing not applicable - no new data generated.

ORCID

J. Kevin Craig https://orcid.org/0000-0002-0148-4989
Jason S. Link https://orcid.org/0000-0003-2740-7161

REFERENCES

Ahrenholz, D. W., Nelson, W. R., & Epperly, S. P. (1987). Population and fishery characteristics of Atlantic menhaden, *Brevoortia tyrannus*. *Fishery Bulletin*, *85*, 569–600.

Ainsworth, C. H., & Walters, C. J. (2015). Ten common mistakes made in Ecopath with Ecosim modelling. *Ecological Modelling*, *308*, 14–17. https://doi.org/10.1016/j.ecolmodel.2015.03.019

Alexander, K. A., & Haward, M. (2019). The human side of marine ecosystem-based management (EBM): 'Sectoral interplay' as a challenge to implementing EBM. *Marine Policy*, *101*, 33–38. https://doi.org/10.1016/j.marpol.2018.12.019

Alexander, K. A., Heymans, J. J., Magill, S., Tomczak, M. T., Holmes, S. J., & Wilding, T. A. (2015). Investigating the recent decline in gadoid stocks in the west of Scotland shelf ecosystem using a foodweb model. *ICES Journal of Marine Science*, *72*, 436–449. https://doi.org/10.1093/icesjms/fsu149

Alexander, K. A., Meyjes, S. A., & Heymans, J. J. (2016). Spatial ecosystem modelling of marine renewable energy installations: Gauging the utility of Ecospace. *Ecological Modelling*, *331*, 115–128. https://doi.org/10.1016/j.ecolmodel.2016.01.016

Andersen, K. H., Brander, K., & Ravn-Jonsen, L. (2015). Trade-offs between objectives for ecosystem management of fisheries. *Ecological Applications*, *25*, 1390–1396. https://doi.org/10.1890/14-1209.1

Angelini, S., Hillary, R., Morello, E. B., Plagányi, É. E., Martinelli, M., Manfredi, C., Isajlović, I., & Santojanni, A. (2016). An ecosystem model of intermediate complexity to test management options for fisheries: A case study. *Ecological Modelling*, *319*, 218–232. https://doi.org/10.1016/j.ecolmodel.2015.07.031

Anstead, K. A., Drew, K., Chagaris, D., Cieri, M., Schueller, A. M., McNamee, J. E., Buchheister, A., Nesslage, G., Uphoff, J. H., Jr., Wilberg, M. J., Sharov, A., Dean, M. J., Brust, J., Celestino, M., Madsen, S., Murray, S., Appelman, M., Ballenger, J. C., Briot, J., … Townsend, H. (2021). The path to an ecosystem approach for forage fish management: A case study of Atlantic menhaden. *Frontiers in Marine Science*, *8*, 607657. https://doi.org/10.3389/fmars.2021.607657

AORA. (2018). *Working group on the ecosystem approach to ocean health and stressors* (p. 27). Mandates.

Arkema, K. K., Abramson, S. C., & Dewsbury, B. M. (2006). Marine ecosystem-based management: From characterization to implementation. *Frontiers in Ecology and the Environment*, *4*, 525–532. https://doi.org/10.1890/1540-9295(2006)4[525:MEMFCT]2.0CO;2

ASMFC. (2022). *Understanding ecological reference points: Everything you need to know about the development of ERPs for Atlantic Menhaden*.

https://storymaps.arcgis.com/stories/6b69018f0f264f61aaac5f1aba3bb5c0

Ateweberhan, M., Feary, D. A., Keshavmurthy, S., Chen, A., Schleyer, M. H., & Sheppard, C. R. C. (2013). Climate change impacts on coral reefs: Synergies with local effects, possibilities for acclimation, and management implications. *Marine Pollution Bulletin*, *74*, 526–539. https://doi.org/10.1016/j.marpolbul.2013.06.011

Bailey, H., Brookes, K. L., & Thompson, P. M. (2014). Assessing environmental impacts of offshore wind farms: Lessons learned and recommendation for the future. *Aquatic Biosystems*, *10*, 8. https://doi.org/10.1186/2046-9063-10-8

Ballesteros, M., Chapela, R., Ramírez-Monsalve, P., Raakjaer, J., Hegland, T. J., Nielsen, K. N., Laksá, U., & Degnbol, P. (2018). Do not shoot the messenger: ICES advice for an ecosystem approach to fisheries management in the European Union. *ICES Journal of Marine Science*, *75*, 519–530. https://doi.org/10.1093/icesjms/fsx181

Bartell, S. M., Nair, S. K., Galic, N., & Brain, R. A. (2020). The comprehensive aquatic systems model (CASM): Advancing computational capability for ecosystem simulation. *Environmental Toxicology and Chemistry*, *39*, 2298–2303. https://doi.org/10.1002/etc.4843

Baudron, A. R., Serpetti, N., Fallon, N. G., Heymans, J. J., & Fernandes, P. G. (2019). Can the common fisheries policy achieve good environmental status in exploited ecosystems: The west of Scotland demersal fisheries example. *Fisheries Research*, *211*, 217–230. https://doi.org/10.1016/j.fishres.2018.10.024

Bauer, B., Horbowy, J., Rahikainen, M., Kulatska, N., Müller-Karulis, B., Tomczak, M. T., & Bartolino, V. (2019). Model uncertainty and simulated multispecies fisheries management advice in the Baltic Sea. *PLoS One*, *14*, e0211320. https://doi.org/10.1371/journal.pone.0211320

Belgrano, A., Sharler, U. M., Dunne, J., & Ulanowicz, R. E. (Eds.). (2005). *Aquatic food webs: An ecosystem approach* (p. 262). Oxford University Press.

Bentley, J. W., Hines, D., Borrett, S., Serpetti, N., Fox, C., Reid, D. G., & Heymans, J. J. (2019). Diet uncertainty analysis strengthens model-derived indicators of food web structure and function. *Ecological Indicators*, *98*, 239–250. https://doi.org/10.1016/j.ecolind.2018.11.008

Bentley, J. W., Hines, D. E., Borrett, S. R., Serpetti, N., Hernandez-Milian, G., Fox, C., Heymans, J. J., & Reid, D. G. (2019). Combining scientific and fishers' knowledge to co-create indicators of food web structure and function. *ICES Journal of Marine Science*, *76*, 2218–2234. https://doi.org/10.1093/icesjms/fsz121

Bentley, J. W., Lundy, M. G., Howell, D., Beggs, S. E., Bundy, A., de Castro, F., Fox, C. J., Heymans, J. J., Lynam, C. P., Pedreschi, D., Schuchert, P., Serpetti, N., Woodlock, J., & Reid, D. G. (2021). Refining fisheries advice with stock-specific ecosystem information. *Frontiers in Marine Science*, *8*, 602072. https://doi.org/10.3389/fmars.2021.602072

Bentley, J. W., Serpetti, N., Fox, C. J., Heymans, J. J., & Reid, D. G. (2019). Fishers' knowledge improves the accuracy of food web model predictions. *ICES Journal of Marine Science*, *76*, 897–912. https://doi.org/10.1093/icesjms/fsz003

Bentley, J. W., Serpetti, N., Fox, C. J., Heymans, J. J., & Reid, D. G. (2020). Retrospective analysis of the influence of environmental drivers on commercial stocks and fishing opportunities in the Irish Sea. *Fisheries Oceanography*, *29*, 415–435. https://doi.org/10.1111/fog.12486

Borja, A., Elliott, M., Andersen, J. H., Cardoso, A. C., Carstensen, J., Ferreira, J. G., Heiskanen, A.-S., Marques, J. C., Neto, J. M., Teixeira, H., Uusitalo, L., Uyarra, M. C., & Zampoukas, N. (2013). Good environmental status of marine ecosystems: What is it and how do we know when we have attained it? *Marine Pollution Bulletin*, *76*, 16–27. https://doi.org/10.1016/j.marpolbul.2013.08.042

Boschetti, F., Hughes, M., Jones, C., & Lozano-Montes, H. (2018). On decision makers' perceptions of what an ecological computer model is, what it does, and its impact on limiting modeling acceptance. *Sustainability*, *10*, 2767. https://doi.org/10.3390/su10082767

Bourdaud, P., Gascuel, D., Bentorcha, A., & Brind'Amour, A. (2016). New trophic indicators and target values for an ecosystem-based management of fisheries. *Ecological Indicators*, *61*, 588–601. https://doi.org/10.1016/j.ecolind.2015.10.010

Brodziak, J., Cadrin, S. X., Legault, C. M., & Murawski, S. A. (2008). Goals and strategies for rebuilding New England groundfish stocks. *Fisheries Research*, *94*, 355–366. https://doi.org/10.1016/j.fishres.2008.03.008

Buchheister, A., Miller, T. J., & Houde, E. D. (2017). Evaluating ecosystem-based reference points for Atlantic Menhaden. *Marine and Coastal Fisheries: Dynamics, Management, and Ecosystem Science*, *9*, 457–478. https://doi.org/10.1080/19425120.2017.1360420

Bull, A. S., & Love, M. S. (2019). Worldwide oil and gas platform decommissioning: A review of practices and reefing options. *Ocean and Coastal Management*, *168*, 274–306. https://doi.org/10.1016/j.ocecoaman.2018.10.024

Burgess, M. G., Giacomini, H. C., Szuwalski, C. S., Costello, C., & Gaines, S. D. (2017). Describing ecosystem contexts with single-species models: A theoretical synthesis for fisheries. *Fish and Fisheries*, *18*, 264–284. https://doi.org/10.1111/faf.12179

Catchpole, T. L., Ribeiro-Santos, A., Mangi, S. C., Hedley, C., & Gray, T. S. (2017). The challenges of the landing obligation in EU fisheries. *Marine Policy*, *82*, 76–86. https://doi.org/10.1016/j.marpol.2017.05.001

Celić, I., Libralato, S., Scarcella, G., Raicevich, S., Marčeta, B., & Solidoro, C. (2018). Ecological and economic effects of the landing obligation evaluated using a quantitative ecosystem approach: A Mediterranean case study. *ICES Journal of Marine Science*, *75*, 1992–2003. https://doi.org/10.1093/icesjms/fsy069

