Article type : Original Article

Changing how we approach fisheries: A first attempt at an operational framework for ecosystem approaches to fisheries management

RUNNING TITLE: *New Operational Framework for Fisheries*

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KEYWORDS: diagnostics, ecological engineering, ecosystem-based fisheries management, living marine resources, risk management, structured decision-making, sustainable fisheries

Abstract

The increasing need to account for the many factors that influence fish population dynamics, particularly those external to the population, has led to repeated calls for an ecosystem approach to fisheries management (EAFM). Yet systematically and clearly addressing these factors, and hence implementing EAFM, has suffered from a lack of clear operational guidance. Here we propose 13 main factors (shift in location, migration route, or timing, overfishing (three types), decrease in physiology, increase in predation, increase in competition, decrease in prey availability, increase in disease or parasites, and a decline in habitat quality or habitat quantity) that can negatively influence fish populations via mechanisms readily observable in ~20 population features. Using these features as part of a diagnostic framework, we develop flowcharts that link probable mechanism(s) underlying population change to the most judicious management actions. We then apply the framework for example case studies that have well known and documented population dynamics. To our knowledge, this is the first attempt to provide a clearly defined matrix of all the probable responses to the most common factors influencing fish populations, and to examine possible diagnostics simultaneously, comparatively, and relatively in an attempt to elucidate the most probable mechanisms responsible. The framework we propose aims to operationalize EAFM, thereby not only better diagnosing factors influencing fish populations, but also suggesting the most appropriate management interventions, and ultimately leading to improved fisheries. We assert the framework proposed should result in both better use of limited analytical and observational resources and more tailored and effective management actions.

KEYWORDS: diagnostics, ecological engineering, ecosystem-based fisheries management, living marine resources, risk management, structured decision-making, sustainable fisheries

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Introduction

There are many factors that influence fish populations (Figure 1; c.f. Link et al., 2012a). These populations represent highly valuable living marine resources (LMRs) supporting fisheries around the globe (FAO, 2018). Therefore, it is wise to ensure that fisheries management practices routinely catalogue, diagnose, and identify those factors that have the largest influence on LMRs. We have known for centuries that fishing, oceanographic conditions, species interactions, disease, and habitat can all cause measurable impacts on LMR populations (Baird, 1873; Hjort, 1914; Smith, 1994; Jackson et al., 2001), observations which have only been reinforced over time (Sissenwine, 1984; Cushing, 1990, 1995; Jennings & Kaiser, 1998; Reno, 1998; Hsieh et al., 2006; Anderson et al., 2008; Cury et al., 2008; Shelton & Mangel, 2011). The challenge remains – how do we respond to these factors in terms of management interventions to ensure sustainable LMR populations and marine ecosystems, as well as their associated harvests and the vitality of coastal communities associated with these harvests and LMRs? Certainly lowering fishing pressure has been recognized (Table 1- Overfishing.I) as prudent in instances where overfishing has been clearly identified, but as a broader array of drivers (i.e. climate change, multiple ocean uses, pollution, etc.; Table 1- EAFM.I; Figure 1) increasingly affects oceanic conditions, simply lowering fishing rates may not be entirely sufficient to maintain (or rebuild) sustainable LMR populations and their associated fisheries (Table 1-Overfishing.II).

While many factors can affect LMR populations via multiple possible mechanisms, the list of the most important factors is finite. We assert that there is sufficient knowledge about these factors from which suitable management actions can be enacted to mitigate, minimize or reverse these influences on LMRs. From the science-based knowledge we have accumulated to-date, coupled with first principles reasoning, a suite of actions that address factors influencing LMRs can emerge. For example, we know that increasing fishing mortality to the point of overfishing can lead to a population decline (Table 1-Overfishing.III). Similarly, increasing predator impacts on a population increases natural mortality rates, and can also lead to a population decline Table 1-Predation.I). Yet the specific population-level responses that occur would exhibit different diagnostics and the management actions to address this increased mortality would be quite different for each case. A clear assignment of the diagnostic response to probable causal factor(s) would then result in more appropriately tailored management recommendations.

We understand that the mechanisms exhibited by these influencing factors operate on and can influence both the population and the broader ecosystem within which these populations exist (Botsford et al., 1997; Jennings & Kaiser, 1998; Jackson et al., 2001; Scheffer et al., 2005; Cury et al., 2008; Wells et al., 2016; Link, 2018). The mechanisms impact a range of LMR population and ecosystem processes (Figure 1), and can occur concurrently. Here we use the term Living Marine Resources (LMR) largely as a fish stock or population, but recognize that there can be other taxa that are harvested. Here we use the term “factors” as those facets of a marine ecosystem that respond to some larger-scale driver, but functionally can be thought of as synonymous to a “mechanism” or “process” that influences LMR populations. In the sense they negatively influence a population, we synonymously use the term “pressure.” We use the term “features” as representative of those aspects of LMR populations that can be tracked to understand the potential causality of a population change, here used synonymously as “diagnostics”. Certainly sorting out the various impacts on a population to disentangle these multiple effects remains a challenge. Considering a wide range of potential mechanisms implies that a suite of features need to be examined and monitored to delineate the most important factors and the most probable causal mechanism(s) influencing LMRs. We assert that there are variables representing characteristics of LMR populations that we routinely measure (row headings in Table 2) that should help elucidate these more dominant, influencing factors. Unique combinations of the prevalence and degree of these features should be indicative of the type of mechanism impacting LMR populations. Once identified, these could be treated analogous to medical diagnostics such that both the underlying mechanism and potential remedies could be elucidated (i.e., fisheries autopsies, *sensu* Smith & Link 2005). This essentially represents a specialized form of ecological engineering applied to marine fisheries (Odum, 1983; Mitsch, 2012; de la Mare 1998, 2005; Mitsch, 2012), whereby standard diagnostic criteria are developed and evaluated against observations, from which workable solutions are then explored and applied. We acknowledge that given the myriad possible mechanisms influencing LMRs it may be difficult to definitively diagnose specific cause-and-effect relationships for these LMR populations. However, the approach proposed here importantly can rule out those mechanisms not likely to be an important factor influencing LMR populations. And despite specific details of causal mechanisms, can begin to identify those mechanisms and hence the most suitable set of management interventions for those factors influencing LMRs.

