Adaptation strategies of coastal fishing communities as species shift poleward

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Introduction

We are in a period of rapid environmental change (Intergovernmental Panel on Climate Change, 2013) that is reshaping ecosystems and dramatically affecting the people who rely upon natural resources (Reilly et al., 2003; Roessig et al., 2004; Kirilenko and Sedjo, 2007; Thornton et al., 2009). While much research has examined how changes in climate affect natural resources (Parmesan, 2006) and has identified ecological (Williams et al., 2008) and social (Kelly and Adger, 2000; Colburn et al., 2016) predictors of vulnerability to such changes, less attention has focused on if and how communities of natural resource users respond to environmental changes in situ. Furthermore, community and culture (Barnes and Dove, 2015), livelihood strategies (Badjeck et al., 2010), and local social-ecological contexts (Ostrom, 2009) are increasingly recognized as playing a key role in adaptation opportunities.
Previous work aiming to understand social-ecological contexts of environmental change has used primarily case studies and ethnographic or other qualitative methods from social science perspectives (Wolf and Moser, 2011). While such studies make clear the multidimensional social, cultural, and economic aspects of vulnerability (Badjeck et al., 2010), adaptive capacity (Berkes and Jolly, 2001), and strategic change in resource use (Birkenholz, 2014), they often do not link directly to the work of natural scientists studying change in ecosystems per se (Walker, 2005) but see (Turner and Robbins, 2008; McCoy et al., 2011; Pinsky and Fogarty, 2012; Hentati-Sundberg et al., 2015) for exceptions. Indeed, while qualitative social and quantitative natural scientists increasingly work together as members of interdisciplinary research teams, their methods (e.g. ethnography, and environmental sampling, respectively) and ontological entry points for analysis (e.g. community, and ecosystem, respectively) often remain disconnected and conceptually distant (Turner and Robbins, 2008). Integrated, scalable, and technically robust methods, metrics, and analytical tools are needed to bridge these gaps and create comprehensive understandings of adaptation to climate change (Brondizio et al., 2016).

Observing strategies employed by natural resource users is one way to discern adaptation in resource-dependent communities. Such strategies might include increasing harvest intensity, changing exploitation practices, switching to new resources, or abandoning resource-based livelihoods altogether (Adger et al., 2005; Porter et al., 2014). Maintaining or increasing portfolio diversity is another common approach for reducing the impact of changing conditions (Heady, 1952; Coulthard, 2009; Colburn et al., 2016). Because spatial range shifts in natural resources are well documented (Parmesan and Yohe, 2003; Sorte et al., 2010; Walther, 2010), here we focused on investigating factors that affect spatial shifts in communities of resource users. We were also interested in the relationship between range shifts in natural resources and departures from resource-based livelihoods.

While a number of case studies has documented how particular communities are responding to changing conditions (Berkes and Jolly, 2001; Wolf and Moser, 2011), studies that empirically and quantitatively examine multiple communities across a region are rare. Developing methodologies to document how communities of resource users respond to environmental change, and the factors that mediate those responses, is crucial for both sustainable and effective resource management as well as for supporting resilience among those communities (Badjeck et al., 2010; McCoy, 2012).

Fisheries are tightly coupled human-natural systems particularly sensitive to environmental change. Fisheries are central to global food economies, providing an important source of protein for more than half the world’s population and sustaining livelihoods for nearly 60 million people worldwide (most of whom are small-scale harvesters) (FAO, 2014). Fishing industries and communities are expected to be highly impacted by climate change in particular (Coulthard, 2009; Badjeck et al., 2010), in part because marine species are responding particularly rapidly to warming, with range expansions on average an order of magnitude faster than on land (Poloczanska et al., 2013).