Chagaris, D., Drew, K., Schueller, A., Cieri, M., Brito, J., & Buchheister, A. (2020). Ecological reference points for Atlantic Menhaden established using an ecosystem model of intermediate complexity. *Frontiers in Marine Science*, *7*, 606417. https://doi.org/10.3389/fmars.2020.606417

Chen, N., Sun, M., Zhang, C., Ren, Y., & Chen, Y. (2022). Non-stationarity natural mortality influencing the stock assessment of Atlantic cod (*Gadus morhua*) in a changing Gulf of Maine. *Frontiers in Marine Science*, *28*, 845787. https://doi.org/10.3389/fmars.2022.845787

Christensen, V., Guénette, S., Heymans, J. J., Walters, C. J., Watson, R., Zeller, D., & Pauly, D. (2003). Hundred-year decline of North Atlantic predatory fishes. *Fish and Fisheries*, *4*, 1–24. https://doi.org/10.1046/j.1467-2979.2003.00103.x

Christensen, V., & Pauly, D. (2004). Placing fisheries in their ecosystem context, an introduction. *Ecological Modelling*, *172*, 103–107. https://doi.org/10.1016/j.ecolmodel.2003.09.002

Christensen, V., & Walters, C. J. (2004). Ecopath with Ecosim: Methods, capabilities, and limitations. *Ecological Modelling*, *172*, 109–139. https://doi.org/10.1016/j.ecolmodel.2003.09.003

Christou, M., de Juan, S., Vassilopoulou, V., Stergiou, K. I., & Maynou, F. (2019). Monitoring the environmental, social and economic dimension of the landing obligation policy. *Frontiers in Marine Science*, *6*, 594. https://doi.org/10.3389/fmars.2019.00594

Coll, M., Akoglu, E., Arreguín-Sánchez, F., Fulton, E. A., Gascuel, D., Heymans, J. J., Libralato, S., Mackinson, S., Palomera, I., Piroddi, C., Shannon, L. J., Steenbeek, J., Villasante, S., & Christensen, V. (2015). Modelling dynamic ecosystems: Venturing beyond boundaries with the Ecopath approach. *Reviews in Fish Biology and Fisheries*, *25*, 413–424. https://doi.org/10.1007/s11160-015-9386-x

Coll, M., & Libralato, S. (2012). Contributions of food web modelling to the ecosystem approach to marine resource management in the Mediterranean Sea. *Fish and Fisheries*, *13*, 60–88. https://doi.org/10.1111/j.1467-2979.2011.00420.x

Colléter, M., Valls, A., Guitton, J., Gascuel, D., Pauly, D., & Christensen, V. (2015). Global overview of the applications of the Ecopath with

Ecosim modeling approach using the EcoBase models repository. *Ecological Modelling*, *302*, 42–53. https://doi.org/10.1016/j.ecolmodel.2015.01.025

Colléter, M., Valls, A. E., Guitton, J., Morissette, L., Arreguín-Sánchez, F. F., Christensen, V., Gascuel, D., & Pauly, D. (2013). *EcoBase: A repository solution to gather and communicate information from EwE models*. Fisheries Centre Research Reports 21(1). University of British Columbia. https://doi.org/10.14288/1.0354309

Collie, J. S., Botsford, L. W., Hastings, A., Kaplan, I. C., Largier, J. L., Livingston, P. A., Plagányi, E. E., Rose, K. A., Wells, B. K., & Werner, F. E. (2016). Ecosystem models for fisheries management: Finding the sweet spot. *Fish and Fisheries*, *17*, 101–125. https://doi.org/10.1111/faf.12093

Cowan, J. H., Rice, J. C., Walters, C. J., Hilborn, R., Essington, T. E., Day, J. W., & Boswell, K. M. (2012). Challenges for implementing an ecosystem approach to fisheries management. *Marine and Coastal Fisheries: Dynamics, Management, and Ecosystem Science*, *4*, 496–510. https://doi.org/10.1080/19425120.2012.690825

CPRA. (2017). *Louisiana's comprehensive master plan for a sustainable coast*. Coastal Protection and Restoration Authority of Louisiana.

Damalas, D. (2015). Mission impossible: Discard management plans for the EU Mediterranean fisheries under the reformed common fisheries policy. *Fisheries Research*, *165*, 96–99. https://doi.org/10.1016/j.fishres.2015.01.006

Day, J. W., Cable, J. E., Cowan, J. H., Jr., DeLaune, D., de Mutsert, K., Fry, B., Mashriqui, H., Justic, D., Kemp, P., Lane, R. R., Rick, J., Rick, S., Rozas, L. P., Snedden, G., Swenson, E., Twilley, R. R., & Wissel, B. (2009). The impacts of pulsed reintroduction of river water on a Mississippi delta coastal basin. *Journal of Coastal Research*, *54*, 225–243. https://doi.org/10.2112/SI54-015.1

de Mutsert, K., Cowan, J. H., Jr., & Walters, C. J. (2012). Using Ecopath with Ecosim to explore nekton community response to freshwater diversion into a Louisiana estuary. *Marine and Coastal Fisheries: Dynamics, Management and Ecosystem Science*, *4*, 104–116. https://doi.org/10.1080/19425120.2012.672366

de Mutsert, K., Lewis, K., Milroy, S., Buszowski, J., & Steenbeek, J. (2017). Using ecosystem modeling to evaluate trade-offs in coastal management: Effects of large-scale river diversion on fish and fisheries. *Ecological Modelling*, *360*, 14–26. https://doi.org/10.1016/j.ecolmodel.2017.06.029

de Mutsert, K., Lewis, K. A., White, E. D., & Buszowski, J. (2021). End-to-end modeling reveals species-specific effects of large-scale coastal restoration on living resources facing climate change. *Frontiers in Marine Science*, *8*, 624532. https://doi.org/10.3389/fmars.2021.624532

Department of Aquatic Resource (DAR). (2022). *Marine 30 × 30: Effective management of Hawai'i's nearshore waters for healthy reefs, fish, and communities*. https://dlnr.hawaii.gov/dar/30x30/

Dickey-Collas, M. (2014). Why the complex nature of integrated ecosystem assessments requires a flexible and adaptive approach. *ICES Journal of Marine Science*, *71*, 1174–1182. https://doi.org/10.1093/icesjms/fsu027

Djenontin, I. N. S., & Meadow, A. M. (2018). The art of co-production of knowledge in environmental sciences and management: Lessons from international practice. *Environmental Management*, *61*, 885–903. https://doi.org/10.1007/s00267-018-1028-3

Dolan, T. E., Patrick, W. S., & Link, J. S. (2016). Delineating the continuum of marine ecosystem-based management: A U.S. fisheries reference point perspective. *ICES Journal of Marine Science*, *73*, 1042–1050. https://doi.org/10.1093/icesjms/fsv242

Dorn, M. W., & Barnes, C. L. (2022). Time-varying predation as a modifier of constant natural mortality for Gulf of Alaska walleye pollock. *Fisheries Research*, *254*, 106391. https://doi.org/10.1016/j.fishres.2022.106391

Drew, K., Cieri, M., Schueller, A. M., Buchheister, A., Chagaris, D., Nesslage, G., McNamee, J. E., & Uphoff, J. H. (2021). Balancing model complexity, data requirements, and management objectives in developing ecological reference points for Atlantic Menhaden. *Frontiers in Marine Science*, *8*, 608059. https://doi.org/10.3389/fmars.2021.608059

EC. (2008). Directive 2008/56/EC of the European Parliament and of the Council of June 17th 2008 establishing a framework for community action in the field of marine environmental policy (marine strategy framework directive). *Official Journal of the European Union*, *L164*, 19–40.

Elvarsson, B. P., Agnarsson, S., Guðmundsdóttir, S., & Viðarsson, J. (2020). Using multi-criteria analysis to assess impacts of change in ecosystem-based fisheries management: The case of the Icelandic cod. *Marine Policy*, *116*, 103825. https://doi.org/10.1016/j.marpol.2020.103825

Espinoza-Tenorio, A., Wolff, M., Taylor, M. H., & Espejel, I. (2012). What model suits ecosystem-based fisheries management? A plea for a structured modeling process. *Reviews in Fish Biology and Fisheries*, *22*, 81–94. https://doi.org/10.1007/s11160-011-9224-8

Essington, T. E. (2007). Evaluating the sensitivity of a trophic mass-balance model (Ecopath) to imprecise data inputs. *Canadian Journal of Fisheries and Aquatic Sciences*, *64*, 628–637. https://doi.org/10.1139/F07-042

Essington, T. E., & Munch, S. B. (2014). Trade-offs between supportive and provisioning ecosystem services of forage species in marine food webs. *Ecological Applications*, *24*, 1543–1557. https://doi.org/10.1890/13-1403.1

Essington, T. E., & Plagányi, É. E. (2014). Pitfalls and guidelines for "recycling" models for ecosystem-based fisheries management: Evaluating model suitability for forage fish fisheries. *ICES Journal of Marine Science*, *71*, 118–127. https://doi.org/10.1093/icesjms/fst047

Esteban, M., & Leary, D. (2012). Current developments and future prospects of offshore wind and ocean energy. *Applied Energy*, *90*, 128–136. https://doi.org/10.1016/j.apenergy.2011.06.011

FAO. (2008). *Best practices in ecosystem modelling for informing an ecosystem approach to fisheries. FAO fisheries technical guidelines for responsible fisheries. No. 4, Supplement 2* (p. 78). FAO.

Ferreira, M. A., Froján, C. B., Gunn, V., & Johnson, D. E. (2022). A role for UNEP's regional Seas Programme under the post-2020 global biodiversity framework. *Marine Policy*, *136*, 104930. https://doi.org/10.1016/j.marpol.2021.104930

Fock, H. O., Kloppmann, M., & Stelzenmüller, V. (2011). Linking marine fisheries to environmental objectives: A case study on seafloor integrity under European maritime policies. *Environmental Science and Policy*, *14*, 289–300. https://doi.org/10.1016/j.envsci.2010.11.005

Fogarty, M. J. (2014). The art of ecosystem-based fishery management. *Canadian Journal of Fisheries and Aquatic Sciences*, *71*, 479–490. https://doi.org/10.1139/cjfas-2013-0203

Fogarty, M. J., & Murawski, S. A. (1998). Large-scale disturbance and the structure of marine systems: Fishery impacts on Georges Bank. *Ecological Applications*, *8*, S6–S22. https://doi.org/10.1890/1051-0761(1998)8[S6:LDATSO]2.0.CO;2

Fogarty, M. J., Overholtz, W. J., & Link, J. S. (2008). *Fishery production potential of the northeast continental shelf of the United States. GARM WP 3.5 GARM-III-BRP meeting*. National Marine Fisheries Service.