For some time now, ecosystem-approaches to fisheries management (Table 1-EAFM.II) have been recognized as having significant benefits (Table 1-EAFM.III). Here we operate with EAFM defined as considering ecosystem factors as part of the analysis of a LMR population (Garcia et al., 2003, Garcia and Cochrane, 2005; Link & Browman, 2014), as opposed to an emphasis on the entire system of fisheries or the entire suite of ocean-use sectors on the one hand or ignoring those factors external to a population on the other. EAFM clearly recognizes the need to consider these broader factors more explicitly, and directly addresses the potential competing objectives facing a suite of fisheries in a given marine ecosystem (Table 1-EAFM.IV). Yet despite the clearly stated— and where implemented, realized— benefits (Pitcher et al., 2009; Link, 2018; Fulton et al., 2019), the implementation of EAFM is not widespread. This is no longer primarily due to linguistic uncertainty (Curtin & Prellezo, 2010; Link & Browman, 2014; NMFS, 2016a; b; Marshak et al., 2017) nor lack of clarity about mandates (Link et al., 2018; Rudd et al., 2018). Rather, it is increasingly recognized that EAFM has not been widely implemented largely due to lack of clear operational guidance on how to actually execute it (Table 1-EAFM.V). Here we propose a framework to operationalize EAFM, thereby better diagnosing factors influencing LMR populations, suggestive of more appropriate management interventions, and ultimately leading to improved fisheries.

Operational Framework

The approach we propose here addresses elements of uncertainty, risk, and complexity as an archetype of ecological engineering (de la Mare, 1998; de la Mare, 2005). In essence, ecological engineering an ecosystem and the goods and services it provides (de la Mare 1998, 2005; Holling, 1996; Mitsch, 2012; Odum, 1983) identifies a range of problems and explores a universe of solutions that are appropriate to the challenges being faced and provides a structured decision making framework to implement those solutions. It is very much a solutions-oriented approach rather than an acknowledgment of, and then paralysis by, the large range of possible cause and effect pathways. De la Mare notes that "*The emphasis is on standards, diagnostics, regulations, accountability, (and) commitment to (iterative) learning, distinction between technical and political processes—rather than to mechanical system optimization that de-emphasizes uncertainties and ecosystem complexities (Odum).*" Here we adopt that mindset by proposing an operational framework to address the factors facing marine fish and fisheries.

The operational framework we propose is aimed at disentangling the different factors that affect population processes. The framework consists of:

1) Observing changes in LMR populations.
2) Diagnosing observed changes.
3) Discriminating among possible mechanisms.
4) Using flowcharts to determine possible management actions.

The overall schema of how we view major factors influencing LMR populations is as a range of possible influencing factors, which once identified would suggest specific management actions (Figure 1). This schematic (Figure 1) depicts relationships between impacts on observable characteristics of fished populations from various drivers acting through specific mechanisms underlying population change. These impacts are then transmuted differentially via various population features that can be diagnostic of the mechanism. Once those population responses are identified, appropriate management measures can be recommended to address different mechanisms. The potential management actions would be differentially employed based upon the diagnostics identified as having the strongest influence on LMRs. Some management measures can also be directly focused on changes affecting fish communities, habitats, fishery markets, and full ecosystems, such as ecosystem-level catch controls, multispecies measures, and habitat restoration, but here our focus is largely on LMR populations. Thus, it seems both prudent and appropriate to unpack the possible mechanisms further.

Observing changes in LMR populations

The starting point for operationalizing EAFM is to observe changes in the characteristics of a LMR population or stock. We provide a list of ~20 commonly measured or derived features, arising from both fisheries independent and dependent observations (Table 2). If a population is experiencing changes in several features, it is advisable to focus on those showing the greatest change or considered to have the greatest effect on population dynamics. Each combination of population responses is indicative of different factors influencing the LMR.

A key observation is that many of these features are routinely measured, but they are not considered in a systematic, standard manner as a cohesive suite of diagnostics responsive to a range of possible influences on population dynamics. We do not mean to imply that these features are not currently used as diagnostics in fisheries. Certainly many of these features are examined in most fisheries stock assessment contexts (Gulland, 1970; Mace et al., 2001; Lynch et al., 2018; Marshall et al., 2019), and certainly informal examination of these features can lead to further elucidation of population dynamics as well. Others have begun to consider when these other factors might be considered in a stock assessment context (e.g. Lynch et al., 2018; Marshall et al., 2019). Yet the salient points we are making is that to our knowledge, no one has provided a clearly defined matrix of *all* these probable responses to common factors influencing LMRs (including factors external to population dynamics), nor has anyone examined all these possible diagnostics *simultaneously, comparatively,* and *relatively* in an attempt to elucidate which probable mechanism/s are responsible.

There is a minimum level of data required to execute the framework proposed here. For a given LMR population under consideration, one would need to have at least some measures, over time, of population size, individual size, reproduction, individual health, and location (Figure 1). These would translate into regularly monitored variables such as relative abundance, plus various measures of fecundity, size structure, location, and vital rates/condition. Secondarily would be any information, even contextual, regarding habitat associations, disease, stomach contents, ecological interactions, stock identification, and possible genetic population structure. We acknowledge that there are often data limited situations, and in those instances using whatever information is available should be applied to this framework, even if not necessarily exhaustive. Yet in many instances, routine monitoring, surveying and sampling should be able to provide many of these commonly measured fishery variables. Here we evaluate these routine measures as a comprehensive whole.

Another important consideration is that these features which detect population change underscore the need for routine and ongoing monitoring. This is monitoring that not only captures trends in abundance or biomass or location (Table 1-Monitoring.I), but monitoring that requires actual biological sampling of LMRs (i.e., measures of fecundity, maturity, age, diet, size, etc.; Table 1-Monitoring.II). It is also clear that these surveys need to be increasingly multidisciplinary in their sampling (Table 1-Monitoring.III) to cover the range of variables warranting continued monitoring.

