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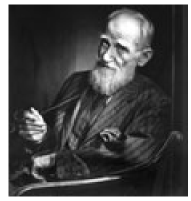

Ghoti aims to serve as a forum for stimulating and pertinent ideas. Ghoti publishes succinct commentary and opinion that addresses important areas in fish and fisheries science. Ghoti contributions will be innovative and have a perspective that may lead to fresh and productive insight of concepts, issues and research agendas. All Ghoti contributions will be selected by the editors and peer reviewed.

Etymology of Ghoti

George Bernard Shaw (1856-1950), polymath, playwright, Nobel prize winner, and the most prolific letter writer in history, was an advocate of English spelling reform. He was reportedly fond of pointing out its absurdities by proving that 'fish' could be spelt 'ghoti'. That is: 'gh' as in 'rough', 'o' as in 'women' and 'ti' as in palatial.

Guidelines for incorporating fish distribution shifts into a fisheries management context

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Abstract

The impacts of climate change have been demonstrated to influence fisheries resources. One way climate has affected fish stocks is via persistent shifts in spatio-temporal distribution. Although examples of climate-forced distribution shifts abound, it is unclear how these shifts are practically accounted for in the management of fish stocks. In particular, how can we take into account shifting stock distribution in the context of stock assessments and their management outputs? Here, we discuss examples of the types of fish stock distribution shifts that can occur. We then propose a decision tree framework of how shifting stock distributions can be addressed. Generally, the approaches for addressing such shifts fall into one of three main alternatives: re-evaluate stock identification, re-evaluate a stock unit area, or implement spatially explicit modelling. We conclude by asserting that the approach recommended here is feasible with existing information and as such fisheries managers should be able to begin addressing the role of changes in stock distribution in these fish stocks. The implications of not doing so could be notably undesirable.

Keywords Climate change, decision trees, distribution, extended stock assessment models, shifting fisheries, spatially explicit models

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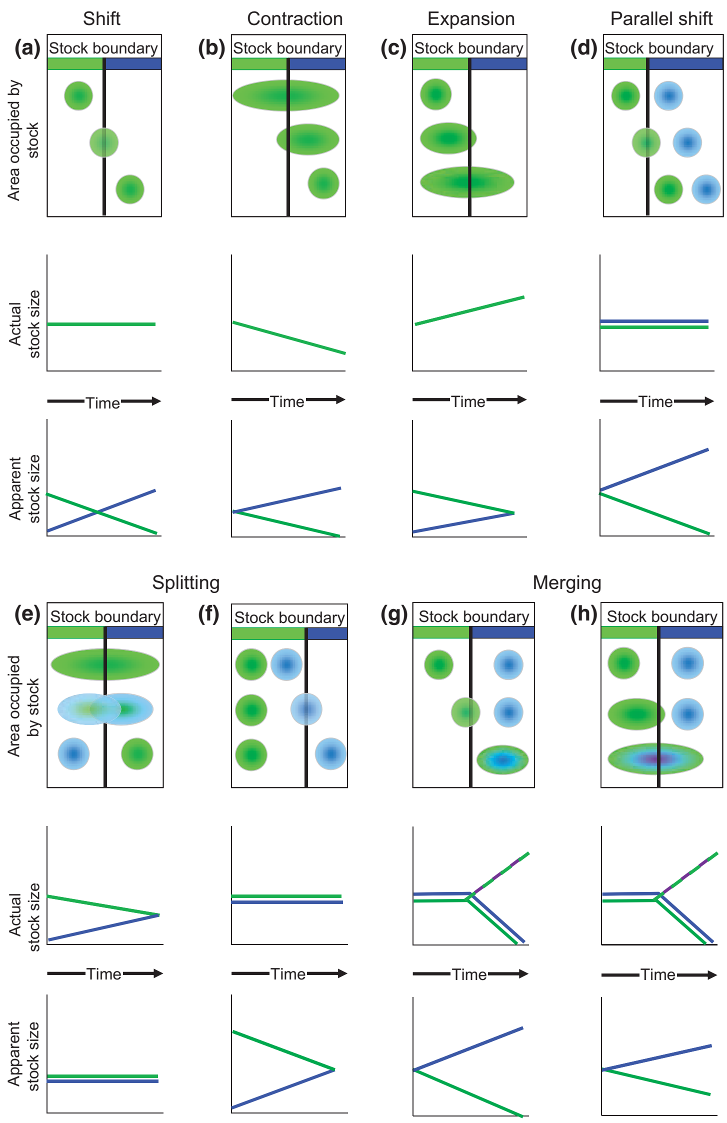
Introduction