Fogarty, M. J., Overholtz, W. J., & Link, J. S. (2012). Aggregate surplus production models for demersal fishery resources of the Gulf of Maine. *Marine Ecology Progress Series*, *459*, 247–258. https://doi.org/10.3354/meps09789

Fondo, E. N., Chaloupka, M., Heymans, J. J., & Skilleter, G. A. (2015). Banning fisheries discards abruptly has a negative impact on the population dynamics of charismatic marine megafauna. *PLoS One*, *10*, e0144543. https://doi.org/10.1371/journal.pone.0144543

Foran, C. M., Link, J. S., Patrick, W. S., Sharpe, L., Wood, M., & Linkov, I. (2016). Relating mandates in the United States for managing the ocean to ecosystem goods and services demonstrates broad but varied coverage. *Frontiers in Marine Science*, *3*, 5. https://doi.org/10.3389/fmars.2016.00005

Froehlich, H. E., Smith, A. A., Gentry, R. R., & Halpern, B. S. (2017). Offshore aquaculture: I know it when I see it. *Frontiers in Marine Science*, *4*, 154. https://doi.org/10.3389/fmars.2017.00154

Fu, C., Xu, Y., Bundy, A., Grüss, A., Coll, M., Heymans, J. J., Fulton, E. A., Shannon, L., Halouani, G., Velez, L., Akoglu, E., Lynam, C. P., & Shin, Y.-J. (2019). Making ecological indicators management ready: Assessing the specificity, sensitivity, and threshold response of ecological indicators. *Ecological Indicators*, *105*, 16–28. https://doi.org/10.1016/j.ecolind.2019.05.055

Fulton, E. A., Boschetti, F., Sporcic, M., Jones, T., Little, L. R., Dambacher, J. M., Gray, R., Scott, R., & Gorton, R. (2015). A multi-model approach to engaging stakeholder and modellers in complex environmental problems. *Environmental Science and Policy*, *48*, 44–56. https://doi.org/10.1016/j.envsci.2014.12.006

Fulton, E. A., Link, J. S., Kaplan, I. C., Savina-Rolland, M., Johnson, P., Ainsworth, C., Horne, P., Gorton, R., Gamble, R. J., Smith, A. D. M., & Smith, D. C. (2011). Lessons in modelling and management of marine ecosystems: The Atlantis experience. *Fish and Fisheries*, *12*, 171–188. https://doi.org/10.1111/j.1467-2979.2011.00412.x

Fulton, E. A., Punt, A. E., Dichmont, C. M., Harvey, C. J., & Gorton, R. (2018). Ecosystems say good management pays off. *Fish and Fisheries*, *20*, 66–96. https://doi.org/10.1111/faf.12324

Fulton, E. A., Sainsbury, K., Noranarttragoon, P., Leadbitter, D., Staples, D. J., Porobic, J., Ye, Y., Phoonsawat, R., & Kulanujaree, N. (2022). Shifting baselines and deciding on the desirable form of multispecies maximum sustainable yield. *ICES Journal of Marine Science*, *79*, 2138–2154. https://doi.org/10.1093/icesjms/fsac150

Fulton, E. A., Smith, A. D. M., & Johnson, C. R. (2003). Effect of complexity on marine ecosystem models. *Marine Ecology Progress Series*, *253*, 1–16. https://doi.org/10.3354/meps253001

Funge-Smith, S., & Bennett, A. (2019). A fresh look at inland fisheries and their role in food security and livelihoods. *Fish and Fisheries*, *20*, 1176–1195. https://doi.org/10.1111/faf.12403

Furness, R. W., Wade, H. M., & Masden, E. A. (2013). Assessing vulnerability of marine bird populations to offshore wind farms. *Journal of Environmental Management*, *119*, 56–66. https://doi.org/10.1016/j.jenvman.2013.01.025

Gaichas, S. K., Fogarty, M., Fay, G., Gamble, R., Lucey, S., & Smith, L. (2017). Combing stock, multispecies, and ecosystem level fishery objectives within an operational management procedure: Simulations to start the conversation. *ICES Journal of Marine Science*, *74*, 552–565. https://doi.org/10.1093/icesjms/fsw119

Gaichas, S. K., Odell, G., Aydin, K. Y., & Francis, R. C. (2012). Beyond the defaults: Functional response parameter space and ecosystem-level fishing thresholds in dynamics food web model simulations. *Canadian Journal of Fisheries and Aquatic Sciences*, *69*, 2077–2094. https://doi.org/10.1139/f2012-09

Garcia, S. M., Kolding, J., Rice, J., Rochet, M. J., Zhou, S., Arimoto, T., Beyer, J. E., Borges, L., Bundy, A., Dunn, D., Fulton, E. A., Hall, M., Neino, M., Law, R., Makino, M., Rijnsdorp, A. D., Simard, F., & Smith, A. D. M. (2012). Reconsidering the consequences of selective fisheries. *Science*, *335*, 1045–1047. https://doi.org/10.1126/science.1214594

Garcia, S. M., Zerbi, A., Aliaume, C., Do Chi, T., & Lasserre, G. (2003). *The ecosystem approach to fisheries. Issues, terminology, principles, institutional foundations, implementation and outlook. FAO fisheries technical paper. No. 443* (p. 71). FAO.

Gårdmark, A., Lindegren, M., Neuenfeldt, S., Blenckner, T., Heikinheimo, O., Müller-Karulis, B., Niiranen, S., Tomczak, M. T., Aro, E., Wikström, A., & Möllmann, C. (2013). Biological ensemble modeling to evaluate potential futures of living marine resources. *Ecological Applications*, *23*, 742–754. https://doi.org/10.1890/12-0267.1

Garrand, G. E., Rumpff, L., Runge, M. C., & Converse, S. J. (2017). Rapid prototyping for decision structuring: An efficient approach to conservation decision analysis. In N. Bunnefeld, E. Nicholson, & E. J. Milner-Gulland (Eds.), *Decision-making in conservation and natural resource management: Models for interdisciplinary approaches* (pp. 46–64). Cambridge University Press.

Gavaris, S. (2009). Fisheries management planning and support for strategic and tactical decisions in an ecosystem approach context. *Fisheries Research*, *100*, 6–14. https://doi.org/10.1016/j.fishres.2008.12.001

Geary, W. L., Bode, M., Doherty, T. S., Fulton, E. A., Nimmo, D. G., Tulloch, A. I. T., Tulloch, V. J. D., & Ritchie, E. G. (2020). A guide to ecosystem models and their environmental applications. *Nature Ecology and Evolution*, *4*, 1459–1471. https://doi.org/10.1038/s41559-020-01298-8

Grüss, A., Rose, K. A., Simons, J., Ainsworth, C. H., Babcock, E. A., Chagaris, D. D., De Mutsert, K., Froeschke, J., Himchak, P., Kaplan, I. C., O'Farrell, H., & Zetina Rejon, M. J. (2017). Recommendations on the use of ecosystem modeling for informing ecosystem-based fisheries management and restoration outcomes in the Gulf of Mexico. *Marine and Coastal Fisheries: Dynamics, Management, and Ecosystem Science*, *9*, 281–295. https://doi.org/10.1080/19425120.2017.1330786

Guesnet, V., Lassalle, G., Chaalali, A., Kearney, K., Saint-Béat, B., Karimi, B., Grami, B., Tecchio, S., Niquil, N., & Lobry, J. (2015). Incorporating food-web parameter uncertainty into Ecopath-derived ecological network indicators. *Ecological Modelling*, *313*, 29–40. https://doi.org/10.1016/j.ecolmodel.2015.05.036

Guillen, J., Holmes, S. J., Carvalho, N., Casey, J., Dörner, H., Gibin, M., Mannini, A., Vasilakopoulos, P., & Zanzi, A. (2018). A review of the European Union landing obligation focusing on its implications for fisheries and the environment. *Sustainability*, *10*, 900. https://doi.org/10.3390/su10040900

Halouani, G., Villanueva, C.-M., Raoux, A., Dauvin, J. C., Lasram, F. B. R., Foucher, E., Le Loc'h, F., Safi, G., Araignous, E., Robin, J. P., & Niquil, N. (2020). A spatial food web model to investigate potential spillover effects of a fishery closure in an offshore wind farm. *Journal of Marine Systems*, *212*, 103434. https://doi.org/10.1016/j.jmarsys.2020.103434

Harvey, C. J., Kelble, C. R., & Schwing, F. B. (2017). Implementing "the IEA": Using integrated ecosystems assessment frameworks, programs, and applications in support of operationalizing ecosystem-based management. *ICES Journal of Marine Science*, *74*, 398–405. https://doi.org/10.1093/icesjms/fsw201

Heymans, J. J., Coll, M., Libralato, S., Morissette, L., & Christensen, V. (2014). Global patterns in ecological indicators of marine food webs: A modelling approach. *PLoS One*, *9*, e95845. https://doi.org/10.1371/journal.pone.0095845

Heymans, J. J., Coll, M., Link, J. S., Mackinson, S., Steenbeek, J., Walters, C., & Christensen, V. (2016). Best practice in Ecopath with Ecosim food-web models for ecosystem-based management. *Ecological Modelling*, *331*, 173–184. https://doi.org/10.1016/j.ecolmodel.2015.12.007

Heymans, J. J., Mackinson, S., Sumaila, U. R., Dyck, A., & Little, A. (2011). The impact of subsidies on the ecological sustainability of North Sea fisheries. *PLoS One*, *6*, e20239. https://doi.org/10.1371/journal.pone.0020239

Hilborn, R. (2010). Pretty good yield and exploited fishes. *Marine Policy*, *34*, 193–196. https://doi.org/10.1016/j.marpol.2009.04.013

Hilborn, R. (2011). Future directions in ecosystem-based fisheries management: A personal perspective. *Fisheries Research*, *108*, 235–239. https://doi.org/10.1016/j.fishres.2010.12.030