Additionally, the amount of change in any observed population feature is an important consideration. Both regarding magnitude and relative variability of any response. On the one hand, there is often a low signal-to-noise ratio in many LMR population dynamics such that detection of any change among typical variability can be difficult. This would run the risk of too readily assigning change as being spurious. On the other hand, setting the standards for change too rigorously may miss some important changes to LMR population dynamics. This would run the risk of setting change criteria too rigidly such that any deviation below some pre-set (and potentially artificial) statistical properties might actually miss legitimate changes. Thus, the challenge remains of how to best quantitatively set a threshold of a response such that it would invoke a diagnosis of legitimate LMR population change. Here we resist the (understandable) desire to prescribe any statistical test of significance for determining such thresholds of change. Rather, we recommend a more ordinal, percentile-based, rule-of-thumb approach. We would generally suggest that any change in value of a LMR population feature above 25% should probably be considered (at least relative to typical variation of that feature) as a possible change worth monitoring more closely, and any change greater than 100% should probably be acknowledged as an important change. Yet the reason we are not entirely prescriptive is that a doubling or halving of some features (e.g. recruitment) may be well within the bounds of what is normally observed, and conversely only a 5-10% change may be critically important for another feature (e.g. growth rate). The salient point is to track population features for persistent changes of a magnitude that is noteworthy for that particular feature.

Diagnosing observed changes

Population response features (rows) and potential influencing mechanisms (columns) can help diagnose causality of LMR population change (Table 2). Akin to a checklist, examining the population response features can winnow down probable mechanisms influencing a population.

For example, if recruitment overfishing were the primary mechanism influencing a LMR population, the expected response across multiple population features would be a decline in the number of recruits, abundance, biomass, maturity, a negative impact to spawning duration and initiation, an increase in fecundity, and maybe a decline in size-at-age and weight-at-length (Table 1.Overfishing.IV). Similar responses would be seen for growth overfishing, but would be distinguished from recruitment overfishing by also having a decline in condition factor and liver weight, perhaps no change in spawning time, limited changes to maturity and fecundity, and size-at-age and weight-at-length would likely decline (Table 1-Overfishing.V). Ecosystem overfishing would be similar to both, but occurring for multiple stocks simultaneously, coupled with a decline in overall ecosystem productivity (e.g. primary production, chlorophyll *a*, etc.), change in ratios of biomass among fish guilds, or lower overall landings (Table 1.Overfishing.VI; not shown in Table 2). Conversely, changes in migration route, migration timing or permanent shift in location would express very few definitive responses, save for changes to distribution, range, and timing of spawning (Table 1-Migration/Movement/Location.I). Changes due to loss of habitat (quantity or quality), increase in competition, decline of available prey, increase in predator abundance, a decline in physiology, or an increase in disease would similarly have the requisite, mostly negative, responses in key population features (Table 2).

We assert that Table 2 is useful to explore potential mechanisms influencing LMR populations. Yet we also recognize that with 13 possible negative influencing mechanisms (out of 19 total, including positive responses), 20+ population features, and three possible responses (+,0,-), the combinations of options to track could be overwhelming and decidedly un-insightful. We also recognize that for many of the population features, the responses are often the same across a range of factors and not entirely useful as distinguishing diagnostics across the range of possible mechanisms. For instance, most negative influences on LMR populations result in a decline in measures of population size (abundance, biomass, abundance-at-age), individual size (size-at-age, weight-at-length, length frequency, maximum length, growth rate), individual health (condition factor, liver weight, stomach weight, diet composition), and reproduction (median age, fecundity, maturation, recruitment). Given these similar responses across a range of possible mechanisms, it would appear difficult to diagnose potential causality to population responses. Yet upon closer inspection, it is in those instances which exhibit distinct responses where there is high promise for diagnosing specific mechanisms (see circled cells in Table 2).

For example, if most population response features are negative but length frequencies, or size- or weight-at-age are increasing, it would be probable that predation is increasing (Table 2; Predator abundance column). This mechanism occurs as predators tend to target smaller fish (Table 1-Predation.II), and although other population responses exhibit decline, the resulting size structure could actually increase. Additionally, several taxa have shown increased growth rates in the presence of predators to grow out of “predator pits” (Bakun, 2006; Peck et al., 2014). We thus identify this as a key diagnostic of predation as most other impacts to size structure exhibit declines in size. Hence collectively these diagnostics could imply increased predation pressure, distinct from other negative features caused by other factors. Other diagnostics potentially indicative of specific mechanism include growth rate (implying not only possible predation, but also growth, rather than recruitment overfishing; Table 1-Physiology.I), condition factor (similarly implying growth but not recruitment overfishing; Table 1-Physiology.II), and perhaps a change in migration route (Table 1-Migration/Movement/Location.II), stomach weight (implying physiological, competition, or food availability mechanisms which are distinguished from mortality-driven responses; e.g. overfishing, predation; Table 1-Predation.III), range, distribution (both of which distinguish locational or migratory influences; Table 1-Migration/Movement/Location.III), fecundity (implying recruitment overfishing; Table 1-Physiology.III), and maturity (implying recruitment but not growth overfishing and ruling out possible habitat influences; Table 1-Physiology.IV) (see circled cells, Table 2). Focusing on these distinguishing features as key diagnostics, and in combination with other population features, should facilitate elucidation of probable mechanisms from which suitable management actions could then be recommended.

An important note is that some diagnostics can indicate a positive population response. Those factors that indicate a positive influence should not be overlooked, and conditions to be attentive to or that maintain positive responses warrant as much attention as negative responses. The resulting management action may be very minimal (i.e. let the situation continue with no intervention; Pomeroy & Berkes, 1997; Fletcher, 2005; Rosenberg et al., 2006) to quite involved (e.g. continue to restore habitat or significantly lower fishing rates; Berkes et al., 2001; Fletcher, 2005; Mora et al., 2009; Beck et al., 2011; Dunn et al., 2011; Beechie et al., 2013). There are instances where a diagnostic would clearly indicate positive LMR population features, implying the ability for a decrease in management interventions (e.g. decrease buffers to catch). The salient point is that not all diagnostics should be expected to indicate negative influences on LMR populations (Hilborn, 2010; Lotze et al., 2011, Link et al., 2012a; Hilborn et al., 2015). However, given that much of management action emphasizes mitigating or reversing poor LMR population status, here we mainly emphasize negative population responses in the flowcharts below.