Climate-related processes are affecting and will continue to affect the production of fisheries resources (Kell *et al.* 2005; Kaje and Huppert 2007; Mackenzie *et al.* 2007; Rockmann *et al.* 2007; Hollowed *et al.* 2009). Future sustainability and conservation of fish populations require incorporation of environmental and ecological information into the scientific advice used as a basis for management (NRC 1999, Pew Oceans Commission 2003, U.S. Commission on Ocean Policy 2004). Fish populations may respond to climate change in a number of different ways, including changes in vital rates, mortality, the timing of migration and shifts in spatio-temporal distribution (Brander 2010). All of these responses have important ramifications for fishery population dynamics and may hinder our ability to properly assess and evaluate population status. These responses may ultimately even compromise the validity of stock forecasts and rebuilding plans (e.g., Kraak *et al.* 2009). Of these potential effects of climate change on fish stocks, the hypothesized first response is often a shift in spatial distribution (Parmesan and Yohe 2003). Thus, here we focus on facets of addressing shifts in fish distribution.

While numerous studies have documented annual fluctuations in the distribution of fish populations attributable to annual fluctuations in



temperature (e.g., Taylor *et al.* 1957; Murawski 1993; Rose 2005), and changing fish distributions have been well placed in a broader biogeographical history (Eckman 1953; Briggs 1974), more recent studies have documented persistent changes in spatial distribution of fishes that are attributable to large-scale changes in oceanographic processes associated with climate change (e.g., Rose *et al.* 2000; Drinkwater 2002; Walther *et al.* 2002; Brander *et al.* 2003; Perry *et al.* 2005; Rose 2005; Brander 2007; Mueter and Litzow 2008; Spencer 2008; Nye *et al.* 2009; see also full issue noted in Alheit *et al.* 2010). Shifts in spatial distribution will likely continue as climate change persists (IPCC 2007; Cheung *et al.* 2008, 2009; Solomon *et al.* 2008; Hare *et al.* 2010). As such, we need to be prepared to adapt to the resultant changes in extant fisheries production, while concurrently preparing for new opportunities associated with emerging fisheries in response to broad-scale shifts in fish distribution. That these shifts in distribution have been well documented and are known is clear (e.g., Rose *et al.* 2000; Drinkwater 2002; Walther *et al.* 2002; Brander *et al.* 2003; Perry *et al.* 2005; Rose 2005; Brander 2007; Mueter and Litzow 2008; Spencer 2008; Nye *et al.* 2009); what to do about these shifts in terms of managing such stocks (based on information from stock assessments) is less obvious.

From these and other examples in the literature, it is clear that a protocol is needed to determine if, to what extent, and what to do if a stock has shifted distribution. Fisheries managers will increasingly require approaches to address these continued shifts in distribution. We propose a decision tree (Moret 1982; Quinlan 1986; Clemen 1996; Peterman and Anderson 1999; Peterman 2004) that will allow fisheries managers to have a consistent approach for determining whether a stock warrants accounting for shifts in distribution.

Distribution shifts and ramifications for stock status

We conceptualize eight generic scenarios of shifting stock boundaries and discuss the implications for evaluation, assessment and projection of those stocks, and ultimately the management advice that such analyses would provide. In any of these scenarios, there are significant ramifications for the true and realized stock status. We present these scenarios in three-panel plots (Fig. 1). The top panel represents the area occupied by the stock (circles or ovals) and how that area occupied can shift over time between two stock unit regions (blue or green, either side of the bold line vertical) over time. What we observe as apparent stock size (bottom panel; in terms of relative abundance or biomass) and what is the actual stock size (middle panel) may actually be quite different (Fig. 1). There are also many other conceivable scenarios, but our point is to illustrate and discuss several that are likely to be common, using them as a basis for the development of a decision tree (described in section below).

