

The flyway construct and assessment of offshore wind farm impacts on migratory marine fauna

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Abstract

The flyway construct was developed in the 1930s to protect networks of bird stopover habitats along annual migration circuits. Here flyway is conceived as a quantifiable vector, a construct of the seasonal velocity and the geographic route taken among networked habitats, generalizable among marine migratory animals, and a way forward in assessing regional offshore wind (OW) development impacts. OW development in the South and East China Sea, North Sea, and US Mid-Atlantic Bight will result in thousands of offshore wind turbines that transect coastal and shelf flyways, not only for birds but also for fishes, sea turtles, and marine mammals. With increased capacity to fully measure the extent and dynamics of migrations through electronic tracking and observing systems, avian-like behaviors are apparent for whales, turtles, and fishes, such as stopover behaviors, migration synchrony, and partial migration. Modeled northwest Atlantic flyways (migration vectors) for northern gannets, striped bass, and North Atlantic right whale quantified seasonal speed, persistence, and variance during seasonal migration phases. From these flyway models, a series of flyway metrics are proposed that lend themselves to hypothesis-testing, dynamic habitat models, and before–after impact assessment. The flyway approach represents a departure from current impact designs, which are dominated by local OW farm studies and, at regional dimensions, survey-based (Eulerian) data structures (overlap models). As a next step, we encourage colleagues to develop flyway databases and test flyway hypotheses for model species.

Flyway construct

This essay is a call to undertake flyway assessments of regional offshore wind (OW) impacts. The flyway construct, borrowed from avian conservation, is advantageous for working across the dimensions driving the behaviors and population dynamics of migrating turtles, fishes, and marine mammals. Flyways and stopover theory as organizing concepts are summarized and applied to case studies of sea turtles in the South and East China Seas, schooling fishes in the North Sea (NS), and baleen whales in the US Mid-Atlantic Bight (MAB). Dimensions (time and space) of OW impacts are then reviewed through Eulerian and Lagrangian perspectives along with climate change. Finally, we review two classes of ongoing regional assessments and propose a new model for flyway impact assessment and next steps in its implementation.

The term flyway developed here is a vector, a construct of the seasonal flight velocity and the geographic route taken (see [Table 1](#) for flyway and related definitions), differentiating it from other assessment terms used for migratory marine fauna such as stocks, populations, and marine protected areas. These latter terms often serve similar conservation aims but are temporally static and exclude seasonal migration rates (Cadrin and Secor 2009, Dunn et al. 2019, Cadrin 2020). The flyway construct was developed in the 1930s to protect waterfowl networks of stopover habitats along annual migration circuits (Boere and Stroud 2006). Thus, the flyway construct captures the potential impacts of intervening offshore wind farms (OWF) on migration connectivity among destination and stopover habitats.

Within avian science and conservation, “flyway” applies to the seasonal routes of contingents, populations, metapopulations, species, and even communities (Galbraith et al. 2014). Flyways capture central premises in avian migration ecology:

- (i) Persistence and dynamics of many species depend upon the success of an annual breeding migration circuit (Shuford et al. 1998, Conklin et al. 2022).
- (ii) They encompass breeding, wintering, and staging areas (aka destination habitats) as well as the migration circuit itself (Boere and Stroud 2006, Kirby et al. 2008, Galbraith et al. 2014).
- (iii) Most flyways are latitudinally oriented (north–south) and comprise individuals moving along similar vectors covering distances > 100 km (Boere and Stroud 2006).
- (iv) Flyway designations and assessments support conservation efforts, which are often interjurisdictional and aimed at protecting networks of flyway habitats, also known as flyway connectivity (Rose 1998, Shuford et al. 1998).

Flyways are sometimes characterized by distinct and predictable seasonal migration phases, but in many cases encompass dispersed individual pathways or may show loop migrations of separate breeding and wintering phases. Migration routes are not always predictable as they are subject to the weather, where unfavorable winds and wind shear can divert or ground birds; thus, stopover habitats may vary seasonally or annually, causing flyway deviations (Cohen et al. 2021).

Table 1. Glossary of terms used to describe the flyway construct.

Adopted migration: Movements that are acquired through social transmission. Behaviors are typically transmitted from experienced (e.g. adults) to naïve (e.g. juveniles) individuals through their interactions, but in some instances, movement behaviors may be transmitted through numerical dominance (Secor 2015).

Contingent: Subpopulation group whose members exhibit a similar migration behavior over major life history phases or over an entire generation (Secor 2015).

Co-migration: Coinciding migration pathways undertaken by two or more species (Cohen and Satterfield 2020).

Connectivity: Degree of demographic exchange between geographically discrete populations or subpopulation groupings (Cowen and Sponaugle 2009). For marine fishes, connectivity often emphasizes larval dispersal, termed larval connectivity, but connectivity also occurs through the migrations of juveniles and adults of fishes and other taxa (Secor 2015).

Destination habitats: Migration endpoints associated with important life functions including breeding, feeding, and seasonal refugia.

Dynamic distribution models: Species distribution models that represent time-varying environmental variables matched with the timing and location of species incidence (Srivastava and Carroll 2023). These models often include animal tagging data.

Eulerian impact dimension: Changes to species incidence or movement observed through a fixed spatial lens, for instance by surveys conducted at a wind turbine or an OWF (see Fig. 5).

Flyway: A migration vector associated with one or more migration phases and defined by both speed and direction. Flyway was originally defined as an annual migration circuit that connects a network of avian stopover and destination habitats (Boere and Stroud 2006), yet this definition applies broadly to non-avian taxa (see Figs 1–3).

Hotspots: Locations where migratory animals disproportionately congregate, often operationally defined by the spatial and temporal resolution of observations and the species distribution modeling approach.

Lagrangian impact dimension: Changes to an individual's spatial fate observed serially, for instance by tracking an electronically tagged animal traversing several OWFs during the course of a season (see Fig. 5).

Migration: Collective movement of individuals that occurs chiefly through motivated behaviors, resulting in changed ecological status (Secor 2015). Migration corridors (*synonyms* migration pathway, migration route) are segments of annual migration cycles undertaken by populations. Seasonal migration phases connect destination habitats.

Migration connectivity: Networks of habitats and ocean basins connected through migration (Dunn et al. 2019).

Migration front: Distribution of individuals across the principal migration vector.

Migration speed: Rate of aggregate movements by a contingent, population, species, or assemblage measured along a principal migration vector (see Fig. 7).

Migration synchrony: Degree of individual variation in migration speed, within migration phases, measured along a principal migration vector (see Table 2).

Migration vector: Orientation of principal axis of a migration circuit or migration phase. Can be approximated by a simple latitudinal or longitudinal vector or a rotated combination of the two; in the northern hemisphere, termed a “migration-north” vector (see Supplementary Material).

Movement: Basic unit of spatial displacement for an individual. *Movement path* is operationally defined by the empirical approach used. Movement phases comprise sets or subsegments of serial movement paths that correspond to goal-oriented behaviors such as foraging or homing (Nathan 2008).

Movescape: Integrated movement vectors across individuals and species, particularly for electronically tagged animals (Lowerre-Barbieri et al. 2021).

Overlap models: Models of co-occurrence between species and the spatial extent of OWFs. Species occurrence is often modeled with time-invariant species distribution models.

Partial migration: Coexistence of two or more life cycles within the same population. Partial migration traditionally considers concurrence of migratory and sedentary contingents (Secor 2015).

Stopover habitats: Habitats that support migration between destination habitats through (i) replenishment of energy reserves, (ii) rest, (iii) refuge from adverse transit conditions and predation, and/or (iv) navigation adjustments (Schmaljohann et al. 2022).

Swimway: Analogue for waterfowl flyways, relevant to the interbasin spatial management of large river fishes (Pracheil et al. 2012).