Discriminating among mechanisms

Discriminating among the many possible factors that can influence LMR populations remains a challenge. Given the myriad possible combinations, knowing where to start the diagnostic assignation can be potentially overwhelming. We posit that to execute this winnowing of plausible causal factors requires three considerations. First is using the diagnostics to rule out possible factors that are not probable. Second is focusing on factors with known risks of substantial negative effects if management interventions are not enacted. And finally is prioritizing those factors which nominally can have some form of the ability to exert management control.

We acknowledge that there are copious risk-based approaches to triage LMRs in response to fishing (Table 1-Risk.I), climate change impacts (Table 1-Risk.II), ecological dynamics (Table 1-Risk.III), and habitat loss (Table 1-Risk.IV), among others (Table 1-Risk.V). A lot of those efforts focus on the system of fishes or fisheries in a given locale, not necessarily the individual populations as noted here (*c.f.* Lynch et al., 2018). Certainly extant information from those efforts could and should inform the delineation of causal mechanisms in the present framework.

We also acknowledge the need for ancillary information beyond the population features noted in Table 2. For example, sampling to determine whether ecosystem productivity has changed or that multiple LMR populations are experiencing overfishing would further inform ecosystem overfishing (Table 1-Overfishing.VI). Or measures of physical and chemical oceanographic phenomena could also inform and confirm these different mechanisms (especially habitat suitability; e.g. temperature, pH, salinity, etc.; Table 1-Monitoring.IV). Additional information indicating changes to other species could also inform possible competition or loss of prey. If overfishing was suspected, certainly fishery dependent measures and estimates of catch, landings, effort, catch-per-unit-effort (CPUE), and related metrics would inform that mechanism as well (Table 1-Overfishing.VII). The salient point is that while the diagnostics focus on features of population response, additional information to confirm or deny hypothesized mechanisms is wise to consider.

We propose the following order to discriminate among possible mechanisms that influence LMR populations.

1. Movement, migration or location
2. Overfishing
3. Physiology
4. Predation
5. Competition or prey abundance
6. Disease or parasites
7. Habitat

We suggest the issues of changing location or migration be examined first. Multiple other factors could be examined first, but we note that ignoring shifts in location results in misinformed understanding of population dynamics, potentially leading to misleading management advice (e.g. biological reference points could be inaccurate; Table 1-Migration/Movement/Location.IV). Then we suggest that the various forms of overfishing be examined. Even if the responses are mostly similar to loss of habitat, increased competition or predation, or lower food availability or declining physiology, and those other factors cannot definitively be ruled out, overfishing is one we can nominally control more directly via management interventions (for example as compared to competition among fishes; Table 1-Competition.I). Thus it should be considered in priority order over those other factors. Then we recommend that changes to physiology be considered. If there are notable changes to fundamental, vital rates (due to pollution, climate change, or whatever driver), any representation of population dynamics will need to account for these vital rate changes or run the risk of misrepresenting population functioning and the management advice derived therefrom (Table 1-Physiology.V). Next is consideration of predation. Although similar to forms of overfishing, the mechanisms of population impact are different and the need to account for predator influences on LMR populations would need to be handled distinctly. Again, management advice in the form of biological reference points is documented to be inaccurate if this factor is occurring but unaccounted for (Table 1-Predation.IV). Then competition or prey abundance needs to be considered. This mechanism results in similar responses to overfishing, predation or physiological changes, but relies on changes to other species in the ecosystem (Table 1-Competition.I). Again, the biological reference points, and resulting management advice derived therefrom, can be misestimated or biased if these factors are occurring but not expressly accounted for (Table 1-Competition.II). The penultimate option is to determine if disease or parasites were influencing a population. The diagnostics associated with this mechanism are likely the most definitive of any among the different population features, and although it might co-occur with other mechanisms and the impacts may be sub-lethal, this feature tends to have a clear signal with clear impacts on fish health (Table 1-Disease/Parasite.I). Finally, we propose considering habitat last, largely as that has the fewest distinguishing diagnostics and emerges after all other factors are ruled out. The changes from habitat, particularly habitat decline, have clear impacts on fish populations in smaller, freshwater and estuarine habitats or for many taxa that have strong site fidelity (e.g. for offshore reef and hard-bottom habitats; Table 1-Habitat.I). While habitat effects can be less pronounced for some species of marine fishes with larger ranges, large daily ambits, higher motility, and less site fidelity (Table 1-Habitat.II), other species and their juvenile stages can have quite specific habitat requirements, which can create bottlenecks in cases of habitat limitation or decline (Table 1-Habitat.III). Again, there is some evidence that key population dynamics can be misestimated if habitat factors that impact populations are not accounted for (Table 1-Habitat.IV).

Once a primary mechanism has been identified, the question remains- what to do next? Upon obtaining the results from this discrimination exercise, we propose using a suite of flowcharts to arrive at suitable management options appropriate for a LMR population under a given set of conditions.

Using flowcharts to determine possible management actions

The final step in our proposed framework is to couple the identified probable mechanism/s to effective management actions. In order to link mechanisms acting on LMR populations to the most appropriate management action/s, we propose a set of flowcharts. We reiterate that it is wise to start with the highest ranked mechanism to determine what action is suggested for that factor before considering the next mechanism and flowchart. These flowcharts are based on a logical, hierarchical decision tree approach, with each step suggestive of subsequent action or further evaluation. In each case, the entry point for each of these flowcharts is based on evidence for the mechanism established by the diagnostics in Table 2. These flowcharts are presented in this order to represent those population diagnostics and features that can be 1) clearly attributed to a particular cause, 2) can be addressed in order of the scope of population impact, and 3) to rule out possible factors, or combinations thereof, before moving onto the next set. We reiterate that the framework is to be used in an ordered and structured manner, and not randomly, in order to rule out potential causes and hence possible actions.

The aim is to rule out those factors that are more impactful (in terms of lasting population impacts) as one steps through the suggested ordering of the flowcharts.