The simplest scenario is a single stock shifting in distribution from one stock area to another

Figure 1 Conceptualization of the interaction between stock distributional shifts, stock unit areas, stock identification and ultimately perceptions of stock abundance. In the upper panel, stock boundaries are designated by the thick black (vertical) line; actual areas of stock distributions are indicated by the coloured circles/ovals. The middle panel shows the trend in actual abundance. The bottom panel shows the trend in apparent abundance – based on the assumed stock boundary. (a) One stock is shifting from one stock area to another. The apparent pattern is a decrease in one stock and an increase in another, while the actual pattern is constant stock size. (b and c) One stock either contracting (b) or expanding (c) in range. In (b), the actual stock size is declining and in (c) actual stock size is increasing. In both (b) and (c), the apparent stock size is increasing in one stock area and decreasing in the adjacent stock area as a result of shifts in distribution. (d) Two stocks shifting in parallel with one stock crossing the stock boundary. The apparent trend in abundance is one declining stock and one increasing stock. The actual abundance does not change. (e) One stock splitting into two. Apparent stock size does not change, but actual stock size of progenitor stock decreases while subsequent stock increases. Here, there is the question of whether the diverged stocks have characteristics of the progenitor stock or those characteristics change in the novel stocks. (f) Two stocks diverging. The apparent size has one stock increasing and the other decreasing. The actual stock size does not change. (g) One stock shifts and merges with another. The apparent stock size is one increasing and the other decreasing. The actual pattern is similar, but there is the question of whether the merged stock has characteristics of either of the original stocks or different from either of the progenitor stocks. (h) One stock is expanding, not shifting, and merges with another. The apparent stock size is of one increasing stock and one decreasing stock while in fact stock sizes are not changing. As in G, there is the question of whether the merged stock has characteristics of the original stock within the stock boundaries, the stock that shifted into the stock boundaries, or different from either of the progenitor stocks.

(Fig. 1a). In this scenario, stock size and population vital rates (growth, recruitment, mortality) remain constant. The apparent pattern is a decrease in one stock and an increase in another as the stock shifts across defined stock boundaries, while the actual pattern is constant stock size. From the perspective of the green stock region, the stock is declining; from the perspective of the blue region, the stock is increasing. When in actuality the stock is remaining at the same population size but just shifting. An example of such a hypothetical scenario is seen via the northward shift of the Humboldt squid (*Dosidicus gigas,* Ommastrephidae; Field *et al.* 2007; Fig. 2), with abundances increasing as this stock moves northward. The greatest danger in this general situation is that a fishery may develop in an area in which the stock is not assessed or monitored, making it vulnerable to rapid depletion. A second consideration is that if a stock shifts further from historical fishing ports, total catch may remain the same, but fishing effort in terms of travel time and the fuel used to reach fishing grounds will increase, making the fishery less profitable and lowering the catch per unit effort (CPUE).

A similar scenario is in the case of one actual stock that is either contracting (Fig. 1b) or expanding (Fig. 1c) its range. There may be cases where two stocks are assessed and managed, but in reality there is only one biologically relevant stock (Fig. 1b, c). If this stock's range contracts in response to climate change or over-exploitation (or for other reasons), its abundance would decrease over time at a rate faster than predicted by separate stock assessments of two stocks (Fig. 1b). This contracted stock inhabiting a smaller area would be more vulnerable to overfishing. An example of this scenario has been proposed for North Atlantic cod (*Gadus morhua,* Gadidae; Rose *et al.* 2000). In contrast, there may be emerging fisheries as a result of a stock moving into a new area (Fig. 1c), similar to Fig. 1a, but attributed to actual expansion of stock area. An example of this latter scenario is Atlantic croaker (*Micropogonias undulates,* Sciaenidae; Hare *et al.* 2010). Croaker abundance has increased and its realized distribution has expanded in recent years. The stock in this new area would likely not be monitored, assessed or managed, at least at the level it had been in its previous area. There may also be situations (not shown) where the boundaries by which the stock is defined are too small and as the fishery expands to a larger area, the stock can quickly be overfished. This is a common problem in developing fisheries; as a resource is fished down, the area fished increases, but stock assessments show that CPUE and effort remains the same or even decreases while in reality effort has increased.