Here, we examined adaptation in fishing communities in the northwest Atlantic, one of the most rapidly warming parts of the global ocean (Pershing et al., 2015). A wide range of marine species important to commercial fisheries in the region are shifting poleward to deeper waters (Nye et al., 2009; Pinsky et al., 2013). Fisheries in the region have also experienced major regulatory change over the last decade, as a catch share management system for New England groundfish was implemented in 2010 (Clay et al., 2014). We assessed changes in fishing communities in this context by examining patterns of commercial trawl fishing fleets over time. In particular, we analysed changes in fleet spatial range and size over the last two decades, and factors correlated with those changes, including vessel size, catch diversity, change in catch composition, port latitude, and change in depth of fishing location. Previous research in the region suggests a northward shift in landing location (McCay, 2012; Pinsky and Fogarty, 2012), but our analysis is the first direct examination of fishing location by community. Our results indicate dramatic and varied community-level spatial changes in resource use over the last 20 years.

Fishing communities are a key social scale at which to document responses to environmental change (St. Martin and Hall-Arber, 2008a, b). Decisions by individual resource users are mediated by networks of relationships, knowledge systems, and available infrastructure, all of which are embedded in a community context. Changes in natural resources—and decisions about use of those resources—have ramifications not just for individuals, but also for groups of individuals bound together by relationships and practices (Jentoft, 2000; St. Martin and Hall-Arber, 2008b). The community as a unit of analysis also speaks to the US Magnuson-Stevens National Standard 8 ("Conservation and management measures shall…take into account the importance of fishery resources to fishing communities" (Magnuson-Stevens Act, 2008)); policy-makers and researchers engaged in natural resource issues have an interest in the ramifications of environmental change on, and the adaptive capacity of, communities, and not just individuals. While community-level processes and practices are accessible through a range of case study approaches, in this study we use a quantitative, data-driven approach to examine a wide range of communities and responses across a region, which helps to link community-level studies to more quantitative analyses including ecosystem modeling and marine spatial planning. In particular, the quantitative approaches used here are similar to those used to analyse responses of fish species in this region and elsewhere (Pinsky and Fogarty, 2012; Pinsky et al., 2013; Poloczanska et al., 2013), thereby enabling parallel analyses between natural resources and communities of natural resource users.

**Methods**

Our overall approach was to examine changes in fleet fishing patterns in northeast US commercial trawl fishing communities from 1996 to 2014 using vessel trip report (VTR, also known as logbook) data from the National Oceanic and Atmospheric Administration (NOAA), National Marine Fisheries Service (NMFS), Northeast Fisheries Science Center (NEFSC). We measured latitudinal change in fishing location, and community fleet size and disappearance over time, and then assessed the relationship between those changes and a number of factors. We describe the data and analysis in greater detail below.

**Vessel trip reports (VTRs)**

VTRs are collected by the NEFSC for fishing trips conducted by vessels holding a commercial federal fishing permit (unless the vessel holds a federal lobster permit but no other federal permits).
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VTR collection began in 1994. The VTRs include self-reported trip dates, number of crew, landing port, type of fishing gear(s) deployed, geographic coordinates of gear deployment, permit number, and cumulative weight of each species caught for commercial fishing trips taken from Maine to North Carolina (St. Martin and Hall-Arber, 2008a; NOAA Fisheries Greater Atlantic Region, 2017). For this analysis, we examined VTR data from 1996 to 2014 for trips using trawl gear. All VTR data used in this study were provided by the NEFSC and pre-processed there to comply with NMFS confidentiality rules; all trips were aggregated into communities and could not be traced back to any individual vessel or grouping containing less than three vessels. See Supplementary material for additional details on VTR data processing.

Communities-at-Sea

We used the Communities-at-Sea framework developed by St. Martin and Hall-Arber (2008a, b) and St. Martin and Olson (2017) to define fishing communities. This approach aggregates peer groups of vessels into community-based fleets, each defined as a unique combination of port, gear, and vessel size. We used two categories of vessel size: vessels that are longer than or equal to 65', and those that are shorter. We used this division of vessel size because interviews with fishing communities indicate that harvesters using vessels within these size categories share information and practices with each other (St. Martin and Hall-Arber, 2008a, b). Example communities included New Bedford trawl vessels <65', and Cape May trawl vessels > 65'. Note that this aggregation approach differs from a common use of “community” that often refers to a port or town; the Communities-at-Sea framework means that a single port can have two community fleets (e.g. Gloucester has a fleet of large trawl vessels as well as a fleet of small trawl vessels). This method instead groups vessels associated with each other through community-level economic processes and territorial practice.