The action endpoint (i.e., advice) in each step of every flowchart has an action verb followed by tangible, operational management options. We structured those in this manner to avoid being too generic or "platitudinal," to focus on specific, actionable steps, and to reinforce the mindset of seeking possible solutions, all while building on extant LMR management measures (Table 1-EAFM.VI). For example, if the advice recommended was to lower Fishing Pressure, we recognize that doing so could occur via one of multiple specific management actions in any given management jurisdiction; as such we do not attempt to prescribe these. (Here we use lowering Fishing Pressure (represented by F), lowering Total Allowable Catch (TAC), lowering Annual Catch Limits (ACLs), lowering fishing mortality rate (classically represented by F), or lowering fishing effort somewhat synonymously. Although we recognize the nuances among them, we do not make clear distinctions among them when recommending particular management actions. For the purposes of this work, we use the general term "fishing pressure" (lowering, modifying, changing, etc.) as represented by the shorthand of "F" and acknowledge that this could be done via many different mechanisms. We also note that Harvest Control Rules (HCRs) could include lowering fishing pressure (F) in many forms, and generally include recommendations to HCRs as part of lowing fishing pressure; herein we only make specific distinctions when there is a multispecies or ecosystem HCR as those HCRs tend to be more strategic in their emphasis. We also acknowledge the use, generally of fishing (classical F) and biomass (B), biological reference points (BRPs) that would be generally subsumed into our fishing pressure rubric, and specifically only identify them in this context when specific changes thereto would be advisable, particularly with respect to increasing buffers when estimating and establishing these BRPs. We also reiterate that the proposed management actions are commonly used measures (Table 1-EAFM.VI), but here are recommended for specific contexts and combinations in response to diagnosed mechanisms. We also note that multiple proposed management actions could equally address the mechanisms identified, and do not prescribe among any one of them.

For example, if a change in population **movement, migration and location** is suggested by the diagnostics (Table 2), one first asks whether there is a decline in range (Figure 2). If so, then one should examine the overfishing flowchart (Figure 3). If no decline in range is observed, one could then ask if there is an increase in range. If so, evaluation of the population could lead either to a lowering of buffers to biological reference point (BRP) buffer or an increase in fishing pressure (F) (Table 1-Migration/Movement/Location.V), else continuation to the next step. Then one needs to determine if there is a shift in distribution. If not, no further action is needed. If so, one then asks if there is a change in the timing of migration. If so, that would lead to recommendations of a seasonal closure and/or spatial fishery allocation measures, to ensure that conservation measures protecting critical life history events are maintained (i.e., establishing fisheries management based on spatial fishing units that vary over time, whether rotating or otherwise; Table 1-Migration/Movement/Location.VI). For example, the importance of accounting for changes to migration in spatial management has been reinforced in studies documenting spawning shifts of fishes in the Norwegian and Barents Seas (Reiss et al., 2009; Langangen et al., 2018; Langangen et al., 2019). The reasoning behind this is to allow for spawning, feeding, etc. that occurs as part of the migration, and ignoring the shift of when the migration occurs would leave the stock susceptible to missing those important life history events. If there is not a shift in migration timing, one then determines if there is a change in migration route. If so, depending upon whether it crosses political boundaries, either spatial allocation, spatial stock assessment (SA) models, or reevaluation of stock identification (ID) would be recommended for consideration (Table 1-Migration/Movement/Location.VII). Finally, if there is a change in spatial stock productivity, some of the same measures would be recommended (Table 1-Migration/Movement/Location.VII). We acknowledge that different specific mechanisms might result in the same recommended management measure. This is not a concern as long as proposed solutions are explored and it is recognized that this duplicity in fact provides a menu of options; for example, reevaluating stock ID has application for multiple scenarios, and in either case regardless of how one arrived at that point, would be beneficial to execute.

If **overfishing** is suggested by the diagnostics (Table 2), one could then ask a series of sequential questions to determine sub-mechanisms and appropriate actions for that mechanism (Figure 3). First, one needs to determine whether the population is the direct target of a fishery, or whether it is caught incidentally. From that determination, a range of possible fishery management actions related to bycatch (including gear modifications) or multispecies Harvest Control Rules (HCR) would be recommended (Table 1-Overfishing.VIII). For example, if the population is caught as bycatch, then measures could be taken to modify the target fishery management to reduce this bycatch such as gear modifications, bycatch limits, or spatial management to avoid areas of high bycatch (Table 1-

Overfishing.IX). In addition, evaluating multifleet interactions could determine whether changes across multiple fisheries could reduce bycatch mortality (Table 1-Overfishing.X).

A different but related set of measures would be appropriate to manage **overfishing** if the population subject to overfishing is a directly targeted stock (Figure 3). Nearly all measures include reducing fishing pressure (i.e., mortality, F) by limiting catches, fishing effort, or some combination thereof (Table 1-Overfishing.XI). Here we use lowering Fishing Pressure (represented by F), lowering Total Allowable Catch (TAC), lowering Annual Catch Limits (ACLs), lowering fishing mortality rate (classically represented by F), or lowering fishing effort somewhat synonymously. Although we recognize the nuances among them, we do not make clear distinctions among them when recommending particular management actions. For the purposes of this work, we use the general term "fishing pressure" (lowering, modifying, changing, etc.) as represented by the shorthand of "F" and acknowledge that this could be done via many different mechanisms. We also note that Harvest Control Rules (HCRs) could include lowering fishing pressure (F) in many forms, and generally include recommendations to HCRs as part of lowing fishing pressure; herein we only make specific distinctions when there is a multispecies or ecosystem HCR as those HCRs tend to be more strategic in their emphasis. We also acknowledge the use, generally of fishing (classical F) and biomass (B), biological reference points (BRPs) that would be generally subsumed into our fishing pressure rubric, and specifically only identify them in this context when specific changes thereto would be advisable, particularly with respect to increasing buffers when estimating and establishing these BRPs. However, evidence of differential influences leads to different management measure combinations beyond lowering fishing pressure. First, if there is evidence of phenotypic effects or evolutionary impacts, then minimum size limits/gear restrictions, closures of nursery grounds, and other measures to protect stock structure and genetic diversity may be necessary (Table 1-Overfishing.XII). If there is no evidence of evolutionary impacts, the next question is whether there is evidence of ecosystem overfishing (e.g. system-wide decrease in productivity, overall fish size, overall landings, and or a shift in biomass ratios). If so, an ecosystem-level TAC or some multispecies HCR would be recommended (Table 1-Overfishing.VIII, XIII). For example, the Eastern Bering Sea had some concerns about regime shifts and total catch available, and implemented an overall cap on groundfish for the ecosystem (Witherell et al., 2000; Goodman et al., 2002; NPFMC, 2018), which has helped to maintain one of the more lucrative and stable fisheries in the world (Link 2018). If recruitment overfishing were identified, again a reduction in F or even spawning closures might be warranted (Table 1-Overfishing.IV, XIV), and if growth overfishing were identified, minimum size or gear regulations might also merit consideration (Table 1-Overfishing.V) beyond lowering fishing pressure. If one checks all these steps but has no conclusive determination, an alternate mechanism should be explored (e.g. physiology, predation, or competition (Figures 4-6)).