Debate on designating feasible and impactful flyways centers on the level of organization, where arguments are defensibly made for either single species or multi-species migration flyways depending on conservation goals (Shuford et al. 1998, Galbraith et al. 2014, Conklin et al. 2022). Further, a recent research avenue addresses entire community flyways where predators and prey co-migrate (Cohen and Satterfield 2020).

Seasonal and annual fidelity to destination habitats and migration circuits also occurs for migratory bony fishes and sharks (Secor 2015, Queiroz et al. 2019), sea turtles (Baudouin et al. 2015, Mettler et al. 2019), and cetaceans (Silva et al. 2013, Johnson et al. 2022). In subsequent sections and case studies, we support the four flyway premises in diverse migratory vertebrates. Still, calling these “flyways” could prove cumbersome as fishes, turtles, and whales do not fly, *per se*, though vertebrate movement mechanics are similar in fluid aerial and aquatic environments (Denny 1993, Secor 2015). Alternative phrases in the literature include “migration corridors” (Secor 2015, Johnson et al. 2022), “swimway”

(Pracheil et al. 2012), and “movescapes” (Lowerre-Barbieri et al. 2021). Networks of habitats connected through migration have also been termed as systems of migration connectivity (Dunn et al. 2019). Migration corridors and connectivity are fairly generic terms, describing migration pathways without specifying visited habitats or their functions. Swimway is quite specific: a stand-in for flyways in addressing inter-jurisdictional management of riverine fishes (Pracheil et al. 2012).

Movescape is a reasonable alternative to the term flyway. First and foremost, it captures both collective movement rates and route. Further, in their initial application, Lowerre-Barbieri et al. (2021) emphasized networked habitats and stopover behaviors. Our essay builds on the flyway construct and related concepts with the intent to generalize across migratory marine taxa, including birds. In contrast, fish ecology has an unfortunate history of idiosyncratic terminology that has focused on migration types rather than migration as a process (Lucas and Baras 2001, Secor 2015). Flyways or

movescapes? We leave it to the scientific community to adopt an appropriate general term. For the purpose of this essay, we use the term “flyway” hereafter.

Stopover concept and flyway interactions with OW development

Across large shelf ecosystems, fields of turbine and substation foundations, deposited scour-protection beds, and buried and protected transmission grids will likely transform the migrations of many marine vertebrates, particularly in changed stopover behaviors. OWFs are often sited in relatively flat, structureless bottoms for ease of construction and permitting, portending large changes in the amount of physical structure (Kaldellis et al. 2016). Fields of turbines will substantially increase resource (structure, refuge, and food web) heterogeneity in large swaths of shelf ecosystems. In avian flights, the heterogenous distribution of resources along migration routes drives stopover behaviors and traditions, attracting concentrations of birds and, in many instances, their human observers (Boere and Stroud 2006). We are discovering that the migrations of fishes, turtles, and cetaceans emulate those of birds (Hussey et al. 2015, Secor 2015). Thus, as with birds, we should expect that stopovers are a common aspect of megafaunal migrations.

Flyway stopovers

Migration comprises alternate phases: passages that deplete energy and stopovers where energy is recouped (Cohen et al. 2021). For migrating birds, the exertions of flight commonly demand layovers at stopover sites. Time spent at these refueling stations is typically much longer than time flying: longest for “hop” migrators that recoup energy on a daily basis; shorter for “skip” migrators that forgo potential stopover habitats to minimize migration times; and negligible for “jump” migrators, that undertake non-stop migrations over long passages such as those over ocean basins (Piersma 1987). Trade-offs for each of these classes relate to the widely accepted “Optimal Migration Theory,” which focuses on stopover departure decisions: choices made based upon marginal gains in fuel stores reaped by staying versus foregone fitness costs caused by delaying arrival at breeding sites (Alerstram 1990, Newton 2008). Still, the exigencies of stopover versus passage decisions present a more complex set of stopover functions (Cohen et al. 2021, Schmaljohann et al. 2022).

Stopover functions (Schmaljohann et al. 2022) and types (Kirby et al. 2008) have been broadly classified and include the following:

- (i) rest and recovery, including refueling, sleep, and recovery from hyperthermia resulting from extreme catabolism during flight;
- (ii) avoidance of adverse conditions for flight (e.g. wind amplitude and shear, obscured vision), navigation (e.g. clouds, wind) or survival (predation); and
- (iii) navigation adjustments through assessment of seasonal progression and ground-based piloting.

Types of stopovers include the following:

- (i) “Fire-escape” sites that are infrequently used in case of emergency. These are often adjacent to migration bar-

riers (large bodies of water, deserts, altered landscapes) and can comprise small isolated refugia.

- (ii) “Convenience store” sites, where individuals briefly rest and easily replenish fuel. Used when fuel needs are moderate (stopover sites are in close proximity). Used for a day or two.
- (iii) “Full-service hotel” sites that are extensive in area providing a full suite of resources—food, water, shelter, and serving many individuals. Used for days to weeks at a time.

Flight decision-making about when and where to stopover is thus informed by resource and risk assessment by the individual bird. Although stopover sites persist over generations, so too do they dynamically change driven by altered habitats, weather, climate change, and population demographics and abundance. Birds colonize new stopover habitats, which on occasion can become end-destinations themselves for feeding and reproduction.

Increasingly, stopover phenomena are being reported for marine vertebrates, including marine fishes, sea turtles, and whales. These taxa show area-restricted foraging behaviors emulating stopovers separated by longer directed migrations. For instance, migrating ocean sunfish *Mola mola* periodically exhibit slower, shorter, and recursive movement paths that persist over several day periods (Sims et al. 2009). This same behavior has been noted for a range of sharks and bony fishes (e.g. Lowerre-Barbieri et al. 2021). Several-day stopovers are common in green turtles, that feed and rest in seagrass beds (Baudouin et al. 2015) and undertake hopping-type migrations from one foraging area to another (Mettler et al. 2019). Large baleen whales also show area-restricted search behavior. Such behaviors identified blue whale stopover sites near the Azores Island that were used for days to weeks (Silva et al. 2013). A stopover role uniquely ascribed to cetaceans is cultural transmission. For example, humpback whales converge and communicate at specific stopover sites at the intersection of overlapping migration routes; here, individuals of different populations gather and transmit information (Owen et al. 2019).

Other flyway interactions

Already, changed aggregation and migration behaviors by demersal fishes within OWFs are well established in the literature. Within OWFs, sustained site fidelity occurs where individuals gain food web and refuge benefits from turbine and scour structure (Reubens et al. 2013, 2014, Degraer et al. 2020). As a non-breeding area of retention, seasonal site fidelity over weeks to months demonstrates that OWFs can serve as stopover habitats. What remains unknown is how these habitats occur within flyways, how they’re networked, and how they collectively influence migration pathways and rates of seasonal migration.

In contrast to the demersal fish example, seabirds are killed by the thousands by wind turbines (Fox et al. 2006, Newton 2008), with some seabirds showing strong avoidance of OWFs (Welcker and Nehls 2016, Fox and Petersen 2019). Seabirds can facilitate foraging efficiency of other subsurface predators such as dolphins and tunas (Goyert et al. 2014). Thus, avoidance of multiple OWFs arrayed across flyways by birds and other migratory fauna could disrupt the use of traditional stopover sites and result in increased energetic costs, diminished access to feeding areas, altered

breeding success (Warwick-Evans et al. 2018), and changed breeding and wintering migrations (Vilela et al. 2021). In other instances, attraction and new stopover traditions are suggested by increased roosting behaviors by gulls on turbine superstructures (Welker et al. 1994, Vanermen et al. 2015).

Although not included in this prospective, flyways writ large could include systems of larval dispersal and connectivity. Demersal fishes and sessile invertebrates attached to wind turbine foundations and scour fields liberate planktonic eggs, embryos, and larvae that disperse 10–100 s of km, settling on other turbine-reef habitats across entire shelf regions (van der Molen et al. 2014). The distribution of OWF sessile and demersal communities thus depends on larval connectivity (Table 1), and would be expected to affect the distribution of mobile predators. Here, however, we limit consideration of flyways to the motivated migrations during juvenile and adult phases of fishes and other marine animals.