We used this framework of community rather than other definitions of community or fleet that have been used in natural resource management (e.g. spatial unit (Sethi et al., 2014) or homogenous social structure (Agrawal and Gibson, 1999)) because interviews in fishing communities in New England have suggested that the primary way groundfish harvesters self-identify and relate to each other is by these categories, and that these affiliations bind fishermen together through a combination of knowledges, technologies, and practices (St. Martin and Hall-Arber, 2008a, b). Furthermore, these groupings of vessels exhibit identifiable spatial patterns at sea, suggesting that information is shared within these peer groups (St. Martin and Hall-Arber, 2008a, b). These groupings might also be described with the term “fleet segment”, but we use the term “community fleet” because we believe that it better captures the human affiliations described above.

Each trip in the VTR trawl data was grouped into a community fleet by the port of landing and vessel size, as long as at least one of the following two conditions were met: (i) the vessel landed at least 50% of its trips that year at that port, or (ii) the vessel reported that landing port as its home port or principal port on its permit. The rationale behind these two conditions is that each indicates some degree of affiliation with the landing port, either by frequency or place of origin (St. Martin and Hall-Arber, 2008a, b). Note that this approach categorizes each trip individually, which means that a single vessel can belong to multiple community fleets in a given year or over the time period of the study. Thus, changes in fishing patterns for a vessel could have ramifications for more than one community. Trips that landed at a port that did not meet either category were not included in this analysis (2, 724, 688 trips included vs. 373, 476 excluded). As aforementioned, to ensure confidentiality of harvester information, we only analysed community fleets that included at least three vessels in a given year. See Supplementary material for additional details on Communities-at-Sea.

Estimating fishing location

For each community fleet in a given year (a “fleet-year”), we estimated an annual geographic effort-weighted centroid of fishing activity using a bootstrapping approach. VTR location data are self-reported, and are thus subject to small but frequent inconsistencies in location resulting primarily from rounding errors rather than systematic biases (Sampson, 2011). By comparing VTR location data with on-board observer data, DePiper (2014) developed a model to estimate confidence intervals around the VTR location data in this region. To take this locational uncertainty into account, we first used DePiper’s (2014) model to calculate a 90% confidence interval for each individual fishing trip. Then, using that confidence interval as a radius around the reported trip location and assuming a uniform distribution, we chose a random point within that area to represent the trip location. For each fleet-year, we used all estimated trip locations to calculate a weighted geographic centroid. Each centroid was weighted by crew size multiplied by trip length to represent a measure of labor time and investment (St. Martin and Olson, 2017). We repeated this process 1,000 times to generate a distribution of centroids for each community-year.

Measuring change in fishing location

We used an inverse weighted regression analysis to assess if and to what degree the annual fishing centre for each community fleet shifted significantly over time. For each community fleet, we fit a linear regression of latitude against year for each set of bootstrap-replicated centroids described above. We weighted each centroid by the inverse variance of the trip latitudes used to calculate that centroid. This approach weights a centroid with tightly clustered trips more heavily than one with more dispersed trips. We used the mean effect strength from those 1,000 regressions as the rate of change in latitude for each fleet. To ensure sufficient data for analysis over time, we restricted this analysis to only community fleets with at least 7 years of trip data (22/33 = 67% large trawl vessel community fleets and 38/68 = 56% of small trawl vessel community fleets).

Factors related to changes in fishing location

To assess the effect of factors correlated with changes in fishing latitude, we fit a series of multiple linear regressions between the rate of latitudinal change and five explanatory variables, explained below.

(1) Vessel size. We included vessel size as a categorical effect [larger or smaller than 65’ (St. Martin and Hall-Arber, 2008a, b)] because we hypothesized that larger vessels would be more mobile and able to travel longer distances than smaller vessels.
(2) **Species diversity of catch.** We expected that communities with low catch species diversity might demonstrate larger latitudinal shifts, i.e. "follow their target species", than communities with diverse portfolios of species that they exploit. For each fleet, we estimated catch diversity as the average yearly Shannon diversity index.