If a change in **physiology** were indicated by the diagnostics, one would need to proceed in a more bifurcated flowchart to evaluate whether the changes were declines or increases in various individual size and vital rate features (Figure 4; Young et al., 2006; Horodysky et al., 2015, 2016). In effect, for each step in the flowchart, an evaluation of each subsequent metabolic process would result in either a change in SA model parameterization, a change in F (increase or decrease depending upon the direction of the physiological change), or if a decline, specific gear or area closure measures (Table 1-Physiology.VI). For example, in instances where growth has been strongly suspected of declining, BRPs and F (largely as TACs and related catch limits) derived therefrom have been lowered in those situations (Table 1-Physiology.VII), with the result of sustainable fisheries over a longer term (Table 1-EAFM.VII). If the flowchart results in inconclusive results, an evaluation of habitat considerations would be warranted (Figure 8). Of note here is the proposal for multiple instances to include temperature adjusted parameters or covariates in SA models. Although not without debate (Table 1-Physiology.VIII), the recognition of thermal conditions driving population dynamics via physiological mechanisms is well-known (Table 1-Physiology.IX) and increasing given climate change considerations (Pörtner & Peck, 2010; Pankhurst & Munday, 2011; Metcalfe et al., 2012). There are certainly some conditions where adding a specific thermal feature is not helpful (e.g., Table 1-Physiology.X), but in some instances it can be beneficial (e.g., Table 1-Physiology.XI).

If an increase in **predation** were indicated by the diagnostics (Figure 5), one first asks if it is designated as a forage fish, and if so recommend forage-specific management actions be undertaken (Table 1-Predation.V). Then a series of steps is explored to determine information availability and whether predation can be handled as predation mortality (M2; e.g., Table 1-Predation.VI) directly or whether multispecies HCRs should be adopted. In almost all end cases, a revision to F is recommended cognizant of predation mortality; the specifics lie in how predation is accounted for in the SA or BRP-setting process. For example, lacking detailed information, the ICES uses multispecies models to inform predation-related parameters for single stock assessment models in the North and Baltic Seas, which are then used to set specific F rates for those fishes (Hollowed et al., 2000b; Vinther, 2001; Dickey-Collas et al., 2010). We acknowledge that no specific management measure to control predators is recommended or likely advisable (Marshall et al., 2016; Lennox et al., 2018). Rather we propose that this additional source of mortality be explicitly considered as it can drastically alter the magnitude of population size (abundance) estimates (Table 1-Predation.VII), resultant biological reference points (BRPs; Table 1-Predation.VIII, Caddy & Mahon, 1995; Collie & Gislason, 2001; Mace et al., 2001; Caddy, 2004; Overholtz et al., 2008; Tyrrell et al., 2011), and hence resultant fishing recommendations for management (e.g., Table 1-Predation.IX).

If an increase in **competition** or decrease in **prey** abundance/availability were indicated, we first ask if this is due to an invasive species (Figure 6). Such invasive species, or even endemic species that exhibit major population "blooms" or outbreaks, are known to significantly impact food webs and population diagnostics of important, fishery-supporting taxa (Table 1-Competition.III). If so and if feasible, we recommend invasive control measures be implemented (e.g., Table 1-Competition.IV). If there is a change in prey productivity, that then bifurcates the flowchart into spatio-temporal overlap or dietary overlap considerations, resulting in the need for spatial management measures or spatial SA models for the former or multispecies HCRs and adjusted single species BRPs and SAs (cognizant of carrying capacity limitations) for the latter (Table 1-Competition.V). If those are not the case, one would then return to the point prior to the bifurcation and then ask if there was a decline in prey-food based (i.e., indicative of a shift in ecosystem productivity) or prey mortality. These would result in recommendations of developing an ecosystem-level or multispecies HCR respectively (Table 1-Competition.VI, Overfishing.VIII, XIII). A lot of these recommended management actions are in the form of multispecies HCRs or adjusting stock-specific BRPs or HCRs in a MS or single species SA context. Again, no specific management measure to control competitors, predators of prey, or prey populations are recommended or likely advisable (Link & Auster, 2013; Marshall et al., 2016; Lennox et al., 2018), but accounting for these species interactions either in SA, multispecies models or HCRs should be a consideration. These factors are especially germane in fish communities and ecosystems with high site fidelity, highly specific fish niches, and food webs with a high potential for limited production or high competition (Munday et al., 2001; Ward et al., 2006; Link & Auster, 2013). Examples of those situations include tropical coral reefs and high latitude demersal ecosystems (Munday et al., 2001; Hixon & Jones, 2005; Forrester et al., 2006; Link & Auster, 2013).

If an increase in **disease** or **parasite** were indicated (Figure 7), the first step is to evaluate the degree of prevalence; if low then the population should be monitored, but no specific management action is recommended. If the prevalence is high, then measures to disrupt either the disease vector (Table 1-Disease/Parasite.II) or parasite life history or habitat (Table 1-Disease/Parasite.III) need to be executed. For example, the sea lamprey (*Petromyzon marinus*, Petromyzontidae) can significantly impact salmonid populations in the Laurentian Great Lakes (i.e., freshwater, inland seas in N. America) and copious effort to disrupt the spawning and spawning habitats of these lamprey has occurred (Smith & Tibbles, 1980; Christie & Goddard, 2003). If the prevalence is not high, but the occurrence of the disease or parasite is a risk to human health, then a fish consumption moratorium would be recommended (Adedeji et al., 2012). These consumption moratoria routinely occur with concerns from biomagnification of trace metals or organochlorine compounds (Table 1-Disease/Parasite.IV), but have also occurred for instances of disease outbreak, particularly for many species of shellfish (Table 1-Disease/Parasite.V). Although we have largely focused on marine capture fisheries herein, this factor also has high applicability to sea-farmed and aquaculture-raised fish (Meyer, 1991; Stentiford et al., 2017). If the disease or parasite does not pose a risk to human health, the next step is to determine if it is lethal to fish. If not but could have perceptual or cosmetic effects, then market substitutions might be advisable (Anderson & Anderson, 1991; Wessels & Anderson, 1995). If so, then accounting for the effects on natural mortality needs to occur, either via stock assessment models, or a risk-based modification in F (e.g., Table 1-Disease/Parasite.VI).