The previous scenarios consider single stocks that are either moving into or leaving a stock area. There are others that involve two actual stocks. One example of such a scenario is the shifting of one stock into the area of another stock, while maintaining its discrete nature (i.e., discrete vital rates, mortality and distribution; Fig. 1d). The apparent stock size differs from actual stock size and assuming one 'unit stock' will eventually result in problems, because the stocks are actually distinct. For example, the stock with lower growth may reach an overfished condition before it is recognized in the assessment based on growth averaged over the two stocks, which can have management implications based on mis-specified reference points. This parallel movement of two stocks can pose significant challenges for detection. Another further compounding aspect of two stocks moving in parallel is that one ultimately can leave the area (an extension of scenario 1d further into time).

Another set of scenarios are where stocks are diverging. In one instance (Fig. 1e), there could be a

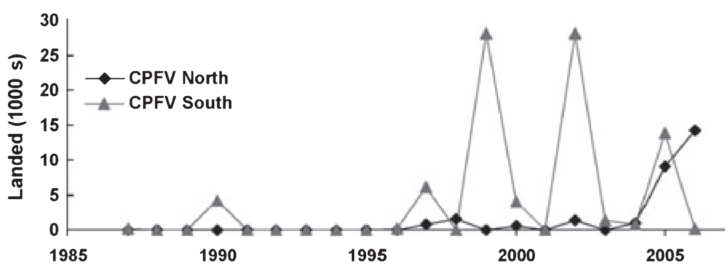


Figure 2 Indices of relative abundance for jumbo squid (*Dosidicus gigas*) from commercial passenger fishing vessels north and south of Point Conception. Adapted from Field *et al.* 2007.

stock that splits. In that instance, the apparent stock size remains the same whereas the actual stock size may or may not change, depending upon how much of the progenitor stock characteristics (i.e., discrete vital rates, mortality, exploitation, etc.) persist in the novel stocks vs. the distinct stocks taking on novel characters. In another instance (Fig. 1f), two stocks diverging out of the same area would lead to an apparent decrease in one and an increase in the other. The actual stock size would not change, similar to Fig. 1d. In either case, a re-evaluation of stock identification would be warranted. An example of this scenario includes Atlantic herring (*Clupea harengus,* Clupeidae) in the Norwegian Sea (Planque *et al.* 2010). Certainly, the observed distributional patterns were driven by both fishing pressure and climatology, but the clear splitting into different stocks is observable.

Another scenario involves two stocks merging with one another (Fig. 1g). The apparent pattern is a continuous increase in the size of one stock and a continuous decrease in the size of the other as the one stock moves across the stock boundary. The actual pattern is constant size for both stocks, until the one stock merges with the other, whereupon a novel, combined stock is instituted. The combined stock might have characteristics different than the two independent stocks and may actually represent a 'new' stock. In the two stock example (Fig. 1g), assessment of the apparent stocks would indicate increased productivity for one stock and decreases in the other. Further, in this case, management may be perceived as succeeding in the increasing stock, but failing in the decreasing stock. Potential changes in stock vital rates over time resulting from the distributional shift could further complicate the analysis of these stocks. An example of this scenario includes silver hake (*Merluccius bilinearis,* Merlucciidae) in the northwest Atlantic (Nye *et al.* 2009). The silver hake stocks have been documented to be merging geographically and the estimates of stock size are also known to be amalgamating, yet historically this species has been assessed and managed as two stocks.