Three flyways in regions of OW development

Three shelf ecosystems—the South and East China Seas, the NS, and US MAB—will experience exceptionally high rates of OW development in the next 30 years (Galparsoro et al. 2022). Near-shelf waters off the South and East China Seas support 6.3 GW OW production, representing ~90% of China's offshore wind production (Baiyu 2020). Taiwan produces another 2.2 GW in the Taiwan Strait (Galparsoro et al. 2022). Projected production by 2030 for these two countries is ~100 GW. The NS has long been a center for OW energy production and will continue to be so. Greater than 100 GW is targeted by 2050. About 30 GW is projected for the USA, mostly within the MAB in the coming 10–20 years (Galparsoro et al. 2022). Based on an approximate average turbine production rate of 10 megawatts (considering smaller existing turbines and future turbine sizes ≥ 15 MW), fields of many hundreds of turbines in scores of individual OWFs will be arrayed across each of the three shelf-ecosystems.

The three case studies presented below convey common attributes: they occur in shelf ecosystems where OWFs will extend over wide temperate latitudinal gradients; their ecosystems are strongly seasonal and exhibit circulation features and productivity gradients; and OWFs will be broadly arrayed across known seasonal migration pathways and stopover habitats for communities of marine vertebrates.

Sea turtle flyway: South and East China Seas

As marginal seas, the South and East China (SECS) shallow shelf regions (<200 m) are among the largest and most productive in the world ($>2 \times 10^6$ km²) (Johnson and Boyer 2015, Zheng et al. 2020, Zhu et al. 2022) (Fig. 1). Continental China borders to the west and a series of archipelagos border to the south and east. The two seas connect through the narrow Taiwan Strait. The Kuroshio and Taiwan Strait currents convey warm waters northward and are opposed by the China Coastal Current. East Asian monsoon and Siberian high circulation systems cause strong seasonality in the SECS. In winter, the East China Sea experiences shelf-mixed waters <10°C; in summer, upper-mixed waters warm to 28°C (Johnson and Boyer 2015). Coastal SECS waters are influenced by the Pearl and Yangtze Rivers, which with other rivers give rise to extensive and productive estuarine and seagrass habitats.

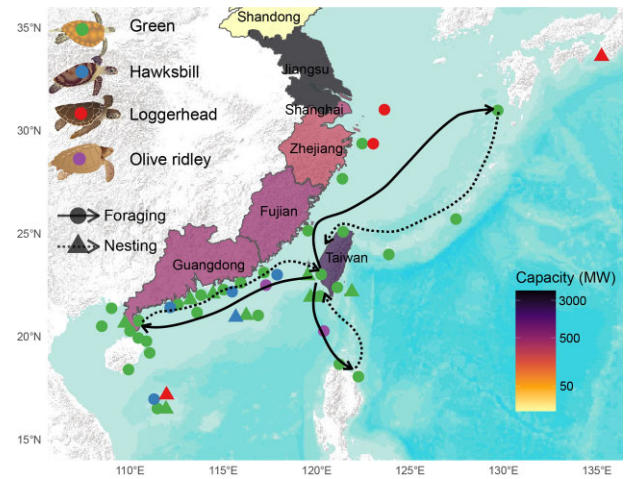


Figure 1. Sea turtle flyway in the South and East China Seas. Intensity of OW development is shown by province (Baiyu 2020) and country (Taiwan; Galparsoro et al. 2022). Generalized seasonal migrations are shown for green turtles and foraging and spawning locations for other sea turtle species. Data from Ng et al. (2018).

The majority of the world's sea turtle species occur within the SECS: the leatherback, olive, Ridley, loggerhead, and hawksbill travel hundreds to thousands of kilometers in their seasonal migrations (Ng et al. 2018). The most abundant of these, the green turtle, shows high levels of fidelity to migration routes and foraging areas after each successive breeding event (Broderick et al. 2007). Stopover habitats and migration pathways cause green turtles to move through shallow shelf regions, which are the focus of OW production in regions such as Hong Kong, Guangdong Province, and Taiwan Strait (Baiyu 2020, Delina et al. 2023). These migration pathways are shared by hawksbill and loggerhead turtles (Ng et al. 2018). In stopover habitats within estuaries and near-shelf habitats, green turtles forage on seagrass. High-quality stopover habitats occur in eastern Taiwan, eastern Hong Kong, and Guangdong Province. The migration pathway crosses interjurisdictional boundaries, including the Philippines, Hong Kong, mainland China, Taiwan, and southern Japan.

Sea turtles in this region face threats from shoreline development, bycatch, and direct exploitation (Ng et al. 2018), and conservation is made difficult by a flyway that requires inter-jurisdictional action. OW development, particularly related to transmission grids, could degrade existing foraging stopover sites. Green turtles and other sea turtles are attracted to pelagic structure (e.g. Sargasso [juveniles], flotsam, reefs, and fish attraction devices; Dagorn et al. 2013, Mansfield et al. 2014, Siegfried et al. 2021) and the imposition of structure could cause new stopover traditions to emerge, particularly for the green and loggerhead turtle flyways that are focused in coastal waters.

Schooling fish flyway: the NS

The NS exhibits complex bathymetry and meteorological forcing, resulting in dynamic changes in the distribution and harvests of schooling fishes (Daan et al. 1990) (Fig. 2). The Sea extends 1000 km from the Norwegian trench southward to the English Channel and, in the east, connects to the Baltic Sea through the Skagerrak and Kattegat Straits. The southern

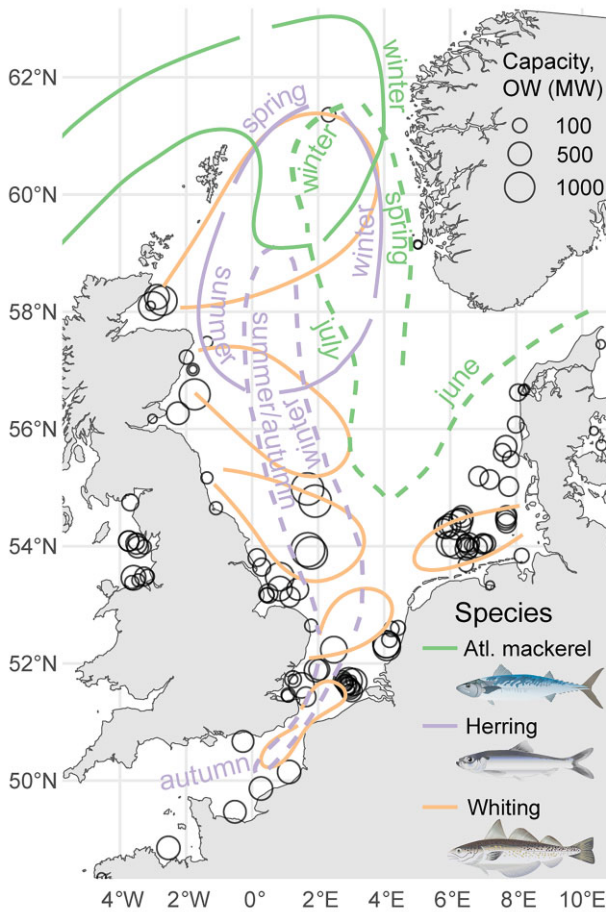


Figure 2. Schooling fish flyway in the NS. Generalized seasonal migration circuits for Atlantic mackerel (green), Atlantic herring (purple), and whiting (orange). Secondary (contingent) migration pathways shown in dashed lines. Migrations from data and depictions by Daan et al. (1990), Corten (2001), and Gonzalez-Irusta and Wright (2017). Spatial extent of online and imminent OWFs from WindEurope asbl/vzw (<https://windeurope.org/intelligence-platform/product/european-offshore-wind-farms-map-public>, 22 May 2024, date last accessed).