If a decline in **habitat** were indicated (Figure 8), the first step would be to determine if that habitat was linked to population metrics and rates, or if the habitat were particularly identified as sensitive (using information not included in Table 2), as compared to a generic decline in habitat that might not be impacting or important to LMR populations. If the habitat were impacting population spatial metrics, then some form of spatial management, closure or spatial SA models would be recommended (Table 1-Habitat.V, Migration/Movement/Location.VII). This might also reiterate the need to check movement mechanisms (Figure 2). If not and the habitat itself were exhibiting substantial decline, then reducing pressure on the habitat and if need be habitat restoration would be recommended, possibly associated with reducing F (Table 1-Habitat.VI). If there is a habitat-linked change to population productivity metrics, then that would need to be considered in a SA model or result in modified F (Table 1-Habitat.VII). For example, in an instance when habitat was known to be expanding for butterfish (*Peprilus triacanthus*), this information was incorporated into a SA model, productivity was actually estimated to increase, and the subsequent F was increased (Manderson et al., 2011; Kohut et al., 2012; Adams et al., 2015; Essington et al., 2016; Marshak & Brown, 2017). It is worth noting that a lot of the potential management actions for habitat relate to habitat restoration, and that these often result in benefits for a broader set of species than just the focal taxa (Table 1-Habitat.VIII).

Case studies

Developing and describing the operational framework is necessary. But we recognize that that alone can be quite theoretical, esoteric and potentially tedious. Thus, here we provide a few illustrative examples that step-though the diagnostics and flowcharts. They were selected from situations familiar to those in the author string, but the ultimate aim is to test the framework for other LMRs. From the observations for each population and using the key diagnostics that emerged (Table 3), we contrast them with what could be the possible causal mechanism (Table 2) and then explore the various flowcharts accordingly. To further these examples, we then examine the salient literature for each of these situations to see if there is evidence supporting the outcome suggested from the operational framework. These examples were selected to demonstrate the proposed framework, but not to exhaustively detail each potential situation.

Northeast Atlantic

Overview

The Northeast Atlantic has experienced some pronounced changes in the regional climate during the last 30 years (Sherman et al., 2009; Drinkwater et al., 2014; Hollowed & Sundby, 2014; Kjesbu et al., 2014; Trenkel et al., 2014). The most pronounced ecosystem effect in this region has been a northward shift in phytoplankton (Edwards et al., 2001), zooplankton (Beaugrand et al., 2002), and fish (Perry et al., 2005; Hollowed & Sundby, 2014; Kjesbu et al., 2014; Fossheim et al., 2015). There has also been a substantial increase in some of the fish stocks such as the Northeast Arctic cod (*Boreogadus saida*, Gadidae; Hollowed & Sundby, 2014; Kjesbu et al., 2014) and Atlantic mackerel (*Scomber scombrus*, Scombridae; Trenkel et al., 2014; Berge et al., 2015). The great abundance of the Northeast Arctic cod has been attributed to synergies between a favorable climatic state and good management of the stock over a long period of time (Kjesbu et al., 2014). An important component of the management has been to eliminate the previous illegal and unreported fishing taking place in the trawling for demersal fish in the Barents Sea (Gullestad et al., 2013). However, there has been a favorable climatic effect on the recruitment of cod with many strong year classes produced in the early 2000s. The ice free area of the Barents Sea has also increased substantially during the last decades and this has increased the primary productivity of the region. The increase in the ice free area of the Barents Sea in the last two decades corresponds to the total area of the North Sea. The Atlantic mackerel has similarly had a sequence of very strong cohorts which has resulted in what appears to be a record high abundance of this stock in recent years, although there are some uncertainties in the stock assessment (ICES, 2014a, 2018). Some other stocks, including the Norwegian Spring Spawning (NSS) Atlantic herring (*Clupea harengus*, Clupeidae), have conversely not produced a strong year class since 2004 (ICES, 2018). This might be related to the climatic condition or to the reduced zooplankton abundance seen both in the Norwegian Sea (Huse et al., 2012) and along the coast (Toresen et al., 2019), but the causes for the poor recruitment are far from being fully understood (ICES, 2014a). The blue whiting (*Micromesistius poutassou*, Gadidae) has had some fluctuations in abundance in last the 30 years with strong variation both in recruitment and in adult abundance.

Applying the framework for pelagic fish in the Norwegian Sea

Here we test the framework for the three abundant pelagic fish stocks feeding in the Norwegian Sea: Atlantic mackerel, NSS herring, and blue whiting. For mackerel, the most pronounced changes in recent years have been the notable expansion in range and northward shift in distribution (Utne et al., 2012; Olafsdottir et al., 2016; Nøttestad et al., 2016), which result in those diagnostics clearly emerging as important (Table 2, 3). There has also been a substantial reduction in weight at age (Olafsdottir et al., 2015) as well as a sequence of very strong recruitment since 2005, and subsequent increase in biomass and abundance (ICES, 2011, 2014, 2018). However, in recent years the weight-at-age has slightly increased. In relation to Table 2, there are several mechanisms that could lead to these diagnostics. From the observations on this population the key diagnostics that emerged (Table 3) were contrasted with what could be possible causal mechanisms (Table 2); from that we then explore the various flowcharts accordingly. In this instance the main diagnostics are suggestive of a change in movement or competition, with the primary possible mechanism an increase in distributional range due to changes in migration. Using the change in the Movement/Location Flowchart (Figure 2) the answer sequence is **Y, N, Y, N** with the management suggestions to **Decrease BRP buffer and allow for increased F.** This is not advocating for raising F to something above F_{MSY} or an equivalent limit BRP, but rather decreasing the buffer to allow for more fishing (e.g. going from a 10% to 5% buffer or something similar). Another possible mechanism is competition for prey (Table 2, 3). This is in line with a previous study finding both inter- and intraspecific foraging competition between the planktivorous fish feeding in the Norwegian Sea (Huse et al., 2012). Using the Competition/Prey Availability flowchart (Figure 6) the answer sequence is **Y, N, N, Y, Y, Y** with the suggested management actions of adjusting **multispecies (or single species) HCRs for competition or changed K**. Thus for mackerel there are a few options that warrant consideration, some of which are currently being discussed as potential management options for this stock (Huse et al., 2018).