(3) **Change in composition of catch species.** We hypothesized that communities might change target species instead of changing fishing location. We measured changes in a community’s catch composition by calculating the pair-wise Bray–Curtis distance between the species composition of the catch in the first available year and that in each subsequent year. For each community, we regressed Bray–Curtis distance against year and used the resulting slope as the covariate in these regressions (Magurran et al., 2015).

(4) **Change in depth of fishing location.** We hypothesized that communities might move to fish in deeper waters rather than northward because some fish species have been shown to demonstrate this pattern (Nye et al., 2009). To estimate change in depth of fishing location for each community, we first found the nearest depth recording for each trip using a US coastal relief model (NOAA National Centers for Environmental Information, U.S. Coastal Relief Model, n.d.), and calculated an effort-weighted average depth for all the trips in a community year. As above, we then regressed depth against year and used the resulting slope as the covariate.

(5) **Port latitude.** Species diversity of catch was correlated with port latitude (fleets from more northern ports had greater catch diversity), so we also included latitude of port as a covariate so that we could assess the separate effects of catch diversity and port latitude.

We evaluated models with all possible combinations of main effects as well as three interactions: vessel size and port latitude, vessel size and catch species diversity, and catch species diversity and change in catch species composition. We calculated the corrected Akaike Information Criterion (AICc) for each model and the Relative Variable Importance (RVI) for each variable and interaction included in the model. For each variable, the RVI is the sum of the Akaike weights across all models in which it appears, indicating its importance relative to the other variables in the model (Burnham and Anderson, 2002).

### Estimating community fleet size and disappearance

We used the number of unique fishing permits in a community as a proxy for community fleet size. Because we analysed only communities with at least three vessels in a given year (to maintain anonymity of individual vessels), if the number of unique permits in a community dropped below three, that community “disappeared” from the data set. Because our analysis focused on communities of vessels using trawl gear, such a disappearance does not necessarily mean that all vessels in that community fleet left fishing altogether; in many cases they instead might have re-rigged to fish with a different gear (e.g. a dredge instead of a trawl).

### Factors mediating change in community fleet size

To assess factors mediating changes in community size, we fit a series of regressions to assess the effect on rate of change in community size (change in number of unique permits over time; linear) and community disappearance (fewer than 3 permits by 2014; logistic) of three predictor variables: (i) vessel size, (ii) species diversity of catch, and (iii) port latitude. We evaluated models with all possible combinations of main effects as well as interactions, and calculated AICc and RVI as described above.

We excluded one outlier data point from the community size model—the large-vessel community trawl fleet based in New Bedford, MA—because that community fleet demonstrated dramatic permit loss over the study period, disproportionately skewing the model results, while the dredge community fleet in New Bedford increased dramatically by about the same number of permits, suggesting that many of those vessels switched gears from trawls to dredges. New Bedford was the only port where we observed an unequivocal increase in another gear with a simultaneous decrease in trawl permits.

### Analytical tools

All analyses were conducted in R v.3.3.0 (R Core Team, 2016).

### Data availability

The data that support the findings of this study came from NOAA–NMFS, and are subject to restrictions from the agency to protect confidentiality of harvesters.

### Results

#### Changes in fishing location

We analysed 22 large-vessel and 38 small-vessel community trawl-fishing fleets (split by vessels longer or shorter than 65’ overall). As described in the Methods section, a community fleet is a peer group of vessels defined as a unique combination of port, gear, and vessel size.

The mean shift for large-vessel community fleets over the course of the study period (1996–2014) was 4 km/year (Figure 1a). Almost a third (7/22) of the large trawl vessel communities demonstrated northward movement of 5 km/year or more over the study period (Supplementary Table S1, Figure S1). For example, the centre of fishing activity for the large-vessel community fleet in Beaufort, NC moved an average of 21 km/year northward (total 433 km from 1996 to 2014). This fleet was fishing in waters off the North Carolina coast in 1997, but was fishing off the coast of New Jersey by 2014 (Figure 1a). The communities demonstrating the most dramatic northward shifts were all located in the southern end of the study region: five in North Carolina (Beaufort, Lowland, Oriental, Wanchese, and Engelhard), and three in Virginia (Chincoteague, Newport News, and Hampton) (Supplementary Table S1, Figure S1). In contrast to the large-vessel community fleets, the mean shift for small-vessel community fleets overall was only 0.36 km/year (Figure 1b and d; Supplementary Table S1, Figure S1), and only one small-vessel community fleet (Engelhard, NC) moved north at more than 5 km/year.