NS is shallower and supports spawning and nursery habitats for schooling fishes. The NS has experienced overall warming in recent decades (Cook and Heath 2005, Dulvy et al. 2008) and exhibits less stable seasonal circulation patterns than other temperate shelf regions owing to the dominant influence of wind and tidal forces acting on winding coastlines, banks, and deep trenches (Howarth 2001).

During spring months prior to spawning, Atlantic mackerel concentrate at the northeast (NE) boundary of the NS between Scotland and Norway (Daan et al. 1990, Jansen and Gislason 2013, Ono et al. 2022). Historically, this group entered the central NS to spawn; it then migrated down the eastern NS during summer and fall and completed the circuit returning to the NE NS (Daan et al. 1990, Jansen and Gislason 2013). Recent evidence (Jansen 2014a, Ono et al. 2022) indicates that this migration is but one of several dominant circuits undertaken by a single superpopulation of mackerel distributed from Spain to Iceland. This particular circuit, however, has been diminished owing to changed climate, oceanography, and overfishing (Jansen 2014b). Observed aggregations of Atlantic mackerel near turbines (Stenberg et al.

2015) could suggest a degree of stopover behavior, as pelagic fishes are commonly attracted to physical structures in the water column (Dagorn et al. 2013). The persistence of these aggregations is unknown. Still, even were they short-lived, the cumulative impact of many turbines (attractors) could conceivably alter seasonal migration behaviors.

Similar to Atlantic mackerel, NS herring overwinter in the NE NS along the western edge of the Norwegian trench (Corten 1999), attracting fisheries. In summer and fall they migrate south, spawning on banks and reefs along the eastern coast of England; a southern population migrates farther south to the English Channel, spawning there in the winter. Adults spawn in areas that are conducive for their larval offspring to be transported to nurseries in broad, shallow waters in the southeast NS such as the German Bight and the Wadden Sea (Daan et al. 1990). The distribution of spawning herring is increasingly northward with climate warming (Corten 2001). As herring require hard bottom reef structures to attach their eggs, their spawning migrations could be impacted should OW development degrade existing spawning habitats or potentially form new spawning habitats through the millions of tons of rock deposited as scour and cable protection.

Whiting, a very abundant bottom fish, exhibits shorter migration circuits (<100 km) that could be particularly altered by OW development. Spawning aggregations concentrate along the coasts of the United Kingdom and Belgium within regions of heavy OW development in shoal regions 20–40 m deep (Tobin et al. 2010, Loots et al. 2011, Kerby et al. 2013, Gonzalez-Irusta and Wright 2017). Although a single population, the same spawning regions are used over decades (Gonzalez-Irusta and Wright 2017). NS whiting principally avoid hard structures associated with OW development (Stenberg et al. 2015, van Hal et al. 2017), which could potentially alter their overall distribution, migration circuits, and regions of spawning.

Baleen whale flyway: MAB

Similar to the SECS, the US MAB is influenced by large estuaries, which in addition to canyons and banks cause productivity gradients and hotspots of plankton and pelagic fishes: forage for baleen whales (Roarty et al. 2020) (Fig. 3). The 900 km distance from Cape Cod in the north to Cape Hatteras in the south results in a strong sea-surface temperature (SST) latitudinal gradient. Further, isobaths (excluding shelf canyons) are gradual, resulting in cross-shelf gradients in temperature that reverse themselves seasonally (Rothermel et al. 2020). The Gulf Stream and Labrador Current jointly influence shelf circulation with persistent stratification during summer months (Roarty et al. 2020). Seasonal SST changes in this relatively shallow shelf ecosystem are quite high: ~20°C (Castelao et al. 2010).

Conventionally, baleen whales were believed to use the MAB for transit between north temperate feeding and subtropical breeding and calving destination habitats. Species include fin, sei, humpback, and North Atlantic right whales (minke and blue whales also occur in the MAB, but their principal migrations and distributions are likely centered northward; Davis et al. 2020). Bucking this view, increased coverage through observer programs and passive acoustics show that most whale species do not exhibit directed migrations through

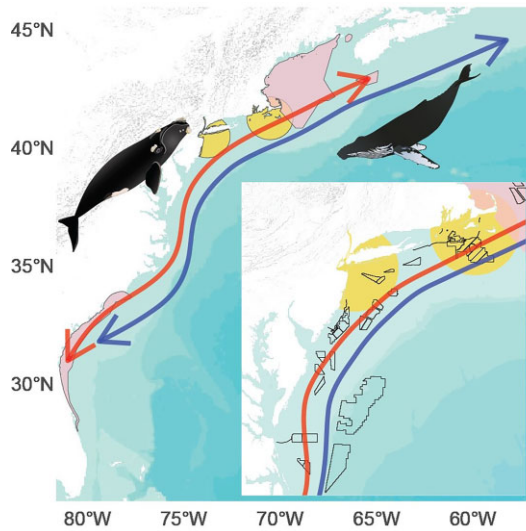


Figure 3. Baleen whale flyway in the US MAB overlaying OWFs (inset polygons). Generalized seasonal migration circuits for North Atlantic right whales (inshore, red) and other baleen whales (offshore, blue) are shown (Davis et al. 2020, Quintana-Rizzo et al. 2021). Note, other baleen whales extend their migrations farther south than North Atlantic right whales. Northern pink regions are protected foraging (USA and Canada) and calving (USA) habitats for right whales. Southern yellow regions indicate foraging stopover sites centered in New York Bight and Nantucket Shoals (Quintana-Rizzo et al. 2021, Brown et al. 2022). Inset shows the MAB and high concentration of planned OWFs.

the MAB (Whitt et al. 2015, Davis et al. 2020, Quintana-Rizzo et al. 2021). Rather, whales may be feeding and even reproducing within specific regions of the MAB.

Observation networks for detecting North Atlantic right whales and humpback whales have changed traditional views on migration behaviors. Right whales, historically concentrated in the Gulf of Maine and Bay of Fundy during summer, have concentrated in the northern MAB since 2010 near Nantucket shoals, a feature that increases local production of their calanoid zooplankton prey (Quintana-Rizzo et al. 2021). Elsewhere in the MAB, some females are year-round residents forgoing an annual breeding migration. In waters off New York City (New York Bight), humpbacks have adopted new behaviors, feeding on large schools of Atlantic menhaden throughout the summer (Brown et al. 2022). Here and in other regions of the MAB, humpbacks, right whales, and fin whales feed and persist during summer months (Whitt et al. 2015, Bailey et al. 2018, Lomac-MacNair et al. 2022).

Year-round residency by a component of a whale population represents partial migration, which is likely widespread among migratory vertebrates, as it is in birds (Chapman et al. 2011, Secor 2015, Quintana-Rizzo et al. 2021). Large-bodied baleen whales are capable of migrating thousands of km (Davis et al. 2020), yet rigidity in migration behaviors and traditions would curtail adaptation to oceanographic and climate change (Harden Jones 1968). Ironically, the behaviors recently discovered in Nantucket right whales and the New York Bight humpback whales put them within the most intense region of MAB OW development (Fig. 3). Further, planned OW development in deeper MAB shelf and slope waters (Galparsoro et al. 2022) will overlap with sei, minke, and blue whale flyways (Davis et al. 2020). Increased vessel traffic