Hilborn, R., Amoroso, R. O., Bogazzi, E., Jenson, O. P., Parma, A. M., Szuwalski, C., & Walters, C. J. (2017). When does fishing forage species affect their predators? *Fisheries Research*, *191*, 211–221. https://doi.org/10.1016/j.fishres.2017.01.008

Hilborn, R., & Litzinger, E. (2009). Causes of decline and potential for recovery of Atlantic cod populations. *The Open Fish Science*

Journal, *2*, 32–38. https://doi.org/10.2174/1874401X00902010032
Hollowed, A. B., Aydin, K. Y., Essington, T. E., Ianelli, J. N., Megrey, B. A., Punt, A. E., & Smith, A. D. M. (2011). Experience with quantitative ecosystem assessment tools in the Northeast Pacific. *Fish and Fisheries*, *12*, 189–208. https://doi.org/10.1111/j.1467-2979.2011.00413.x
Hollowed, A. B., Bax, N., Beamish, R., Collie, J., Fogarty, M., Livingston, P., Pope, J., & Rice, J. C. (2000). Are multispecies models an improvement on single-species models for measuring fishing impacts on marine ecosystems? *ICES Journal of Marine Science*, *57*, 707–719. https://doi.org/10.1006/jmsc.2000.0734
Holsman, K. K., Haynie, A. C., Hollowed, A. B., Reum, J. C. P., Aydin, K., Hermann, A. J., Cheng, W., Faig, A., Ianelli, J. N., Kearney, K. A., & Punt, A. E. (2020). Ecosystem-based fisheries management forestalls climate-driven collapse. *Nature Communications*, *11*, 4579. https://doi.org/10.1038/s41467-020-18300-3
Howell, D., Schueller, A. M., Bentley, J. W., Buchheister, A., Chagaris, D., Cieri, M., Drew, K., Lundy, M. G., Pedreschi, D., Reid, D. G., & Townsend, H. (2021). Combining ecosystem and single-species modeling to provide ecosystem-based fisheries management advice within current management systems. *Frontiers in Marine Science*, *7*, 607831. https://doi.org/10.3389/fmars.2020.607831
Hyder, K., Rossberg, A. G., Allen, J. I., Austen, M. C., Barciela, R. M., Bannister, H. J., Blackwell, P. G., Blanchard, J. L., Burrows, M. T., Defriez, E., Dorrington, T., Edwards, K. P., Garcia-Carreras, B., Heath, M. R., Hembury, D. J., Heymans, J. J., Holt, J., Houle, J. E., Jennings, S., … Paterson, D. M. (2015). Making modelling count—Increasing the contribution of shelf-seas community and ecosystem models to policy development and management. *Marine Policy*, *61*, 291–302. https://doi.org/10.1016/j.marpol.2015.07.015
ICES. (2019). *Working group on multispecies assessment methods (WGSAM). ICES scientific reports*. 1:91 (320 pp). https://doi.org/10.17895/ices.pub.5758
Jennings, S., & Rice, J. (2011). Toward an ecosystem approach to fisheries in Europe: A perspective on existing progress and future directions. *Fish and Fisheries*, *12*, 125–137. https://doi.org/10.1111/j.1467-2979.2011.00409.x
Jessen, S. (2011). A review of Canada's implementation of the oceans act since 1997—From leader to follower? *Coastal Management*, *39*, 20–56. https://doi.org/10.1080/08920753.2011.544537
Jones, K., & Seara, T. (2020). Integrating stakeholders' perceptions into decision-making for ecosystem-based fisheries management. *Coastal Management*, *48*, 275–288. https://doi.org/10.1080/08920753.2020.1773211
Kaplan, I. C., Gaichas, S. K., Stawitz, C. C., Lynch, P. D., Marshall, K. N., Deroba, J. J., Masi, M., Brodziak, J. K. T., Aydin, K. Y., Holsman, K., Townsend, H., Tommasi, D., Smith, J. A., Koenigstein, S., Weijerman, M., & Link, J. L. (2021). Management strategy evaluation: Allowing the light on the hill to illuminate more than one species. *Frontiers in Marine Science*, *8*, 624355. https://doi.org/10.3389/fmars.2021.624355
Kaplan, I. C., & Marshall, K. N. (2016). A guinea pig's tale: Learning to review end-to-end marine ecosystem models for management applications. *ICES Journal of Marine Science*, *73*, 1715–1724. https://doi.org/10.1093/icesjms/fsw047
Karnauskas, M., Walter, J. F., Kelble, C. R., McPherson, M., Sagarese, S. R., Craig, J. K., Rios, A., Harford, W. J., Regan, S., Giordano, S. D., & Kilgour, M. (2021). To EBFM or not to EBFM? That is not the question. *Fish and Fisheries*, *22*, 646–651. https://doi.org/10.1111/faf.12538
Karp, M. A., Link, J. S., Grezlik, M., Cadrin, S., Fay, G., Lynch, P., Townsend, H., Methot, R. D., Adams, G. D., Blackhart, K., Barceló, C., Buchheister, A., Cieri, M., Chagaris, D., Christensen, V., Craig, J. K., Cummings, J., Damiano, M. D., Dickey-Collas, M., … Voss, R. (2023). Increasing the uptake of multispecies models in fisheries management. *ICES Journal of Marine Science*, fsad001. https://doi.org/10.1093/icesjms/fsad001
Kempf, A., Mumford, J., Levontin, P., Leach, A., Hoff, A., Hamon, K. G., Bartelings, H., Vinther, M., Stäbler, M., Poos, J. J., Smout, S., Frost, H., van den Burg, S., Ulrich, C., & Rindorf, A. (2016). The MSY concept in a multi-objective fisheries environment—Lessons from the North Sea. *Marine Policy*, *69*, 146–158. https://doi.org/10.1016/j.marpol.2016.04.012
Kim, S., Hollowed, A. B., Barange, M., & MacKenzie, B. R. (2014). ICES and PICES strategies for coordinating research on the impacts of climate change on marine ecosystems. *Oceanography*, *27*, S160–S167.
Kolding, J., van Zwieten, P., Marttin, F., Funge-Smith, S., & Poulain, F. (2019). *Freshwater small pelagic fish and fisheries in major African lakes and reservoirs in relation to food security and nutrition. FAO fisheries and aquaculture technical paper no. 642* (p. 124). FAO.
Kopp, D., Marianne, R., Tiphaine, C., & Sonia, M. (2016). Some expected impacts of the common fishery policy on marine food webs. *Marine Policy*, *66*, 8–14. https://doi.org/10.1016/j.marpol.2016.01.002
Lake Victoria Fisheries Organization (LVFO). (2022). *Fisheries management plan III (FMP III) for Lake Victoria fisheries, 2016–2020*. https://www.lvfo.org/sites/default/files/Final%20FMP%20III%202016%20to%202020_0.pdf
Lamb, P. D., Hunter, E., Pinnegar, J. K., Doyle, T. K., Creer, S., & Taylor, M. I. (2019). Inclusion of jellyfish in 30+ years of Ecopath with Ecosim models. *ICES Journal of Marine Science*, *76*, 1941–1950. https://doi.org/10.1093/icesjms/fsz165
Larkin, P. A. (1996). Concepts and issues in marine ecosystems management. *Reviews in Fish Biology and Fisheries*, *6*, 139–164. https://doi.org/10.1007/BF00182341
Lassalle, G., Bourdaud, P., Saint-beat, B., Rochette, S., & Niquil, N. (2014). A toolbox to evaluate data reliability for whole-ecosystem models: Application on the Bay of Biscay continental shelf food-web model. *Ecological Modeling*, *285*, 12–21. https://doi.org/10.1016/j.ecolmodel.2014.04.002
Lassen, H., Pedersen, S. A., Frost, H., & Hoff, A. (2013). Fishery management advice with ecosystem considerations. *ICES Journal of Marine Science*, *70*, 471–479. https://doi.org/10.1093/icesjms/fss208
Lehuta, S., Girardin, R., Mahévas, S., Travers-Trolet, M., & Vermard, Y. (2016). Reconciling complex system models and fisheries advice: Practical examples and leads. *Aquatic Living Resources*, *29*, 208. https://doi.org/10.1051/alr/2016022
Lester, S. E., Stevens, J. M., Gentry, R. R., Kappel, C. V., Bell, T. W., Costello, C. J., Gaines, S. D., Kiefer, D. A., Maue, C. C., Rensel, J. E., Simons, R. D., Washburn, L., & White, C. (2018). Marine spatial planning makes room for offshore aquaculture in crowded coastal waters. *Nature Communications*, *9*, 945. https://doi.org/10.1038/s41467-018-03249-1
Leung, D. Y. C., & Yang, Y. (2012). Wind energy development and its environmental impact: A review. *Renewable and Sustainable Energy Reviews*, *16*, 1031–1039. https://doi.org/10.1016/j.rser.2011.09.024
Levin, P. S., Fogarty, M. J., Murawski, S. A., & Fluharty, D. (2009). Integrated ecosystem assessments: Developing the scientific basis for ecosystem-based management of the ocean. *PLoS Biology*, *7*, 23–28. https://doi.org/10.1371/journal.pbio.1000014
Lewis, K. A., Rose, K. A., de Mutsert, K., Sable, S., Ainsworth, C., Brady, D. C., & Townsend, H. (2021). Using multiple ecological models to inform environmental decision-making. *Frontiers in Marine Science*, *8*, 625790. https://doi.org/10.3389/fmars.2021.625790
Link, J., Overholtz, W., O'Reilly, J., Green, J., Dow, D., Palka, D., Legault, C., Vitaliano, J., Guida, V., Fogarty, M., Brodziak, J., Methratta, L., Stockhausen, W., Col, L., & Griswold, C. (2006). The northeast U.S. continental shelf energy modeling and analysis exercise (EMAX): Ecological network model development and basic ecosystem metrics. *Journal of Marine Systems*, *74*, 453–474. https://doi.org/10.1016/j.jmarsys.2008.03.007

Link, J. S. (2010a). *Ecosystem-based fisheries management: Confronting tradeoffs*. Cambridge University Press.