#### What factors mediated shifts in fishing location?

In addition to being located in the southern portion of the study region, large-vessel community trawl fleets demonstrating dramatic shifts northward also had low catch species diversity. In contrast, large-vessel community trawl fleets that caught many species, as well as all small-vessel community trawl fleets, did not...
demonstrate large-scale latitudinal shifts (Figure 2a). Specifically: the three large-vessel community fleets demonstrating the most dramatic shifts northward were Beaufort, Lowland, and Oriental, NC, which demonstrated shifts of 13–21 km/year. All three of those large-vessel community fleets had low-diversity catch compositions (Shannon indices <1) overwhelmingly dominated by two species—summer flounder (*Paralichthys dentatus*) and Atlantic croaker (*Micropogonias undulatus*) (Supplementary Table S1), both of which have been documented as shifting northward over this time period (Hare and Able, 2007; Nye et al., 2009; Pinsky and Fogarty, 2012). The large-vessel community fleets with greater catch diversity demonstrated much smaller or no northward shift (Supplementary Table S1).

Catch diversity was correlated with port latitude (correlation coefficient = 0.65 across all community fleets), especially for large-vessel fleets (0.78): community fleets at the southern end of the range in North Carolina and Virginia had lower catch diversity (Shannon index mean ± s.e. = 0.86 ± 0.13 in NC and 1.24 ± 0.17 in VA), in contrast to those in northern New England (Shannon index mean ± s.e. = 1.95 ± 0.06 in ME and 1.86 ± 0.07 in NH).

Our multiple regression models for shifts in community fleet fishing location helped to disentangle the effects of catch diversity with those of port latitude to some extent. Vessel size, port latitude, and their interaction were the most important predictors of whether a community fleet changed latitude of fishing location.

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**Figure 1.** In (a) and (b), distribution of latitudinal shift in fishing location by community fleets is shown, separated by vessel size, with (a) showing community fleets of large vessels (≥65') and (b) showing community fleets of small vessels (<65'). Exact annual latitudinal shift of four example communities is also indicated. In (c) and (d), annual fishing location is plotted over time for those same four example communities to show differences in movement in northern species-rich (Portland, ME) and southern species-poor trawl fleets (Beaufort and Engelhard, NC), again divided by vessel size: (c) large-vessel and (d) small-vessel community fleets. In (c) and (d), lighter circles represent fishing locations in earlier years and darker circles represent fishing locations in later years. Black diamonds indicate landing ports.
Figure 2. Relationship between species diversity of catch (Shannon index) and latitudinal shift of annual fishing location for community fleets of (a) large vessels (≥65') and (b) small vessels (<65') (b, d). Each point represents a community fleet over the whole time frame of the data set (1996–2014). Open circles indicate community fleets with zero or fewer than three vessels by 2014, while filled circles indicate community fleets extant in 2014. Ribbons indicate 95% confidence intervals. Dotted lines indicate no latitudinal shift. Equations, $R^2$ and $p$-values are for linear regressions between catch species diversity and latitudinal shift.

Figure 3. Relative variable importance in the models for (a) latitudinal shift in fishing location, (b) community fleet disappearance, and (c) change in community size.
(RV1 1.0, Figure 3a, Supplementary Table S2), suggesting that vessel mobility and geography both played strong roles in shaping adaptive responses. However, species diversity of catch, change in species composition of catch and fishing depth also demonstrated high levels of relative variable importance (RV1 0.3–0.4, Figure 3a) and all appeared in the top models (ΔAIC < 3).

Community disappearance and shrinkage

A substantial fraction of community fleets disappeared from the data set over the study period: more than half (22/38 = 58%) of the small-vessel communities, and nearly a quarter (5/22 = 23%) of large-vessel communities (Supplementary Figure S2, Table S1). (As discussed in the Methods section, the disappearance of a community fleet from the data set does not necessarily mean that all vessels in that community fleet left fishing altogether; it means only that fewer than three vessels in that fleet conducted trips using trawl gear.) Community fleet disappearance from the data set was mediated strongly by catch species diversity, port latitude, and vessel size, and less so by the interactions between those covariates (vessel size x catch diversity, vessel size x port latitude) (Figure 3b, Supplementary Table S3). Across all latitudes, small-vessel trawl communities with low catch diversity all disappeared by the end of the data set (Supplementary Figure S2), suggesting here that catch diversity was the pertinent factor rather than port latitude.