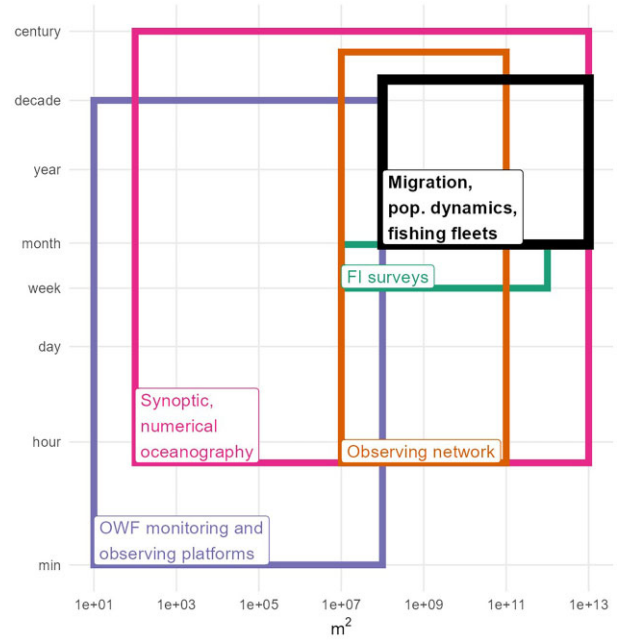


Figure 4. Approaches to monitor OWF impacts range from sub- m^2 to $>1000 \text{ km}^2$ and from minutes to decades. These dimensions are investigated by observing systems, fishery-independent (FI) surveys, and oceanographic models. Dimensions most relevant to flyways, migration, population dynamics, and fishing fleets are overlain.

associated with OW development reduces the efficiency of social communication and increases the risk of collisions. Similar to seals and porpoises, whales may avoid OWF regions during construction (Russell et al. 2016, Bailey et al. 2018). Once an OWF is operational, altered food webs associated with increased structure could promote feeding opportunities, particularly for whales such as humpback, sei, and fin whales that feed on schooling fishes.

Impact dimensions for migratory marine fauna

Regional footprint

Continental shelf and near-shelf waters in temperate latitudes offer expansive areas and weather regimes favorable for wind harvesting. As reviewed above, the most rapid development; in the European Union, UK, China, Taiwan, Japan, and the USA; occurs in shelf and near-shelf ecosystems that extend north-to-south many hundreds of kilometers. As reviewed above, strong seasonality across these latitudes drives the migrations of many marine animals, including fishes, sea turtles, pinnipeds, and cetaceans. Migratory fauna often receive priority in evaluating OW energy impacts, yet the assessed dimensional unit is the individual OWF, rather than the regional extent of many OWFs arrayed across migration circuits.

OWF impacts are rarely considered at the dimensions that affect populations and communities of migrating animals (Fig. 4). Monitoring dimensions of impacts is daunting, ranging 1 m^2 for stressors such as electromagnetic fields and foundation fouling, $\sim 10 \text{ km}^2$ for OWF disruptions, including operational noise to local fisheries, and entire shelf ecosystems ($10^5\text{--}10^6 \text{ km}^2$) across which multiple OWFs affect migratory species and fishing fleets (Fig. 4). Concepts

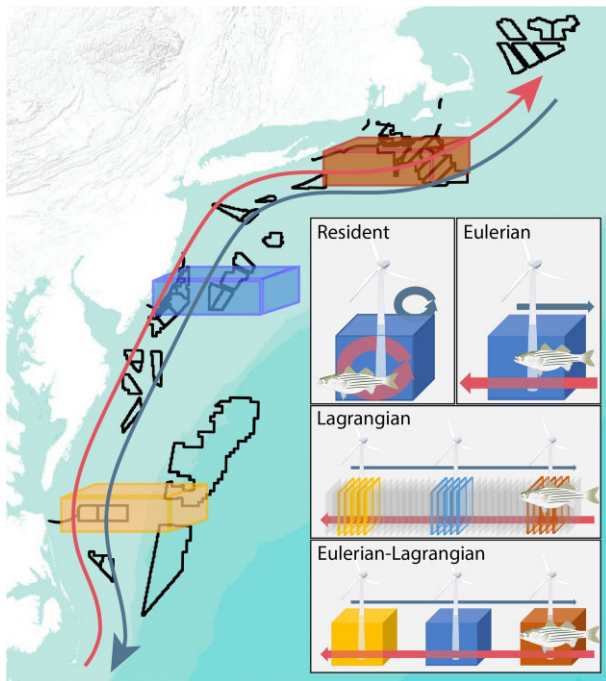


Figure 5. Hypothetical flyway telemetry observation system showing Eulerian and Lagrangian perspectives. Current OWF project and planning areas are shown transecting the flyway of migratory striped bass, occupying three cross-shelf regions shown in the inset. At a single OWF (top inset panels), resident behaviors are tracked continuously through an OWF network of telemetry receivers. At the same site, seasonal movement past the OWF is monitored. Across the three regions, the movement through OWFs is tracked using a network of receivers and a hybrid Eulerian–Lagrangian system of observations (bottom inset panel) supporting a flyway vector assessment. OWF project and planning areas from the BOEM Office of Renewable Energy Programs; map is from World Terrain Base, ESRI. Figure modified from Rothermel et al. (2024).

of OWF impacts on mobile marine fauna thus emerge from a dimensional hierarchy, recognizing that hypothesized impacts must align with the scale of observation (Schneider 2001). Indeed, the term “scale” is prolifically used in reviews of OWF impacts (Willstead et al. 2018, Gill et al. 2020, Methratta et al. 2020, Friedland et al. 2021, Galparsoro et al. 2022), epitomized by a recent technical review in which the term occurred >200 times (Hogan et al. 2023). Scale can reference levels of biological organization (Stokesbury et al. 2022), spatial orders of magnitude (Methratta et al. 2023), or levels of complexity and interactions (Willstead et al. 2018).

Impacts at the unit scale of the turbine and OWF occur at tractable dimensions for understanding responses to changes in the sensory and physical environments of an individual (Gill et al. 2020), and changed food webs (Degraer et al. 2020), and likely exact only a marginal influence on migratory fauna (see Fig. 6). At these dimensions, responses are feasibly observed for sessile and sedentary fauna, and for mobile fauna, concepts of change have emphasized local movement behaviors such as attraction and avoidance even for highly migratory turtles and whales (Kraus et al. 2019). Local OWF impacts might be expected to exact marginal effects to the vital rates of populations and communities of migratory fauna (Vilela et al. 2021, Cresci et al. 2024), regrettably difficult to evaluate in practice (May et al. 2019), and likely intractable

owing to non-overlapping dimensions of observation (Fig. 4).

Fields of thousands of turbine structures arrayed over large marine ecosystems will create novel seascapes that will alter migration, feeding, reproduction, and overall population dynamics in migrating marine fauna (Figs 1–3). Evaluating these changes is challenging but tractable within the rapidly improving capabilities of observing networks and synoptic oceanography.

Eulerian versus Lagrangian impact dimensions

Dynamic oceanographic processes are observed through two lenses: the Eulerian method views particle flux through a fixed spatial lens, and the Lagrangian method follows individual particles along their coordinate fates. Both methods evaluate the temporal dynamics of fluids and particles, but do so through different windows of observation and attendant assumptions (Garrafo et al. 2001). For instance, a deployed conductivity–temperature–depth instrument might support an Eulerian view of temperature flux within an OWF area based on assumptions related to connections between spatially or temporally adjacent casts, where we are curtailed to a single spatiotemporal lens (Itakura et al. 2021). Alternatively, an AUV glider can maintain itself in isothermal water and plot the movement of that parcel (Rudnick 2016), yet we are constrained to observe the coordinates of only that mass of water. Synoptic oceanography integrates satellite observations to represent surface oceanography over ecosystem scales yet these remain Eulerian (static) snapshots, unless driven by numerical models that allow Lagrangian methods to drive mass oceanographic fluxes (Cazenave et al. 2016, Kavanaugh et al. 2016).

Feasibility and precedence lead to OWF observations that tend to be Eulerian: fixed-site observations of water properties and marine faunal vectors. Still, Lagrangian approaches are quite practical at the turbine—OWF scale through coordinated sets of sensors and numerical modeling (Fig. 5) (Secor et al. 2019). For instance, Atlantic cod were continuously tracked using a network of acoustic tag receivers, transforming an Eulerian perspective (single fixed site) to a Lagrangian one (site network) (Reubens et al. 2013).