Link, J. S. (2010b). Adding rigor to ecological network models by evaluating a set of pre-balance diagnostics: A plea for PREBAL. *Ecological Modelling*, *221*, 1580–1591. https://doi.org/10.1016/j.ecolmodel.2010.03.012

Link, J. S. (2018). System-level optimal yield: Increased value, less risk, improved stability, and better fisheries. *Canadian Journal of Fisheries and Aquatic Sciences*, *75*, 1–16. https://doi.org/10.1139/cjfas-2017-0250

Link, J. S., & Browman, H. I. (2014). Integrating what? Levels of marine ecosystem-based assessment and management. *ICES Journal of Marine Science*, *71*, 1170–1173. https://doi.org/10.1093/icesjms/fsu026

Link, J. S., Bundy, A., Overholtz, W. J., Shackell, N., Manderson, J., Duplisea, D., Hare, J., Koen-Alonso, K., & Friedland, K. D. (2011). Ecosystem-based fisheries management in the Northwest Atlantic. *Fish and Fisheries*, *12*, 152–170. https://doi.org/10.1111/j.1467-2979.2011.00411.x

Link, J. S., Gamble, R., Overholtz, W. J., Legault, C., Col, L., & Fogarty, M. J. (2008). *An aggregate and MS production model: A simulator tool. GARM WP 3.4 GARM-III-BRP meeting*. National Marine Fisheries Service.

Link, J. S., Ihde, T. F., Harvey, C. J., Gaichas, S. K., Field, J. C., Brodziak, J. K. T., Townsend, H. M., & Peterman, R. M. (2012). Dealing with uncertainty in ecosystem models: The paradox of use for living marine resource management. *Progress in Oceanography*, *102*, 102–114. https://doi.org/10.1016/j.pocean.2012.03.008

Link, J. S., & Marshak, A. R. (2019). Characterizing and comparing marine fisheries ecosystems in the United States: Determinants of success in moving toward ecosystem-based fisheries management. *Reviews in Fish Biology and Fisheries*, *2*, 23–70. https://doi.org/10.1007/s11160-018-9544-z

Link, J. S., Overholtz, W. J., Legault, C., Col, L., & Fogarty, M. J. (2008). *Energy budget contextualization of fish biomasses at B_MSY. GARM WP 3.2 GARM-III-BRP meeting*. National Marine Fisheries Service.

Long, R. D., Charles, A., & Stephenson, R. L. (2015). Key principles of marine ecosystem-based management. *Marine Policy*, *57*, 53–60. https://doi.org/10.1016/j.marpol.2015.01.013

Lucey, S. M., Aydin, K. Y., Gaichas, S. K., Cadrin, S. X., Fay, G., Fogarty, M. J., & Punt, A. (2021). Evaluating fishery management strategies using an ecosystem model as an operating model. *Fisheries Research*, *234*, 105780. https://doi.org/10.1016/j.fishres.2020.105780

Lucey, S. M., Cook, A. M., Boldt, J. L., Link, J. S., Essington, T. E., & Miller, T. J. (2012). Comparative analyses of surplus production dynamics of functional feeding groups across 12 northern hemisphere marine ecosystems. *Marine Ecology Progress Series*, *459*, 219–229. https://doi.org/10.3354/meps09825

Lynam, C. P., & Mackinson, S. (2015). How will fisheries management measures contribute towards the attainment of good environmental status for the North Sea ecosystem? *Global Ecology and Conservation*, *4*, 160–175. https://doi.org/10.1016/j.gecco.2015.06.005

Lynam, C. P., Uusitalo, L., Patrício, J., Piroddi, C., Queirós, A. M., Teixeira, H., Rossberg, A. G., Sagarminaga, Y., Hyder, K., Niquil, N., Möllmann, C., Wilson, C., Chust, G., Galparsoro, I., Forster, R., Veríssimo, H., Tedesco, L., Revilla, M., & Neville, S. (2016). Uses of innovative modeling tools within the implementation of the marine strategy framework directive. *Frontiers in Marine Science*, *3*, 182. https://doi.org/10.3389/fmars.2016.00182

Mackinson, S., Daskalov, G., Heymans, J. J., Neira, S., Arancibia, H., Zetina-Rejón, M., Jiang, H., Cheng, H. Q., Coll, M., Arreguin-Sanchez, F., Keeble, K., & Shannon, L. (2009). Which forcing factors fit? Using ecosystem models to investigate the relative influence of fishing and changes in primary productivity on the dynamics of marine ecosystems. *Ecological Modelling*, *220*, 2972–2987. https://doi.org/10.1016/j.ecolmodel.2008.10.021

Mackinson, S., Platts, M., Garcia, C., & Lynam, C. (2018). Evaluating the fishery and ecological consequences of the proposed North Sea multi-annual plan. *PLoS One*, *13*, e0190015. https://doi.org/10.1371/journal.pone.0190015

Marshall, K. N., Koehn, L. E., Levin, P. S., Essington, T. E., & Jensen, O. P. (2019). Inclusion of ecosystem information in U.S. fish stock assessments suggests progress toward ecosystem-based fisheries management. *ICES Journal of Marine Science*, *76*, 1–9. https://doi.org/10.1093/icesjms/fsy152

Marshall, K. N., Levin, P. S., Essington, T. E., Koehn, L. E., Anderson, L. G., Bundy, A., Carothers, C., Coleman, F., Gerber, L. R., Grabowski, J. H., Houde, E., Jensen, O. P., Möllmann, C., Rose, K., Sanchirico, J. N., & Smith, A. D. M. (2018). Ecosystem-based fisheries management for social-ecological systems: Renewing the focus in the United States with next generation fishery ecosystem plans. *Conservation Letters*, *11*, e12367. https://doi.org/10.1111/conl.12367

May, R. M., Beddington, J. R., Clark, C. W., Holt, S. J., & Laws, R. M. (1979). Management of multispecies fisheries. *Science*, *205*, 257–277. https://doi.org/10.1126/science.205.4403.267

McLeod, K., & Leslie, H. (Eds.). (2009). *Ecosystem-based management for the oceans*. Island Press.

Methot, R. D. (2009). Stock assessment: Operational models in support of fisheries management. In R. J. Beamish & B. J. Rothschild (Eds.), *The future of fisheries science in North America. Fish & fisheries series* (Vol. *31*, pp. 137–165). Springer. https://doi.org/10.1007/978-1-4020-9210-7_9

Moutopoulos, D. K., Libralato, S., Solidoro, C., & Stergiou, K. I. (2013). Toward an ecosystem approach to fisheries in the Mediterranean Sea: Multi-gear/multi-species implications from an ecosystem model of the Greek Ionian Sea. *Journal of Marine Systems*, *113*, 13–28. https://doi.org/10.1016/j.jmarsys.2012.12.002

Moutopoulos, D. K., Tsagarakis, K., & Machias, A. (2018). Assessing ecological and fisheries implications of the EU landing obligation in eastern Mediterranean. *Journal of Sea Research*, *141*, 99–111. https://doi.org/10.1016/j.seares.2018.08.006

Mueter, F. J., & Megrey, B. A. (2006). Using multi-species surplus production models to estimate ecosystem-level maximum sustainable yields. *Fisheries Research*, *81*, 189–201. https://doi.org/10.1016/j.fishres.2006.07.010

Musinguzi, L., Natugonza, V., & Ogutu-Ohwayo, R. (2017). Paradigm shifts required to promote ecosystem modeling for ecosystem-based fishery management for African inland lakes. *Journal of Great Lakes Research*, *43*, 1–8. https://doi.org/10.1016/j.jglr.2016.11.007

Natugonza, V., Ainsworth, C., Sturludóttir, E., Musinguzi, L., Ogutu-Ohwayo, R., Tomasson, T., Nyamweya, C., & Stefansson, G. (2019). Ecosystem models of Lake Victoria (East Africa): Can Ecopath with Ecosim and Atlantis predict similar policy outcomes? *Journal of Great Lakes Research*, *45*, 1260–1273. https://doi.org/10.1016/j.jglr.2019.09.018

Natugonza, V., Ainsworth, C., Sturludóttir, E., Musinguzi, L., Ogutu-Ohwayo, R., Tomasson, T., Nyamweya, C., & Stefansson, G. (2020a). Ecosystem modelling of data-limited fisheries: How reliable are Ecopath with Ecosim models without historical time series fitting? *Journal of Great Lakes Research*, *46*, 414–428. https://doi.org/10.1016/j.jglr.2020.01.001

Natugonza, V., Ainsworth, C., Sturludóttir, E., Musinguzi, L., Ogutu-Ohwayo, R., Tomasson, T., Nyamweya, C., & Stefansson, G. (2020b). Simulating trade-offs between socio-economic and conservation objectives for Lake Victoria (East Africa) using multispecies, multifleet ecosystem models. *Fisheries Research*, *229*, 105593. https://doi.org/10.1016/j.fishres.2020.105593

Natugonza, V., Nyamweya, C., Sturludóttir, E., Musinguzi, L., Ogutu-Ohwayo, R., Bassa, S., Mplaponi, E., Tomasson, T., & Stefansson, G. (2022). Spatiotemporal variation in fishing patterns and fishing pressure in Lake Victoria (East Africa) in relation to balanced harvest. *Fisheries Research*, *252*, 106355. https://doi.org/10.1016/j.fishres.2022.106355

Natugonza, V., Ogutu-Ohwayo, R., Musinguzi, L., Kashindye, B., Jónsson, S., & Valtysson, H. T. (2016). Exploring the structural and functional properties of the Lake Victoria food web, and the role of fisheries, using a mass balance model. *Ecological Modelling*, *342*, 161–174. https://doi.org/10.1016/j.ecolmodel.2016.10.002

NEFSC. (2008). *Assessment of 19 Northeast Groundfish stocks through 2007: Report of the 3rd Groundfish Assessment Review Meeting (GARM III), Northeast Fisheries Science Center, Woods Hole, Massachusetts, August 4–8, 2008. US Dept Commer, Northeast Fish Sci Cent Ref Doc. 08-15; 884 p + xvii*. National Marine Fisheries Service.