Rate of change in community size (i.e. change over time in the number of unique permits in a community) was similarly mediated by port latitude, vessel size, and catch diversity (Figure 3c, Supplementary Table S4). Small-vessel community trawl fleets in New England (at higher latitudes) demonstrated the most dramatic shrinkages (Supplementary Table S4).

Discussion

We document here contemporary, dramatic, and varying adaptive practices among natural resource users in a rapidly changing environment: our analysis reveals substantial community-level changes in fishing patterns in the northwest Atlantic over the past 20 years. Of the community trawl fleets in our analysis, many are now fishing much further north (especially large-vessel community trawl fleets from North Carolina and Virginia), and/or have shrunken or disappeared from the data set (especially small-vessel community trawl fleets).

These effects manifest differently for large-vessel and small-vessel community fleets and appear to be mediated at least in part by a combination of port latitude and catch diversity: southern large-vessel community fleets with low catch diversity have demonstrated larger shifts northward, while small-vessel community fleets with low catch diversity across all latitudes have disappeared from the data set. We discuss ramifications of catch diversity at greater length below. Furthermore, the adaptive responses documented here—in particular, change in fishing location and exiting from fishing—are strategies that harvesters have demonstrated in response to a host of changes, including changes in stock abundance, regulation, markets, and other economic opportunities (Holland and Sutinen, 2000; Wilen et al., 2002; Murray et al., 2010; Daw et al., 2012; Stoll et al., 2015). These findings suggest that lessons about adaptation among resource users in the face of broader change may be relevant in the context of changing climate.

Changes in fishing location

Communities with fleets of large vessels in the Mid-Atlantic have dramatically altered their fishing locations over the past 15 years. Large-vessel fleets from North Carolina and Virginia in particular, which used to fish near their ports of origin, are now fishing 800 km north, off the coast of New Jersey.

Are these changes in fishing location mediated by changes in fish species distribution? Harvesters make decisions about where to fish based on a host of factors, including resource location and abundance, but also local knowledge and experience, regulatory regime, shoreside infrastructure, and costs incurred (Holland and Sutinen, 2000; Wilen et al., 2002; St. Martin and Hall-Arber, 2008a; Murray et al., 2010; Stoll et al., 2015). Definitively determining the mechanism for the changes in fishing location documented here is outside the scope of this analysis, but we suspect that the change in fishing location is the result of a combination of environmental and regulatory pressures. On the environmental side: the communities shifting the most dramatically have catch dominated by two species (summer flounder and Atlantic croaker) that have been documented as shifting northward over this time period (Hare and Able, 2007; Nye et al., 2009; Pinsky and Fogarty, 2012). It is also worth noting that the geographic shifts of these two species are influenced by factors beyond warming ocean temperatures: while recent work suggests that changes in abundance and range of Atlantic croaker may be mediated largely by temperature (Hare and Able, 2007; Hare et al., 2016), but those of summer flounder are likely driven by changes in fishing pressure as well (Bell et al., 2014, 2015).

On the regulatory side, we hypothesize that two major factors could be influencing the changes in fishing location we describe. One factor is that summer flounder quota is allocated by state (Management Measures for the Summer Flounder Fisheries, 2011), and that state allocation percentages—based on historic landings—have remained static since 1990. Summer flounder distribution, however, has shifted substantially (Nye et al., 2009). As fish shift northward, harvesters may fish at increasingly high latitudes, but the static and state-based management structure incentivizes harvesters to continue to land at southern ports where landing quota remains available. The combination of new fishing locations but consistent landing ports also leads to a substantial increase in trip length. In addition, harvesters targeting summer flounder report that some northern vessels land some of their catch in southern ports (E. Papaioannou and R. Selden, pers. comm.). Further interviews with harvesters could help contextualize these patterns and better assess the degree to which they are indeed responses to climate change, regulatory constraints, or yet other factors.