Satellite and archival animal tags lend themselves to Lagrangian perspectives on OWF impacts. Such tags yield near-continuous observations on the coordinates of migrating animals through algorithms of light- or depth-based geolocation, or direct satellite geolocation of surfacing animals. Further, these tags can measure physical and even social conditions, providing a true Lagrangian window into how and why animals migrate (Hussey et al. 2015, McMahon et al. 2021). Still, tag size and the effects of tag emplacement can curtail their deployments on smaller (<1 m length) organisms, younger life stages, and protected species (Hazen et al. 2012). Geolocation precision can also limit applications, albeit state-space modeling has provided a much-improved approach, in constraining positional errors (Jonsen et al. 2013, Secor 2015).

Tracking individuals across a network of regional observatories would represent a hybrid Eulerian–Lagrangian perspective (Fig. 5), curtailed by large gaps in spatial coverage, yet supported by serial observations of the same individuals (Dunn et al. 2019, Lowerre-Barbieri et al. 2019). And, similar

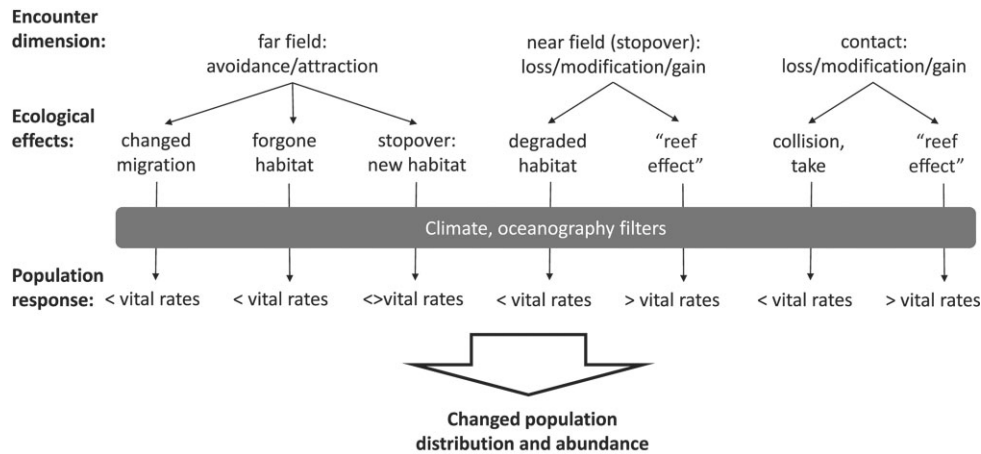


Figure 6. Cascade of possible OWF \times species interactions from encounter dimension to population response (adapted from Fox and Petersen 2019). Far field and near field encounters are those occurring outside and inside of the OWF footprint. Note that for many species, these encounters are affected by changed soundscapes. Contact indicates physical interactions with rotors, sub-foundations, and scour material. Take references impacts that harm or kill species of concern. Vital rates are growth, reproduction, and survival that may be diminished (<) or enhanced (>).

to the manner in which numerical oceanography can drive synoptic observations, so too can dynamic habitat models serve to integrate regional observations of migrating animals (see *Flyways and dynamic distribution models* section). These observing systems for migratory animals depend on passive reception of animal vocalizations or telemetry, the latter depending on small implanted or attached coded acoustic pingers or satellite transmitters. Distributed OWFs provide new opportunities to view migration through networked observing systems.

Flyways in impact assessments

Regional ecosystem-level assessments

Offshore wind development together with climate change will produce unintended and unpredictable changes to migratory animals and the fishery and conservation benefits they provide. Climate change will alternatively obscure, dampen, or amplify OWF impacts, yet only a minority of studies have investigated interactive climate and ecosystem effects (Galparosoro et al. 2022). Further, for exploited species, fishing fleets have been responsive to changed resource availability (Pinsky and Fogarty 2012), and will in the future face changed accessibility as they bump up against fields of fixed structures (Gill et al. 2020).

Regional ecosystem-level OWF assessments have lagged behind other assessments owing to lack of coordination, expense, and the challenges of making observations that convey process dynamics at large ecosystem dimensions (NOAA 2022). An exception are studies predicting potential effects by modeling species distributions (see next section). Yet a further barrier is the lack of concepts to guide hypotheses and assessment objectives. The Integrated Ecosystem Assessment is a widely adopted framework and provides a means to leverage available observations and analyses of ecosystem components towards societal benefits, such as fisheries. Further, these assessments bring in key aspects of oceanographic and climate change at large marine ecosystem dimensions (Levin et al. 2009). Climate impacts are tractably analyzed by evaluating oceanographic variables, such as surface and bottom temperatures, current systems, weather events, and

climate oscillations, which represent important manifestations of climate change. Typically, though, the assessments represent annual depictions of ecosystems: summaries of data at annual time steps in part owing to their reliance on fixed-season vessel surveys rather than year-round observing systems. Such surveys fail to capture many aspects of seasonal changes in climate and oceanography, extreme events, and changed ecosystem and migration phenology.

An assessment scheme suitable to migratory fauna would leverage Eulerian observations across regional networks to provide dynamic seasonal responses to large ecosystem changes, asking the fundamental question of how flyways are altered by mass additions of structured habitats, compounded by climate change. Avian impact studies have already pursued this question (Goodale and Milman 2020), yet this flyway construct has not been adopted for other marine fauna. In the following sections, we review two existing approaches (overlap and dynamic distribution models) and propose a new method (flyway vector model), all aimed at assessing OWF impacts across large regions. Note that classic BACI designs are near impossible to apply because shelf impact areas would consume any region set aside as a control area. Rather, assessments focus on changed distributions and migration patterns that would be evaluated in a before–after impact design.

Flyway snapshots and overlap models

Species utilization distributions (UDs), developed through geospatial models (Hui et al. 2023, Dovers et al. 2024), are a potential means for understanding cumulative effects of many OWFs on surveyed species. Here, UD are overlain upon the areal OWF footprint and the level of overlap is assessed as a measure of impact. For instance, long-term fixed-season trawl surveys in the US NW Atlantic showed high overlap among the UD of select demersal fish species and OWF areas (Friedland et al. 2021). On the other hand, these same species were the most prevalent within the trawl survey itself (NOAA 2021). Similarly, hotspots derived from modeled UD depicted overlapping distributions between OWFs and NS gannets (Busch et al. 2013), Baltic Sea curlews (Schwemmer et al. 2023), and forage fishes (Friedland et al. 2023). Further, geospatial data provided a highly articulated sensitivity

analysis of multiple and cumulative impacts associated NS OWFs on migratory birds, fishes, and marine mammals (Gusatu et al. 2021). Overlap models can also demonstrate potential impacts to fisheries and other sectors (Stelzenmuller et al. 2022, Allen-Jacobson et al. 2023). Overlap models hold important advantages in synthesizing available data, building in relevant environmental variables through species distribution models, and providing visual depictions that are easily communicated to stakeholders. Further, overlap models have supported policy based on thresholds of lost or foregone habitat or population loss (May et al. 2019).

Although often used, overlap models entail unrealistic assumptions: (i) they do not specify how spatial overlap is expected to affect species distribution and ecology; (ii) they cannot represent distributions that change over days, weeks, seasons, and years; and (iii) overlap effects may not be clearly bounded. Overlap between species incidence and OWF areas precipitates a cascade of possible species-by-OWF interactions (Masden et al. 2010), with multiple feasible pathways of population response (Fig. 6), which can then be used to inform risk and vulnerability assessments (Brabant et al. 2015, Warwick-Evans et al. 2018). Encounter dimensions range from entire continental shelves to OWFs to turbines, resulting in diverse ecological outcomes and consequences to marine populations that are modified by climate, oceanography, changed soundscapes, and in some instances, fishing. Temporal changes in distributions were highlighted in the case studies: seasonal migration behaviors (weekly and monthly distributions) control how green sea turtles will encounter nearshore turbines in the East China Sea, how schooling fish encounter concentrated patches of turbines in the NS, and how cetaceans in the US MAB will be exposed to increased noise associated with OWF development. These seasonal dynamics are also important to understand how OWF impacts are jointly influenced by climate and oceanographic change (e.g. Horwitz et al. 2023). Finally, overlap is not always easily bounded, but rather influenced by oceanographic gradients and currents that can spread an OWF's influence well beyond the OWF's footprint (Fox and Petersen 2019, van Berkel et al. 2020).