Another 'merging' scenario involves the range expansion of one stock into the area of a second stock without leaving its previous stock area (Fig. 1h). The apparent stock size is similar to scenario G: one increasing and one decreasing, but the decreasing stock does not disappear because a portion of the distribution remains within the defined stock boundary. Upon merging, the characteristics of the stock may be different than the prior two stocks, again similar to scenario G. This would pose challenges for stock identification issues and associated vital rate differences exhibited between the formerly distinct two stocks and the newly formed merged stock. In this case, managers would also want to shift from two separate stock assessments to one and reassess population vital rates as they relate to determining reference points.

There are likely other potential scenarios, but these eight examples should encompass most of the major possible changes. In all of these scenarios, stock distribution must be monitored and incorporated into the evaluation, assessment and projections because apparent stock size (based on static stock boundaries) changes differently than actual stock size in each case. What is observed as apparent stock size and what the actual stock size is will elicit different management measures. There are many other potential scenarios; our purpose here again is to illustrate and discuss several likely examples and then use these main scenarios as the basis for the development of a decision tree (described in the section below). This decision tree could be used in the analysis of stocks to ascertain the potential for changing stock distributions (i.e., the stock unit area) and more importantly changes in the composition and structure of any 'unit stock' instances.

A proposed protocol

We recommend that a distribution shift flow chart be consulted in a decision tree framework at the beginning of an analysis of a stock (Fig. 3). The first step in this decision tree is determining whether distribution shifts have occurred. An evaluation of a stock or contiguous, conspecific stocks distributions should be executed. Geolocation data are routinely recorded in both survey programs and fishing operations and can be used to estimate indicators of distributional shifts (c.f. Nye *et al.* 2009). These indicators include changes in the centre of biomass or abundance of a stock over time, as well as changes in presence-absence over the distributional range, among many others (e.g. Dulvy *et al.* 2008, Mueter and Litzow 2008; Nye *et al.* 2009), all of which are readily calculable. These methods are commonly available and should become a common tool for a first-order exploration of stock analysis input data to evaluate if distribution shifts have occurred. We recognize the importance of identify-