Another regulatory factor with potential relevance is the requirement for trawlers to use turtle excluder devices (TEDs) when fishing south of Cape Charles, Virginia (United States Code, 1999). Harvesters report that the TED requirements resulted in their fishing north of that line (E. Papaioannou and R. Selden, pers. comm.). While TED regulations may be one factor that contributes to decisions about fishing location, we suspect that they are not the primary driver of the movement we have observed for two reasons: (i) harvesters need only to fish off Virginia to escape the TED zone, not an additional 300 km further to New Jersey and (ii) the TED regulations were implemented in 1987 (Yaninek, 1995), so any related change in fishing location would likely have occurred prior to the start of our study period in 1996.
Shrinkage and disappearance of fishing communities

The empirical documentation of shrinkage and disappearance of fishing communities on a regional scale is another important finding of this analysis. As we have made clear, the decline or disappearance of a community fleet as defined in this study does not necessarily mean an unequivocal loss of fishing in any particular locale. Community members and their corresponding vessels may retool and move from one fishery to another (e.g. from trawling to dredging or gillnetting). (And in fact, our analysis suggests that the large-vessel community trawl fleet in New Bedford did exactly that.) But declines in one or more fleets are likely to correspond with absolute community declines and departures from fishing altogether (Hall-Arber et al., 2001). Furthermore, even when communities remain engaged in fishing, the adaptation strategies documented here have implications beyond employment and revenue. For example, a change in fishing grounds may result in involuntary displacement from a site where people have labored for multiple generations and about which they hold extensive environmental knowledge (Murray et al., 2008). Leaving a given fishing community (even while remaining in others) may result in the loss of social ties and social and cultural context (Jentoft, 2000).

These changes in community size (whether they indicate a change in gear or a departure from fishing altogether) will come as no surprise to anyone who has worked in or with northwest Atlantic fishing communities. We do not mean to imply in this analysis that those changes are exclusively attributable to changes in the natural environment. To the contrary: it is well understood that changes in management regime, such as the implementation of catch shares and other transferable quota management schemes, were intended to and have resulted in dramatic fleet consolidation in both New England (Clay et al., 2014) and the Mid-Atlantic (McCay and Brandt, 2001; Murray et al., 2010). It is also worth noting that while the collapse of cod stocks in the northwest Atlantic occurred in the mid-1990s, largely before the beginning of the data set analysed here (Myers et al., 1996), the human and ecological ramifications of the cod collapse undoubtedly stretched into the time frame of this analysis. Furthermore, extensive work has demonstrated that decisions to leave fishing are mediated by a complex host of economic and social factors (Coulthard, 2009), in addition to changing regulatory regimes, including evolving youth aspirations (Bjarnason and Thorlindsson, 2006), gentrification of coastal communities (Hall-Arber et al., 2001; Colburn and Jeppson, 2012), and livelihood diversification (Cinner et al., 2009; Daw et al., 2012). Research indicates that climate change will only increase the vulnerability of fishing communities in the face of such factors (Coulthard, 2009; Colburn et al., 2016).

Does catch diversity act as a buffer for fishing communities?

Catch species diversity appeared to have different effects on fishing patterns of small- and large-vessel community fleets in our analysis. For large-vessel community fleets, those with diverse catch assemblages demonstrated little or no change in fishing location, while those targeting only a few species demonstrated dramatic changes in fishing location (Figure 2a). Catch diversity is not the only possible explanation for this pattern, however: port latitude was also a strong predictor of latitudinal shift for large-vessel community fleets and is correlated with catch diversity in this region (Supplementary Figure S2). The northern large-vessel community trawl fleets have more species-diverse catch than do southern ones (Supplementary Table S1, Figure S2), and it is possible that northern movement by large-vessel fleets in New England are constrained by the Maine and Canadian shorelines to the north, running west to east. However, large-vessel community trawl fleets with high catch diversity far south of the Gulf of Maine (e.g. Point Pleasant, NJ and Stonington, CT) without such geographic limitation did not demonstrate substantial northward movement. Fish in the Gulf of Maine appear to be dealing with this northern shoreline limitation by moving deeper, as described by Nye et al. (2009); we thus expected that we might see a movement to deeper fishing grounds in the more northern communities. We did not, however, see a consistent relationship between fishing depth and port latitude. We suspect that the limited spatial resolution of the VTR data obscured any depth-related changes in fishing location. In short, despite the clear importance of geography in our statistical models, the mechanism by which port latitude affects the fishing patterns observed here for large-vessel community fleets remains somewhat unclear and warrants additional inquiry.