Newton, A., Borja, A., Solidoro, C., & Grégoire, M. (2015). Implementing the European marine strategy framework directive: Scientific challenges and opportunities. *Continental Shelf Research*, *108*, 141–143. https://doi.org/10.1016/j.csr.2015.09.016

NOAA Fisheries. (2016). *Ecosystem-based fisheries management road map, policy 01-120*. NOAA Fisheries. https://www.fisheries.noaa.gov/resource/document/ecosystem-based-fisheries-management-road-map

Nogues, Q., Araignous, E., Bourdaud, P., Halouani, G., Raoux, A., Foucher, É., Le Loc'h, F., Loew-Turbout, F., Lasram, F. B. R., Dauvin, J.-C., & Niquil, N. (2022). Spatialized ecological network analysis for ecosystem-based management: Effects of climate change, marine renewable energy, and fishing on ecosystem functioning in the bay of seine. *ICES Journal of Marine Science*, *0*, 1–15. https://doi.org/10.1093/icesjms/fsac026

Nyamweya, C., Sturludottir, E., Tomasson, T., Fulton, E. A., Taabu-Munyaho, A., Njiru, M., & Stefansson, G. (2016). Exploring Lake Victoria ecosystem functioning using the Atlantis modeling framework. *Environmental Modelling and Software*, *86*, 158–167. https://doi.org/10.1016/j.envsoft.2016.09.019

Nyamweya, C., Sturludottir, E., Tomasson, T., Taabu-Munyaho, A., Njiru, M., & Stefansson, G. (2017). Prediction of Lake Victoria's response to varied fishing regimes using the Atlantis ecosystem model. *Fisheries Research*, *194*, 76–83. https://doi.org/10.1016/j.fishres.2017.05.014

Ogutu-Ohwayo, R., Natugonza, V., Olokotum, M., Rwezawula, P., Lugya, J., & Musinguzi, L. (2020). Biogeography: Lakes—African great lakes. In M. I. Goldstein & D. A. DellaSala (Eds.), *Encyclopedia of the world's biomes* (pp. 243–260). Elsevier. https://doi.org/10.1016/B978-0-12-409548-9.12090-1

Olsen, E., Fay, G., Gaichas, S., Gamble, R., Lucey, S., & Link, J. S. (2016). Ecosystem model skill assessment. Yes we can! *PLoS One*, *11*, e0146467. https://doi.org/10.1371/journal.pone.0146467

Onofri, L., & Maynou, F. (2020). Unwanted catches, quota systems, and the EU Landing Obligation: An economic and econmetric anaylsis. *Ocean and Coastal Management*, *189*, 105159. https://doi.org/10.1016/j.ocecoaman.2020.105159

Overholtz, W. J., Fogarty, M. J., Link, J. S., Legault, C., & Col, L. (2008). *Estimates of aggregate surplus production for the GARM and other stock groups for the U.S. Northeast Shelf LME. GARM WP 3.3 GARM-III-BRP meeting*. National Marine Fisheries Service.

Overholtz, W. J., Link, J. S., Fogarty, M. J., Col, L., & Legault, C. (2008). *U.S. Northeast Shelf LME Biomass, target biological reference points for fish and worldwide cross-system comparisons. GARM WP 3.1 GARM-III-PRP meeting*. National Marine Fisheries Service.

Pascoe, S. D., Plagányi, É. E., & Dichmont, C. M. (2017). Modelling multiple management objectives in fisheries: Australian experiences. *ICES Journal of Marine Science*, *74*, 464–474. https://doi.org/10.1093/icesjms/fsw051

Pauly, D., Christensen, V., & Walters, C. J. (2000). Ecopath, Ecosim, and Ecospace as tools for evaluating ecosystem impacts of fisheries. *ICES Journal of Marine Science*, *57*, 697–706. https://doi.org/10.1006/jmsc.2000.0726

Pennino, M. G., Bevilacqua, A. H., Torres, M. A., Bellido, J. M., Sole, J., Steenbeek, J., & Coll, M. (2020). Discard ban: A simulation-based approach combining hierarchical Bayesian and food web spatial models. *Marine Policy*, *116*, 103703. https://doi.org/10.1016/j.marpol.2019.103703

Peterman, R. M. (2004). Possible solutions to some challenges facing fisheries scientists and managers. *ICES Journal of Marine Science*, *61*, 1331–1343. https://doi.org/10.1016/j.icesjms.2004.08.017

Pezy, J. P., Raoux, A., & Dauvin, J. C. (2020). The environmental impact from an offshore wind farm: Challenge and evaluation methodology based on an ecosystem approach. *Ecological Indicators*, *114*, 106302. https://doi.org/10.1016/j.ecolind.2020.106302

Pikitch, E. K., Rountos, K. J., Essington, T. E., Santora, C., Pauly, D., Watson, R., Sumaila, U. R., Boersma, P. D., Boyd, I. L., Conover, D. O., Cury, P., Heppell, S. S., Houde, E. D., Mangel, M., Plagányi, É., Sainsbury, K., Steneck, R. S., Geers, T. M., Gownaris, N., & Munch, S. B. (2014). The global contribution of forage fish to marine fisheries and ecosystems. *Fish and Fisheries*, *15*, 43–64. https://doi.org/10.1111/faf.12004

Pikitch, E. K., Santora, C., Babcock, E. A., Bakun, A., Bonfil, R., Conover, D. O., Dayton, P., Doukakis, P., Fluharty, D., Heneman, B., Houde, E. D., Link, J. S., Livingston, P. A., Mangel, M., McAllister, M. K., Pope, J., & Sainsbury, K. J. (2004). Ecosystem-based fishery management. *Science*, *305*, 346–347. https://doi.org/10.1126/science.1098222

Piroddi, C., Akoglu, E., Andonegi, E., Bentley, J. W., Celić, I., Coll, M., Dimarchopoulou, D., Friedland, R., de Mutsert, K., Girardin, R., Garcia-Gorriz, E., Grizzetti, B., Hernvann, P.-Y., Heymans, J. J., Müller-Karulis, B., Libralato, S., Lynam, C. P., Macias, D., Miladinova, S., … Tsikliras, A. C. (2021). Effects of nutrient management scenarios on marine food webs: A Pan-European assessment in support of the marine strategy framework directive. *Frontiers in Marine Science*, *8*, 596797. https://doi.org/10.3389/fmars.2021.596797

Piroddi, C., Teixeira, H., Lynam, C. P., Smith, C., Alvarez, M. C., Mazik, K., Andonegi, E., Churilova, T., Tedesco, L., Chifflet, M., Chust, G., Galparsoro, I., Garcia, A. C., Kämäri, M., Kryvenko, O., Lassalle, G., Neville, S., Niquil, N., Papadopoulou, N., … Uyarra, M. C. (2015). Using ecosystem models to assess ecosystem status in support of the European marine strategy framework directive. *Ecological Indicators*, *58*, 175–191. https://doi.org/10.1016/j.ecolind.2015.05.037

Plagányi, É. E., & Butterworth, D. S. (2004). A critical look at the potential of Ecopath with Ecosim to assist in practical fisheries management. *African Journal of Marine Science*, *26*, 261–287. https://doi.org/10.2989/18142320409504061

Plagányi, É. E., Punt, A. E., Hillary, R., Morello, E. B., Thébaud, O., Hutton, T., Pillans, R. D., Thorson, J. T., Fulton, E. A., Smith, A. D. M., Smith, F., Bayliss, P., Haywood, M., Lyne, V., & Rothlisberg, P. C. (2014). Multispecies fisheries management and conservation: Tactical applications using models of intermediate complexity. *Fish and Fisheries*, *15*, 1–22. https://doi.org/10.1111/j.1467-2979.2012.00488.x

Polovina, J. J. (1984). Model of a coral reef ecosystem. I. The Ecopath model and its application to French Frigate Shoals. *Coral Reefs*, *3*, 1–11. https://doi.org/10.1007/BF00306135

Prellezo, R., & Curtin, R. (2015). Confronting the implementation of marine ecosystem-based management within the common fisheries policy reform. *Ocean and Coastal Management*, *117*, 43–51. https://doi.org/10.1016/j.ocecoaman.2015.03.005

Punt, J. J., Groeneveld, R. A., van Ierland, E. C., & Stel, J. H. (2009). Spatial planning of offshore wind farms: A windfall to marine environmental protection? *Ecological Economics*, *69*, 11–15. https://doi.org/10.1016/j.ecolecon.2009.07.013

Queirós, A. M., Strong, J. A., Mazik, K., Carstensen, J., Bruun, J., Somerfiled, P. J., Bruhn, A., Coavatta, S., Flo, E., Bizsel, N., Özaydinli, M., Chuševė, R., Muxika, I., Nygård, H., Papadopoulou, N., Pantazi, M., & Krause-Jensen, D. (2016). An objective framework to test the quality of candidate indicators of good environmental status. *Frontiers in Marine Science*, *3*, 73. https://doi.org/10.3389/fmars.2016.00073

Ramírez-Monsalve, P., Raakjær, J., Nielsen, K. N., Santiago, J. L., Ballesteros, M., Laksá, U., & Degnbol, P. (2016). Ecosystem approach to fisheries management (EAFM) in the EU—Current science-policy-society interfaces and emerging requirements. *Marine Policy*, *66*, 83–92. https://doi.org/10.1016/j.marpol.2015.12.030

Raoux, A., Lassalle, G., Pezy, J. P., Teechio, S., Safi, G., Ernamde, B., Maze, C., Le Loc'h, F., Lequesne, J., Girardin, V., Dauvin, J. C., & Niquil, N. (2019). Measuring sensitivity of two OSPAR indicators for a coastal food web model under offshore wind farm construction. *Ecological Indicators*, *96*, 728–738. https://doi.org/10.1016/j.ecolind.2018.07.014

Raoux, A., Pezy, J.-P., Ernande, B., Niquil, N., Dauvin, J.-C., & Grangeré, K. (2020). Isotopic analyses, a good tool to validate models in the context of marine renewable energy development and cumulative impacts. *Estuarine, Coastal, and Shelf Science*, *237*, 106690. https://doi.org/10.1016/j.ecss.2020.106690

Raoux, A., Tecchio, S., Pezy, J.-P., Lassalle, G., Degraer, S., Wilhelmsson, D., Cachera, M., Ernande, B., Le Guen, C., Haraldsson, M., Grangeré, K., Le Loc'h, F., Dauvin, J.-C., & Niquil, N. (2017). Benthic and fish aggregation inside an offshore wind farm: Which effects on trophic web functioning? *Ecological Indicators*, *72*, 33–46. https://doi.org/10.1016/j.ecolind.2016.07.037

Reed, D., Wang, Y., Meselhe, E., & White, E. (2020). Modeling wetland transitions and loss in coastal Louisiana under scenarios of future relative sea-level rise. *Geomorphology*, *352*, 106991. https://doi.org/10.1016/j.geomorph.2019.106991