Flyways and dynamic distribution models

At flyway dimensions, “dynamic” distribution models (Table 1) specify temporal change in (i) distribution responses, (ii) environmental and other explanatory data, or (iii) both (Srivastava and Carroll 2023). Lagrangian agent-based models simultaneously evaluate temporal and spatial dynamics, which as simulations can address scenarios of complex interactions between physical forces and distributions, particularly for planktonic organisms that have reduced movement repertoires (van der Molen et al. 2014, Barbut et al. 2020, van Berkel et al. 2020). These simulations have seen limited application in the motivated movements of migratory fauna (Dunlop et al. 2021, O’Connell et al. 2021). Alternatively, distribution data can be made dynamic by modeling migration pathways constructed from telemetry data. Examples include state-space and Brownian bridge movement models (Jonsen et al. 2005, Spiegel et al. 2017). Both of these account for the temporal and spatial covariance of serial positions by individual animals, while integrating fundamental movement principals. Operational oceanographic data, available from satellites, buoys, and other continuous observing systems, further contribute to

realism in dynamic distribution models (Hidalgo et al. 2016, Kavanaugh et al. 2016).

Spatiotemporal structures underlying dynamic distribution models are well supported by modeling frameworks that allow nonlinear, spatially correlated responses and predictors, most often by general additive, and general additive mixed models (hereafter jointly referenced as GAMS). GAMS accommodate extrapolation of complex nonlinear and interactive responses to areas without direct observation while retaining estimates of inherent uncertainty. Hierarchical GAMS utilizing Bayesian methods such as integrated nested Laplace approximation or Markov chain Monte Carlo sampling, have allowed extension of dynamic distribution models to include spatiotemporally correlated random effects and capture the effect of unidentified latent processes (Clark and Wells 2023, Hui et al. 2023, Anderson et al. 2024, Dovers et al. 2024).

Dynamic distribution models, many supported by GAM structures, are being used to predict flyway attributes, not only for seabirds but also for cetaceans, sea turtles, and fishes. Departing south from summer breeding areas in the late summer, telemetered northern gannets migrated across the Gulf of Maine as a broad slow-moving asynchronous front, which then narrowed, increased in speed, and became increasingly synchronous through the US MAB (Spiegel et al. 2017, Stenhouse et al. 2020). Modeled fall and spring flyway habitats (Brownian Bridge Movement Model) were substantially different than those previously estimated using sightings data, uncovering previously unknown inshore hotspots. For North Atlantic right whales, seasonal shifts in the position of the Gulf stream curtailed the calving portion of the flyway to inshore regions of the US South Atlantic Bight (Gowan and Ortega-Ortiz 2014). These dynamics were inferred from a GAM fitted to sightings and satellite-derived SST data. Seasonal flyway migrations for telemetered loggerhead sea turtles, modeled as monthly utility distributions from diverse tagging studies (Point Process Model), showed rates of summer habitat expansion from the US South Atlantic Bight into near shelf regions of the US MAB (Winton et al. 2018). Telemetered smooth hammerhead sharks were also influenced by daily changes in SST in their seasonal migrations from Cape Hatteras (North Carolina, USA) to the New York Bight, predicted from a GAM (Logan et al. 2020). Across these applications, inferences on flyway rates and pathways were drawn by the inclusion of temporally resolved geospatial data either in the predictor or explanatory variables, or both.

Flyway vector assessments

Regional and global observation networks can support flyway vector assessments. As a demonstration (Fig. 7), we compiled data for northern gannets, North Atlantic right whales, and striped bass throughout the US Atlantic shelf waters, principally the MAB and Gulf of Maine (Davis et al. 2017, Spiegel et al. 2017, Stenhouse et al. 2020, Secor et al. 2020a, b). Weekly latitudinal distributions, modeled by GAMS (Wood 2011, Simpson 2024), exhibited large-amplitude seasonal migrations across species. Northern migrations in late winter and spring were rapid, migration vectors varying between 0.8 and 1.8 degrees latitude per week. The three species “flat-lined” in high-latitude destination habitats associated with breeding (northern gannet) and feeding (North Atlantic right whales and striped bass). Southern migrations were slower than northern ones, ranging between 0.3 and 1.2 degrees

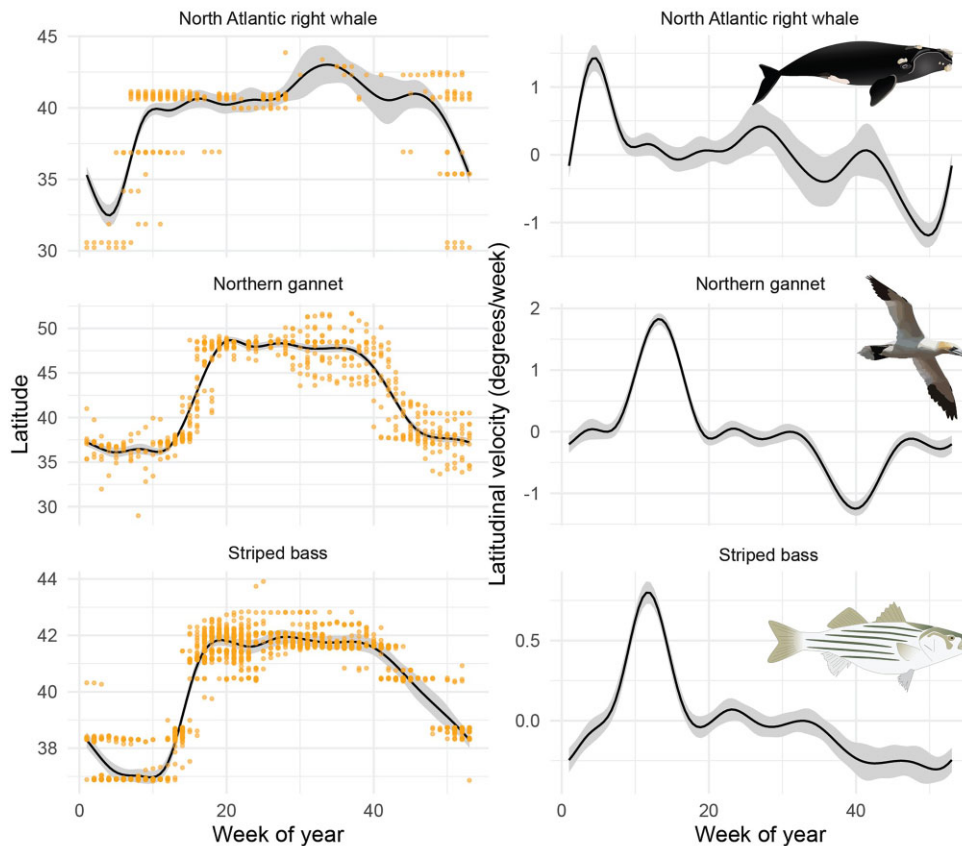


Figure 7. Flyway depictions and metrics for North Atlantic right whale, northern gannet, and striped bass, e.g. years 2013, 2015, and 2017, respectively. (a) Weekly mean latitude with GAM-modeled smooths and 95% confidence intervals; and (b) latitudinal velocities estimated as the derivative of GAM-modeled smooths. Data from Davis et al. (2017), Spiegel et al. (2017), Stenhouse et al. (2020), and Secor et al. (2020a, b).

latitude per week. Across the diverse species, low weekly latitudinal variance occurred at high latitudes during summer and fall months, suggesting regional habitat selection. Latitudinal variance, a measure of migration asynchrony, was particularly evident for northern migrations. For North Atlantic right whale, migration asynchrony occurred during other parts of the year, perhaps indicative of partial migration (multiple contingents) for this population. The depicted flyways; and the vectors, velocity, and variance metrics they support represent a feasible assessment framework. Note that this framework is generalizable across a diverse set of species and observation methods, which included (i) northern gannet, satellite telemetry, Lagrangian data, and a global network; (ii) North Atlantic right whale, passive acoustic monitoring, Eulerian–Lagrangian data, and a regional network; and (iii) striped bass, acoustic telemetry receivers, Eulerian–Lagrangian data, and a regional network.