In contrast to the case for large-vessel community trawl fleets, catch diversity much more clearly mediated disappearance for small-vessel community trawl fleets from the data set, rather than change in fishing location. No small-vessel community trawl fleets demonstrated substantial latitudinal movement, which is consistent with general differences in trip length between large and small fishing vessels (Murphy et al., 2015). However, small-vessel trawl fleets with low catch diversity (regardless of latitude) consistently disappeared from the data set by 2014 (Supplementary Figure S2). While, again, these disappearances from the data set do not mean that those vessels left fishing altogether, they clearly indicate that those vessels either changed gear or ceased fishing rather than changing fishing location.

These findings contribute to a robust body of work highlighting ramifications of diversification in fisheries. Sethi (2010) identified diversification as a key element of effective risk management in fisheries, and a number of studies has shown or predicted reduced variability in revenue (Sanchirico et al., 2008; Kasperski and Holland, 2013; Sethi et al., 2014) or catch (van Oostenbrugge et al., 2002) associated with fishery diversification. Diversification has also been identified as an important climate adaptation strategy in agriculture (Porter et al., 2014). Fewer studies have assessed the effect of diversification on large-scale community consequences such as movement or persistence rather than revenue as we did here. Our findings that catch diversity may mediate adaptation strategy corresponds with work in Australia that identified diversification as a key factor in an unusual degree of fleet stability in a single Australian port (Minnagel and Dwyer, 2008). Our results also support other work demonstrating dramatic differences in adaptations between small- and large-vessel harvesters (Hentati-Sundberg et al., 2015).

Management strategies to support resilience

Given the potential effects of both fleet mobility and catch diversity for fishing communities, one crucial question is: what are the factors that may promote or limit these features of a fishery? When considering fleet mobility, as increased attention is paid to spatially oriented planning (e.g. marine spatial planning (MSP)), such spatially oriented approaches must be implemented
thoughtfully to avoid reduced mobility of fishing communities (Murray et al., 2010). A number of variables must be considered with regard to the influence catch diversity. Catch diversity may be mediated by the underlying ecology of the region; some regions simply contain a higher species diversity than others. Catch diversity of a fleet may also be mediated by expertise of harvesters within a given community fleet, and it may be easier to develop the knowledge to catch a few species than to seek to harvest a wide range (Kasperski and Holland, 2013). Catch diversity is likely limited severely, however, by shore-side factors such as markets and infrastructure and also by management measures. Harvesters land species that dealers and processors will buy. As an example, Stoll et al. (2015) point out that spiny dogfish landings dropped precipitously after the European Union stopped importing the product in 2013. In addition, management strategies such as catch shares and limiting access to fisheries can result in reduced diversification or make it difficult for harvesters to switch between species (Kasperski and Holland, 2013; Stoll et al., 2016; Holland et al., 2017). Any conversation about diversification in fisheries necessitates taking these multiple factors into consideration.

Conclusions
We have described substantial behaviour changes among communities dependent on natural resources in a changing environment, including large-scale spatial changes in fishing location and community disappearance, both mediated by catch diversity, vessel size, and geography. Using community as a unit of quantitative analysis provides a novel link between qualitative social science studies on community adaptation and quantitative natural science studies of ecosystem and climate change. In this time of rapid environmental change, environmental, and socio-cultural displacement is likely to become a common feature in communities dependent on natural resources. Understanding and anticipating these effects is the best—and perhaps only—way to attempt to manage the challenges ahead. This work has the potential to directly inform the adaptation strategies of communities as well as the development of policies that affect resource access and use by communities.

Supplementary data
Supplementary material is available at the ICES/JMS online version of the manuscript.

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