Reed, J., Shannon, L., Velez, L., Akoglu, E., Bundy, A., Coll, M., Fu, C., Fulton, E. A., Grüss, A., Halouani, G., Heymans, J., Houle, J. E., John, E., Le Loc'h, F., Salihoglu, B., Verley, P., & Shin, Y.-J. (2017). Ecosystem indicators—Accounting for variability in species' trophic levels. *ICES Journal of Marine Science*, *74*, 158–169. https://doi.org/10.1093/icesjms/fsw150

Reum, J. C. P., Kelble, C. R., Harvey, C. J., Wildermuth, R. P., Trifonova, N., Lucey, S. M., McDonald, P. S., & Townsend, H. (2021). Network approaches for formalizing conceptual models in ecosystem-based management. *ICES Journal of Marine Science*, *78*, 3674–3686. https://doi.org/10.1093/icesjms/fsab211

Reum, J. C. P., Townsend, H., Gaichas, S., Sagarese, S., Kaplan, I. C., & Grüss, A. (2021). It's not the destination, it's the journey: Multispecies model ensembles for ecosystem approaches to fisheries management. *Frontiers in Marine Science*, *26*, 631839. https://doi.org/10.3389/fmars.2021.631839

Rindorf, A., Dichmont, C. M., Levin, P. S., Mace, P., Pascoe, S., Prellezo, R., Punt, A. E., Reid, D. G., Stephenson, R., Ulrich, C., Vinther, M., & Clausen, L. W. (2017). Food for thought: Pretty good multispecies yield. *ICES Journal of Marine Science*, *74*, 475–486. https://doi.org/10.1093/icesjms/fsw071

Rodríguez, J. P., Keith, D. A., Rodríguez-Clark, K. M., Murray, N. J., Nicholson, E., Regan, T. J., Miller, R. M., Barrow, E. G., Bland, L. M., Boe, K., Brooks, T. M., Oliveira-Miranda, M. A., Spalding, M., & Wit, P. (2015). A practical guide to the application of the IUCN red list of ecosystems criteria. *Philosophical Transactions of the Royal Society B*, *370*, 20140003. https://doi.org/10.1098/rstb.2014.0003

Romagnoni, G., Mackinson, S., Hong, J., & Eikeset, A. M. (2015). The Ecospace model applied to the North Sea: Evaluating spatial predictions with fish biomass and fishing effort data. *Ecological Modelling*, *300*, 50–60. https://doi.org/10.1016/j.ecolmodel.2014.12.016

Rose, K. A., Allen, J. I., Artioli, Y., Barange, M., Blackford, J., Carlotti, F., Cropp, R., Daewel, U., Edwards, K., Flynn, K., Hill, S. L., HilleRisLambers, R., Huse, G., Mackinson, S., Megrey, B., Moll, A., Rivkin, R., Salihoglu, B., Schrum, C., … Zhou, M. (2010). End-to-end models for the analysis of marine ecosystems: Challenges, issues, and next steps. *Marine and Coastal Fisheries: Dynamics, Management, and Ecosystem Science*, *2*, 115–130. https://doi.org/10.1577/C09-059.1

Rose, K. A., Sable, S., DeAngelis, D. L., Yurek, S., Trexler, J. C., Graf, W., & Reed, D. J. (2015). Proposed best modeling practices for assessing the effects of ecosystem restoration on fish. *Ecological Modelling*, *300*, 12–29. https://doi.org/10.1016/j.ecolmodel.2014.12.020

Ruckelshaus, M., Klinger, T., Knowlton, N., & DeMaster, D. R. (2008). Marine ecosystem-based management in practice: Scientific and governance challenges. *Bioscience*, *58*, 53–63. https://doi.org/10.1641/B580110

Schmolke, A., Thorbek, P., DeAngelis, D. L., & Grimm, V. (2010). Ecological models supporting environmental decision making: A strategy for the future. *Trends in Ecology and Evolution*, *25*, 479–486. https://doi.org/10.1016/j.tree.2010.05.001

Scott, E., Serpetti, N., Steenbeek, J., & Heymans, J. J. (2016). A step-wise fitting procedure for automated fitting of Ecopath with Ecosim models. *SoftwareX*, *5*, 25–30. https://doi.org/10.1016/j.softx.2016.02.002

Serpetti, N., Benjamins, S., Brain, S., Collu, M., Harvey, B. J., Heymans, J. J., Hughes, A. D., Risch, D., Rosinski, S., Waggitt, J. J., & Wilson, B. (2021). Modeling small scale impacts of multi-purpose platforms: An ecosystem approach. *Frontiers in Marine Science*, *8*, 694013. https://doi.org/10.3389/fmars.2021.694013

Shannon, L., Coll, M., Bundy, A., Gascuel, D., Heymans, J. J., Kleisner, K., Lynam, C. P., Piroddi, C., Tam, J., Travers-Trolet, M., & Shin, Y. (2014). Trophic level-based indicators to track fishing impacts across marine ecosystems. *Marine Ecology Progress Series*, *512*, 115–140. https://doi.org/10.3354/meps10821

Siple, M. C., Essington, T. E., & Plagányi, É. E. (2019). Forage fish fisheries management requires a tailored approach to balance trade-offs. *Fish and Fisheries*, *20*, 110–124. https://doi.org/10.1111/faf.12326

Skern-Mauritzen, M., Ottersen, G., Handegard, N. O., Huse, G., Dingsør, G. E., Stenseth, N. C., & Kjesbu, O. S. (2016). Ecosystem processes are rarely included in tactical fisheries management. *Fish and Fisheries*, *17*, 165–175. https://doi.org/10.1111/faf.12111

Skogen, M. D., Ji, R., Akimova, A., Daewel, U., Hansen, C., Hjøllo, S. S., van Leeuwen, S. M., Maar, M., Macias, D., Mousing, E. A., Almroth-Rosell, E., Sailley, S. F., Spence, M. A., Troost, T. A., & van de Wolfshaar, K. (2021). Disclosing the truth: Are models better than observations? *Marine Ecology Progress Series*, *680*, 7–13. https://doi.org/10.3354/meps13574

Smythe, T. C., & McCann, J. (2018). Lessons learned in marine governance: Case studies of marine spatial planning practice in the US. *Marine Policy*, *94*, 227–237. https://doi.org/10.1016/j.marpol.2018.04.019

Smythe, T. C., & McCann, J. (2019). Achieving integration in marine governance through marine spatial planning: Findings from practice in the Unites States. *Ocean and Coastal Management*, *167*, 197–207. https://doi.org/10.1016/j.ocecoaman.2018.10.006

Spence, M. A., Blanchard, J. L., Rossberg, A. G., Heath, M. R., Heymans, J. J., Mackinson, S., Serpetti, N., Speirs, D. C., Thorpe, R. B., & Blackwell, P. G. (2018). A general framework for combining ecosystem models. *Fish and Fisheries*, *219*, 1031–1042. https://doi.org/10.1111/faf.12310

Stäbler, M., Kempf, A., Mackinson, S., Poos, J. J., Garcia, C., & Temming, A. (2016). Combining efforts to make maximum sustainable yields and good environmental status match in a food-web model of the southern North Sea. *Ecological Modelling*, *331*, 17–30. https://doi.org/10.1016/j.ecolmodel.2016.01.020

Stäbler, M., Kempf, A., Smout, S., & Temming, A. (2019). Sensitivity of multispecies maximum sustainable yields to trends in the top (marine mammals) and bottom (primary production) compartments of the southern North Sea food-web. *PLoS One*, *14*, e0210882. https://doi.org/10.1371/journal.pone.0210882

Steenbeek, J., Buszowski, J., Chagaris, D., Christensen, V., Coll, M., Fulton, E. A., Katsanevakis, S., Lewis, K. A., Mazaris, A. D., Macias, D., de Mutsert, K., Oldford, G., Pennino, M. G., Piroddi, C., Romagnoni, G., Serpetti, N., Shin, Y.-J., Spence, M. A., & Stelzenmüller, V. (2021). Making spatial-temporal marine ecosystem modelling better—A perspective. *Environmental Modelling*