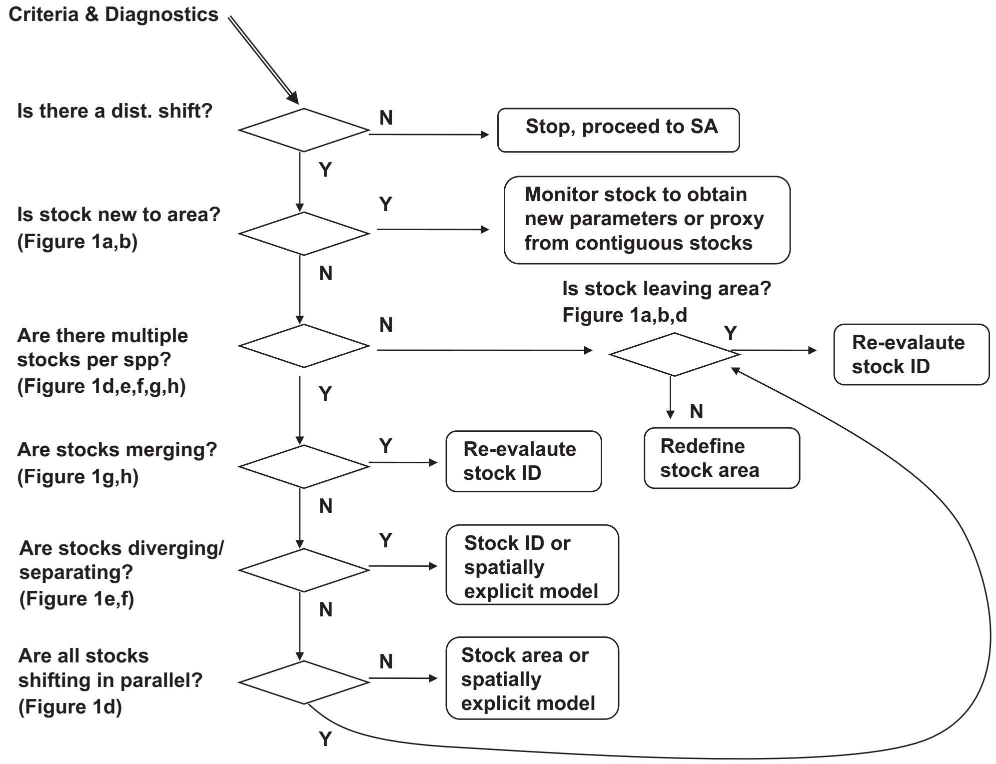


Figure 3 A flow chart – decision tree for how to address whether a shift in stock distribution needs to be considered in an assessment context. Y = yes, N = no. If one reaches an ending box, then an assessment would be initiated after the appropriate action indicated has been undertaken. Letters correspond to scenarios shown in Fig. 1. SA = stock assessment, ID = identification, spp = species.

ing underlying mechanisms responsible for distributional shifts, but mechanistic detail is not singularly critical for incorporating a demonstrated shift into the stock evaluation and management process if such a shift has clearly been determined to have occurred.

If distributional shifts have been documented, the second step in the decision tree is to determine if the stock has shifted to a new area. If so, then typically more information is needed (either from direct surveys or institutions where the stock has shifted from) including vital rates, stock-recruitment relations, mortality estimates, and movement patterns. Once this information is obtained, a revised analysis for the stock in the new area could be executed, with a precautionary approach to management emplaced prior to obtaining such novel information.

If it is not a novel stock, the third step is to identify whether one or multiple stocks exist in the stock area. If one stock exists, then it needs to be determined whether the stock is shifting out of the area or simply shifting within pre-defined stock boundaries. If the stock is moving out of the area, then a re-evaluation of stock identification is warranted. If the stock is redistributing, then a re-evaluation of stock unit area is warranted.

If there is evidence for multiple stocks, then one needs to determine whether the stocks are merging, diverging, or shifting in parallel. If merging, stock identification needs to be re-evaluated. If diverging, then either stock identification needs to be re-evaluated (from the opposite perspective) or a spatially explicit model should be considered. If the stocks are shifting in parallel, then either a re-evaluation of stock area or a spatially explicit model allowing for dynamic movement is warranted.

A key point of this flow chart is that in any of these scenarios, for either one or multiple stocks, the way to address a shift in distribution would be the appropriate use of one of three common options widely used in fisheries: re-evaluation of stock identification, re-evaluation of a stock unit area or spatially explicit modelling. The first two approaches are not novel to fisheries science and management and in addition to warranting periodic examination for stocks anyways, represent a commonly used approach to help address documented and projected shifts in stock distribution. Spatially explicit stock assessments and metapopulation models are not as commonly used, but are emerging as a unique subdiscipline in fisheries science (Cadrin *et al.* 2004; Cadrin and Secor 2009) and have had a wide array of approaches developed to address spatial structure of fish stocks. The challenges to using these spatially explicit models are parameterizing the models and recognizing that the parameters may not be stationary through time (i.e., they are responding to climate-driven environmental and ecological change). However, the benefit is that they can account for spatial processes in the analysis of fishery species and it is clear from the aforementioned examples that spatial processes can be an important component of population dynamics.

Obiter dicta

Here, we highlight that there are implications of distribution shifts for the management of fish stocks and emphasize that there are practical ways to deal with these shifts. We assert that if there is compelling evidence that a stock has shifted, the analysis of a stock needs to consider these shifts and perform a range of sensitivity analyses on various stock delineations (sensu Peterman and Anderson 1999; Peterman 2004; Kraak *et al.* 2009).