Flyway assessments will depend on estimable and meaningful metrics. That is, metrics that can be estimated across flyway dimensions, provide amplitudes unobscured by error and bias, lend themselves to impact study designs, and be readily communicated to diverse stakeholders (Link 2005). Flyways as depicted in the demonstration (Fig. 7) are predicated on a dominant north–south migration cycle (Boere and Stroud 2006); however, projections can be altered to adjust for a “migration-north.” For the demonstration, we rotated projections counter-clockwise to dominant migra-

tion vectors and again evaluated trends in adjusted latitudinal distributions and velocity, which produced mostly subtle differences (Supplementary Material S1). A notable difference occurred for striped bass where the northern migration failed to capture a co-occurring spawning migration along the same latitudinal axis, but deflected westward towards the Hudson River. Still, such vector exploration of possible missed migrations is straightforward (Supplementary Material S1). As another example, sea turtle flyways in the South and East China Seas (Fig. 1) would clearly require vector exploration and geographic rotation. An important outcome is that flyway velocities, expressed as vectors in latitude and longitude can be readily converted to speeds in meters per second, knots, or animal lengths per second.

Flyways, modeled using GAMs (Fig. 7), are amenable to before–after impact and before–after gradient (BAG) tests of offshore wind impacts to migration and stopover behaviors. In particular, BAG designs could include time as a gradient (covariate), utilizing GAMs to evaluate the effect of OW development phases (before, during, and after) on the expected seasonal distributions and transit rates of migratory fauna (Fig. 7). Further, such designs could evaluate displacement of flyway vectors or changed metrics caused by a single or series of OWFs arrayed across large regions. Here, GAMs were fit to each species, but it is quite feasible to model pooled species or pooled population migration behaviors (Rothermel et al.

Table 2. Flyway metrics for offshore wind impact assessment of migratory fauna.

Flyway metric	Definition	Relevance
	Distribution metrics	
Flyway extent	Annual species distribution envelope.	Population health depends on conserving full breadth of destination and stopover habitats, and migration corridors.
Seasonal species distribution	Monthly to seasonal distribution envelopes.	Relates to flyway functions (destination, stopover habitats, migration, breeding, feeding, etc.) to regions of impact.
Destination habitats	Long term (months, multi-season) persistence in regions associated with feeding, breeding, mating, and overwintering.	Contributes to population sustainability.
Hotspots, stopovers	Concentrated distributions along the flyway. May be defined by period of persistence (e.g. 30 days).	Relates to stopover functions that support migrations and population sustainability.
	Migration metrics	
Migration front	Longitudinal (migration vector excursion) variance over time.	Relates to how cross-shelf gradients affect the flyway.
Migration synchrony	Latitudinal (migration vector) variance over time.	Relates to within population synchrony in seasonal migrations and/or partial migration.
Migration speed	Migration vector transit speeds over time.	Relates to periods of population flux and exposure to regional impacts.
Stopover and destination habitat thresholds	Distribution of dwell times (persistence by latitude).	Timing and persistence at stopover and destination habitats.

2024). Additionally, GAMs can be used to detect responses to anomalous seasonal or annual events such as extreme storms, heatwaves, and shifts in oceanographic features such as the Gulf Stream or Mid-Atlantic Cold Pool (Friedland et al. 2022).

To promote development of metrics that support OWF impact studies, we propose a set of feasible flyway metrics (Table 2). These metrics can support before–after, BAG, and other experimental designs of regional and cumulative OW impacts. Limiting assumptions attend the proposed metrics. For electronically tagged animals, the tagged sample should represent the target population or seasonal population component. For Flyway Extent, observation platforms should cover the entire flyway and regions outside the flyway; however, partial coverage may suffice for the other distribution metrics (seasonal species distribution, destination habitats, and hotspots/stopovers) and all of the migration metrics. Important for all these metrics, is year-round and near-continuous observation systems. Latitudinal (migration vector) variance stems from both between and within-individual data, which were partitioned for northern gannets and striped bass, but not North Atlantic right whales, which are detected as either individual or collective vocalizations. Here, it would be important to recognize the assumption that flyway metrics potentially represent group rather than individual behaviors. Finally, in development of baseline behaviors, there is the expectation of repeatability across years. In birds, a recent meta-analysis estimated 41% repeatability in migration metrics among years (Franklin et al. 2022). Within the literature for marine fishes, repeatability in spawning run behaviors and return to specific habitats is frequently reported, albeit without a systematic review of the repeatability metric (Secor 2015). Across all metrics, error and bias should be evaluated (Link 2005).

Outlook and impediments

The dimensions over which marine fauna are tracked have grown exponentially during the past two decades, and now

challenge scientists, policymakers, and managers to more systematically include migration connectivity in conservation decisions (Secor 2015, Dunn et al. 2019, Alós et al. 2022). Through electronic tagging, telemetry arrays, regional and global ocean observing networks, and associated data repositories, entire populations of seabirds, fishes, sea turtles, and cetaceans can be seasonally followed through their migration cycles, destinations, and stopover habitats. This information is underutilized in OWF impact studies. The current emphasis in regional OWF impact studies is to build on fixed-season surveys, such as large vessel trawl surveys and low-altitude overflight visual surveys, which in many instances will be reduced or precluded by the expanding OWF footprint (Methratta et al. 2023). More importantly, this Eulerian data structure is incompatible with understanding regional impacts on distributions of marine fauna, which are highly dynamic over time and are better evaluated through Lagrangian and Eulerian–Lagrangian perspectives. Here, we advocate the conservation of migratory fauna by advancing (i) concepts of how OWF development might affect flyway and stopover behaviors and (ii) feasible flyway models and metrics that lead to conservation reference points. A logical next step is to beta-test flyway baseline models and metrics for well-studied model species (Cresci et al. 2024).

Observing systems, increasingly deployed across ocean flyways, promise increased provision of animal movement pathways and oceanographic data, yet these advantages can only be realized through coordinated science. Ongoing coordination occurs through bottom-up efforts in regional networks of collaborating scientists (Lowerre-Barbieri et al. 2019, Bangle et al. 2020, Davis et al. 2020, Alós et al. 2022). During the imminent period of rapid global development of OWF, there is now an important opportunity to use OWF platforms themselves as observing systems that will substantially increase coverage across flyways. Doing so will require continued collaboration among scientists. It will also depend upon greater levels of government leadership, coordination, and resources, as well as OWF developer engagement to support long-term flyway monitoring and assessment.

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Author contributions

D.H.S., M.H.P.O., and H.B. contributed to conceptualization. D.H.S. was lead on scholarship and writing with M.H.P.O. and H.B. contributing to review and editing. M.H.P.O. was lead on data curation, formal analysis, and visualization (figures).

Supplementary data

Supplementary data is available at *ICES Journal of Marine Science* online.

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Data availability

The datasets were derived from sources in the public domain (striped bass and northern gannet) or upon request from the data owner (North Atlantic right whale, G. Davis). Striped Bass: <https://doi.org/10.5061/dryad.6hdr7sqxt>. Northern gannet: Movebank project, https://www.movebank.org/cms/webapp?gwt_fragment=page%3Dstudies%2Cpath%3Dstudy3168000943.

North Atlantic right whale: Davis *et al.* (2017), <https://www.nature.com/articles/s41598-017-13359-3>, publicly available upon request from the data owner.

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