and Software, *145*, 105209. https://doi.org/10.1016/j.envsoft.2021.105209
Steenbeek, J., Buszowski, J., Christensen, V., Akoglu, E., Aydin, K., Ellis, N., Felinto, D., Guitton, J., Lucey, S., Kearney, K., Mackinson, S., Pan, M., Platts, M., & Walters, C. (2016). Ecopath with Ecosim as a model-building toolbox: Source code capabilities, extensions, and variations. *Ecological Modelling*, *319*, 178–189. https://doi.org/10.1016/j.ecolmodel.2015.06.031
Steenbeek, J., Corrales, X., Platts, M., & Coll, M. (2018). Ecosampler: A new approach to assessing parameter uncertainty in Ecopath with Ecosim. *SoftwareX*, *7*, 198–204. https://doi.org/10.1016/j.softx.2018.06.004
Stephenson, R. L., Benson, A. J., Brooks, K., Charles, A., Degnbol, P., Dichmont, C. M., Kraan, M., Pascoe, S., Paul, S. D., Rindorf, A., & Wiber, M. (2017). Practical steps toward integrating economic, social and institutional elements in fisheries policy and management. *ICES Journal of Marine Science*, *74*, 1981–1989. https://doi.org/10.1093/icesjms/fsx057
Strona, G., Lafferty, K. D., Fattorini, S., Beck, P. S. A., Guilhaumon, F., Arrigoni, R., Montano, S., Seveso, D., Galli, P., Planes, S., & Parravicini, V. (2021). Global tropical reef fish richness could decline by around half if corals are lost. *Proceedings of the Royal Society B*, *288*, 20210274. https://doi.org/10.1098/rspb.2021.0274
Sully, S., Burkepile, D. E., Donovan, M. K., Hodgson, G., & van Woesik, R. (2019). A global analysis of coral bleaching over the past two decades. *Nature Communications*, *10*, 1264. https://doi.org/10.1038/s41467-019-09238-2
Tebbett, S. B., Morais, R. A., Goatley, C. H. R., & Bellwood, D. R. (2021). Collapsing ecosystem functions on an inshore coral reef. *Journal of Environmental Management*, *289*, 112471. https://doi.org/10.1016/j.jenvman.2021.112471
Tedesco, L., Piroddi, C., Kämäri, M., & Lynam, C. (2016). Capabilities of Baltic Sea models to assess environmental status for marine biodiversity. *Marine Policy*, *70*, 1–12. https://doi.org/10.1016/j.marpol.2016.04.021
Teilmann, J., & Carstensen, J. (2012). Negative long-term effects on harbor porpoises from a large scale offshore wind farm in the Baltic—Evidence of slow recovery. *Environmental Research Letters*, *7*, 045101. https://doi.org/10.1088/1748-9326/7/4/045101
Thorpe, R. B., Spence, M. A., Dolder, P. J., & Nash, R. D. M. (2021). Commentary: Combining ecosystem and single-species modeling to provide ecosystem-based fisheries management advice within current management systems. *Frontiers in Marine Science*, *8*, 707841. https://doi.org/10.3389/fmars.2021.707841
Tolimieri, N., Haltuch, M. A., Lee, Q., Jacox, M. G., & Bograd, S. J. (2018). Oceanographic drivers of sablefish recruitment in the California current. *Fisheries Oceanography*, *27*, 458–474. https://doi.org/10.1111/fog.12266
Tommasi, D., de Reynier, Y., Townsend, H., Harvey, C. J., Satterthwaite, W. H., Marshall, K. N., Kaplan, I. C., Brodie, S., Field, J. C., Hazen, E. L., Koenigstein, S., Lindsay, J., Moore, K., Muhling, B., Pfeiffer, L., Smith, J. A., Sweeney, J., Wells, B., & Jacox, M. G. (2021). A case study in connecting fisheries management challenges with models and analysis to support ecosystem-based management in the California current ecosystem. *Frontiers in Marine Science*, *8*, 624161. https://doi.org/10.3389/fmars.2021.624161
Townsend, H., Aydin, K., Holsman, K., Harvey, C., Kaplan, I., Hazen, E., Woodworth-Jefcoats, P., Weijerman, M., Kellison, T., Gaichas, S., Osgood, K., & Link, J. (Eds.). (2017). *Report of the 4th National Ecosystem Modeling Workshop (NEMoW 4): Using ecosystem models to evaluate inevitable trade-offs* (p. 77). U.S. Dept. of Commerce, NOAA Tech. Memo. NMFS-F/SPO 173.
Townsend, H., Harvey, C. J., de Reynier, Y., Davis, D., Zador, S. G., Gaichas, S., Weijerman, M., Hazen, E. L., & Kaplan, I. C. (2019). Progress on implementing ecosystem-based fisheries management in the United States through the use of ecosystem models and analysis. *Frontiers in Marine Science*, *6*, 641. https://doi.org/10.3389/fmars.2019.00641
Townsend, H. M., Harvey, C., Aydin, K. Y., Gamble, R., Grüss, A., Levin, P. S., Link, J. S., Osgood, K. E., Polovina, J., Schirripa, M. J., & Wells, B. (Eds.). (2014). *Report of the 3rd National Ecosystem Modeling Workshop (NEMoW 3): Mingling models for marine resource management – Multiple model inference* (p. 93). U.S. Dept. of Commerce, NOAA Tech. Memo. NMFS-F/SPO-149.
Townsend, H. M., Link, J. S., Osgood, K. E., Gedamke, T., Watters, G. M., Polovina, J. J., Levin, P. S., Cyr, N., & Aydin, K. Y. (Eds.). (2008). *Report of the NEMoW (National Ecosystem Modeling Workshop)* (p. 93). U.S. Dept. of Commerce, NOAA Tech. Memo. NMFS-F/SPO-87.
Trijoulet, V., Fay, G., Curti, K. L., Smith, B., & Miller, T. J. (2019). Performance of multispecies assessment models: Insights on the influence of diet data. *ICES Journal of Marine Science*, *76*, 1464–1476. https://doi.org/10.1093/icesjms/fsz053
Trijoulet, V., Fay, G., & Miller, T. J. (2020). Performance of a state-space multispecies model: What are the consequences of ignoring predation and process errors in stock assessments? *Journal of Applied Ecology*, *57*, 121–135. https://doi.org/10.1111/1365-2664.13515
Tyrell, M. C., Link, J. S., & Moustahfid, H. (2011). Importance of including predation in fish population models: Implications for biological reference points. *Fisheries Research*, *108*, 1–8. https://doi.org/10.1016/j.fishres.2010.12.025
U.S. Army Corps of Engineers New Orleans District (USACE). (2022). *Final EIS (FEIS) – Mid-Barataria Sediment Diversion (MBSD)*. https://www.mvn.usace.army.mil/Missions/Regulatory/Permits/Mid-Barataria-Sediment-Diversion-EIS/
Uusitalo, L., Blenckner, T., Puntila-Dodd, R., Skyttä, A., Jernberg, S., Voss, R., Müller-Karulis, B., Tomczak, M. T., Möllmann, C., & Peltonen, H. (2022). Integrating diverse model results into decision support for good environmental status and blue growth. *Science of the Total Environment*, *806*, 150450. https://doi.org/10.1016/j.scitotenv.2021.150450
van Hoof, L. (2015). Fisheries management, the ecosystem approach, regionalisation and the elephants in the room. *Marine Policy*, *60*, 20–26. https://doi.org/10.1016/j.marpol.2015.05.011
Villasante, S., Arreguín-Sánchez, F., Heymans, J. J., Libralato, S., Piroddi, C., Christensen, V., & Coll, M. (2016). Modelling marine ecosystems using the Ecopath with Ecosim food web approach: New insights to address complex dynamics after 30 years of developments. *Ecological Modelling*, *331*, 1–4. https://doi.org/10.1016/j.ecolmodel.2016.04.017
Vince, J., Smith, A. D. M., Sainsbury, K. J., Cresswell, I. D., Smith, D. C., & Haward, M. (2015). Australia's oceans policy: Past, present and future. *Marine Policy*, *57*, 1–8. https://doi.org/10.1016/j.marpol.2015.02.014
Walker, W. E., Harremoës, P., Rotmans, J., van der Sluijs, J. P., van Asselt, M. B. A., Janssen, P., & Krayer von Krauss, M. P. (2003). Defining uncertainty: A conceptual basis for uncertainty management in model-based decision support. *Integrated Assessment*, *4*, 5–17. https://doi.org/10.1076/iaij.4.1.5.16466
Walters, C., Christensen, V., & Pauly, D. (1997). Structuring dynamic models of exploited ecosystems from trophic mass-balance assessments. *Reviews in Fish Biology and Fisheries*, *7*, 139–172. https://doi.org/10.1023/A:1018479526149
Walters, C., Pauly, D., & Christensen, V. (1999). Ecospace: Prediction of mesoscale spatial patterns in trophic relationships of exploited ecosystems, with emphasis on the impacts of marine protected areas. *Ecosystems*, *2*, 539–554. https://doi.org/10.1007/s100219900101
Wang, J., Zou, X., Yu, W., Zhang, D., & Wang, T. (2019). Effects of established offshore wind farms on energy flow of coastal ecosystems: A case study of the Rudong offshore wind farms in China. *Ocean and Coastal Management*, *171*, 111–118. https://doi.org/10.1016/j.ocecoaman.2019.01.016

Weijerman, M. (2020). *Development of an Atlantis mode for Hawai'i to support ecosystem-based management* (p. 140). U.S. Dept. of Commerce, NOAA Technical Memorandum NOAA-TM-NMFS-PIFSC-113. https://doi.org/10.25923/cwqb-1z04

Weijerman, M., Gove, J. M., Williams, I. D., Walsh, W. J., Minton, D., & Polovina, J. J. (2018). Evaluating management strategies to optimize coral reef ecosystem services. *Journal of Aquatic Ecology*, *55*, 1823–1833. https://doi.org/10.1111/1365-2664.13105

Weijerman, M., Leong, K. M., & Wongbusarakum, S. (2019). *Second Hawai'i Atlantis ecosystem modeling planning workshop: Where is the "S" in EBFM?* (p. 36). NOAA Admin Rep. H-19-05. https://doi.org/10.25923/bfwa-7084

Weijerman, M., Oyafuso, Z. S., Leong, K. M., Oleson, K. L. L., & Winston, M. (2021). Supporting ecosystem-based fisheries management in meeting multiple objectives for sustainable use of coral reef ecosystems. *ICES Journal of Marine Science*, *78*, 2999–3011. https://doi.org/10.1093/icesjms/fsaa194

Weijerman, M., Veazey, L., Yee, S., Vaché, K., Delevaux, J. M. S., Donovan, M. K., Falinski, K., Lecky, J., & Oleson, K. L. L. (2018). Managing local stressors for coral reef condition and ecosystem services delivery under climate scenarios. *Frontiers in Marine Science*, *5*, 425. https://doi.org/10.3389/fmars.2018.00425

Whitehouse, G. A., & Aydin, K. Y. (2020). Assessing the sensitivity of three Alaska marine food webs to perturbations: An example of Ecosim simulations using Rpath. *Ecological Modelling*, *429*, 109074. https://doi.org/10.1016/j.ecolmodel.2020.109074

Wilding, T. A., Gill, A. B., Boon, A., Sheehan, E., Dauvin, J. C., Pezy, J. P., O'Beirn, F., Janas, U., Rostin, L., & De Mesel, I. (2017). Turning off the DRIP ('data-rich, information-poor') – Rationalizing monitoring with a focus on marine renewable energy developments and the benthos. *Renewable & Sustainable Energy Reviews*, *74*, 848–859. https://doi.org/10.1016/j.rser.2017.03.013

Woodstock, M. S., & Zhang, Y. Y. (2022). Towards ecosystem modeling in the deep sea: A review of past efforts and primer for the future. *Deep Sea Research Part I: Oceanographic Research Papers*, *188*, 103851. https://doi.org/10.1016/j.dsr.2022.103851

Worm, B., Hilborn, R., Baum, J. K., Branch, T. A., Collie, J. S., Costello, C., Fogarty, M., Fulton, E., Hutchings, J., Jennings, S., Jensen, O., Lotze, H., Mace, P., Mcclanahan, T., Minto, C., Palumbi, S., Parma, A., Ricard, D., Rosenberg, A., & Zeller, D. (2009). Rebuilding global fisheries. *Science*, *325*, 578–585. https://doi.org/10.1126/science.1173146

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