As noted earlier, a thorough understanding of the underlying mechanisms that cause a distribution shift is important, although not essential for a management context. There are clearly many mechanisms that can cause shifts in fish distribution, including shifts in preferred habitats, migration pathways, dispersal, mortality patterns and reproductive patterns, among others. Most of these mechanisms can be linked to climate-induced changes in thermal conditions experienced by fish or by species that interact with fish, all as conditioned by fishing pressure. As such, much more research is warranted to elucidate the mechanisms responsible for distributional shifts and to identify the factors that drive relationships among changes in climate to observed responses. But in a management context, we assert that there currently is sufficient information to take action when action is clearly demonstrated as warranted.

What advantages would fisheries managers obtain from using the proposed method? That is, why should a manager use the proposed decision tree system? Shifts in stock distribution are already well documented (e.g., Rose *et al.* 2000; Drinkwater 2002; Walther *et al.* 2002; Brander *et al.* 2003; Perry *et al.* 2005; Rose 2005; Brander 2007; Mueter and Litzow 2008; Spencer 2008; Nye *et al.* 2009; see also full issue noted in Alheit *et al.* 2010). Such shifts (in response to future climate change) are projected to increase substantially enough to cause large-scale redistribution of fisheries productivity (Cheung *et al.* 2008, 2009) and threaten food security in some regions (Allison *et al.* 2009; Srinivasan *et al.* 2010). By using a systematic approach to evaluate stock shifts, fisheries managers will be able to account for such shifts in a manner consistent with the realized stock abundance in the regions they are focused upon. Thus, we submit that there are at least five main reasons why the proposed protocol should be considered.

First, if a stock is moving from an area or is contracting such that its stock unit area is misspecified, then reference points and management which do not account for such shifts will tend to be at levels that are not feasibly obtainable given such shifts. That is, reference point levels based on historical stock distributions or stock properties may be overly optimistic as to what is actually possible for a stock to produce if it is in fact leaving an area. Second, if a stock is moving into an area, expanding or merging with another, extant stock, and the stock area or identification are mis-specified, there would be the strong potential for foregone yield, with the stock being potentially under-utilized. Similarly, if a stock is entirely novel to an area the opportunity to develop a novel fishery could be hindered if this is not recognized (or if there is a failure to collect any information for the novel stock to base management decisions off of), also resulting in foregone yield. Third, if a stock is splitting, the management benchmarks could be either too optimistic or low, depending upon conditions of the novel stocks; either way mis-specified management benchmarks would be likely. Fourth, if no systematic approach is employed, managers remain open to the criticism of ignoring these potentially significant changes in stock distribution in response to changing ocean conditions; most institutions are now moving towards the recognition that at least considering such factors, even if only contextually, is wise. The proposed approach represents a pragmatic way to begin to do so in a more quantitatively rigorous manner. Finally, the proposed approach is logical, systematic and forces one to consider all available information. Without such a protocol, anyone is open to claim that various types of distributional shifts are occurring and more so open to suggest highly *ad hoc* measures to address them. What we propose is a way to organize such discussions and formalize the process for including any such information.

The many observations that fish distributions are changing reinforces the need for models that explicitly consider spatial dynamics. This is not an easy task and there are situations where spatially explicit models are unnecessary. However, the tools and models to accommodate distributional shifts are extant and not including spatial dynamics could significantly affect the management advice from stock assessments and associated projections (sensu Kraak *et al.* 2009). When there is uncertainty about stock structure, the affect of changes in spatial distribution can be examined by a comparison of models assuming different stock structure and by testing how sensitive estimates of stock size are to assumptions about stock area. Thus, we endorse the development of models that include dispersal, movement, migration and distributional shifts for use in stock analyses (Cadrin and Secor 2009).

Many marine fish populations are shifting in response to climate change, and these shifts need to be considered in the management processes associated with such fishery resources. Doing so will be a significant and much needed step towards ecosystem-based approaches to fisheries. We have already observed changing distribution of fish stocks, which is the first predicted response to climate change; such shifts are only predicted to continue. The ramifications for fisheries are too important to ignore. Here, we assert not only the need but also the feasibility of assessing fish distribution shifts and incorporating approaches to address such shifts directly in analysis of stocks and the management based thereon. The implications of continuing to not do so are unwise.

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