The diagnostics for NSS herring are less clear (Table 3, 1). The most pronounced pattern in recent years has been a decline in stock size, mainly in relation to poor recruitment since 2004 (Skagseth et al., 2015, Toresen et al., 2019). The mechanisms give a lot of similar signs for recruitment, biomass and abundance. All the three types of overfishing can clearly cause these effects. However, this is likely not occurring since the stock has been fished at a low level the last 20 years, in line with the target fishing mortality of 0.125 (ICES, 2014a). We also acknowledge that excluding other factors in SA models can lead to misinformed BRPs (Mace et al., 2001; Caddy, 2004; Tyrrell et al., 2011); thus we still need to evaluate this potential mechanism in the flowchart. In this instance the main diagnostics that emerge would be suggestive of changes in competition, predation, or overfishing (Table 3). Using the Overfishing flowchart (Figure 3), the answer sequence is **maybe (treated as Y), Y, N, N, N, N** which results in recommendations of **checking other mechanisms**. The same diagnostics can emerge from mechanisms associated with decreased prey abundance (or increased competition) and increased predator abundance (Table 2, 3). Upon initial glance, the latter is rather unlikely as the predators of adult NSS herring are relatively few (Holst et al. 2004) and have not increased (D. Howell & B. Bogstad, pers. comm.). But predation could be occurring as an effect on herring recruitment due to the expansion of mackerel, which can be a predator on juvenile herring (Skaret et al., 2015). Potential additional evidence for predation is increased predation pressure on herring in the nearby Barents Sea where the herring spends its first 3-4 juvenile years (Dragesund, 1970). The Barents Sea has had a strong increase in biomass of piscivorous fish in the last decade, particularly large Atlantic cod (*Gadus morhua*) that are known herring predators (Johansen, 2003). Thus, we need to evaluate the predator flowchart. Using the Increase in Predation flow chart (Figure 5) gives the sequence **Y, N, N, Y** with the resulting management suggestion of **reducing F, increasing buffer to BRPs** or using **M2 explicitly in the SA model** to set adjusted BRPs. Of these, we think the latter may be more appropriate given the ambiguous evidence for predation. Another important diagnostic population feature has been a long term reduction in length-at-age (Table 3; Huse et al., 2012, ICES, 2018). The decrease in zooplankton abundance (Huse et al., 2012; ICES, 2014b; Dupont et al., 2017; Toresen et al., 2019) is further evidence that also supports this possible mechanism. Our proposed framework necessitates stepping through higher risk mechanisms first, but still allows for the exploration of all possible mechanisms. Using the Competition/Prey Availability flowchart (Figure 6) gives the answer sequence **Y, N, N, Y, Y, Y** and the management suggestion would be to adjust **multispecies (or single species) HCRs for competition or changed K**. This is similar to the result for mackerel above. For NSS herring, the sum result is that some form of adjustment to either BRPs or HCRs would be recommended that accounts for the effect of ecological interactions, whilst monitoring for overfishing continues.

The blue whiting is presently at fairly stable population levels of abundance and biomass, but has gone through some dramatic changes in abundance during the last 20 years (Payne et al., 2012). Of particular note was a quadrupling of recruitment during 1996-2005 compared to the preceding 20 year period (Payne et al., 2012). The causes for this increase in productivity are not well understood, and the most likely explanation is a combination of changes in the large scale circulation of the sub-polar gyre (Hátún et al., 2005) causing variation in mackerel predation on the larval blue whiting (Payne et al., 2012). The diagnostics for blue whiting are not entirely clear, but the few key features suggest a possible increase in predation or competition (Table 3). Using the increase in predation flowchart (Figure 5) gives the answer sequence **Y, N, Y, Y** which results in the management suggestion of **modifying F** or **evaluating multispecies HCRs**. Similar to mackerel and NSS herring there was a reduction in length-at-age over time for the blue whiting (Table 3), probably related to competition (Huse et al., 2012). Using the Competition flowchart (Figure 6) gives the answer sequence **Y, N, N, Y, Y, Y** and the management suggestion would be to adjust **multispecies (or single species) HCRs for competition or changed K**, which is similar to the other two stocks discussed above.

For these pelagic stocks in the Norwegian Sea, that are known to be well managed regarding fishing pressure (ICES, 2018), it is no surprise that ecological interactions emerge as some of the more important mechanisms influencing their population dynamics. These features are common to small pelagic fishes around the world (Peck et al., 2014; Tyrrell et al., 2011), and the need to better incorporate these considerations remains (Skern-Mauritzen et al., 2016). Some form of multispecies modeling seems highly warranted (Skern-Mauritzen et al., 2018), and fortunately is ongoing in this region (e.g., Howell & Filin, 2014). To what extent multispecies HCRs can or will be adopted remains unclear, but the need for them is quite clear.

Applying the framework for Aquaculture – the case of salmon lice

Atlantic Salmon (*Salmo salar*, Salmonidae) farming has become a major industry along the Norwegian coast. The production takes place in net pens which are openly connected to the surrounding environment. Salmon lice (*Lepeophtheirus salmonis*, Caligidae) is a major pest in salmon farming and one of the most important challenges for the industry. In addition to causing problems for the growth and survival of the farmed salmon, the salmon farms act as major reservoirs of pathogens for the wild salmon and sea trout (*Salmo trutta trutta*, Salmonidae; Torrissen et al., 2013). The wild salmon populations in Norway have been reduced during recent decades. The sea fisheries have been closed since the 1980s, but there is still a fishery in the rivers. The salmon lice infestation can lead to increased mortality in outward migrating salmon smolts (Torrissen et al., 2013). It has also been hypothesized that the food conditions in the Norwegian Sea (Jensen et al 2012) and the competition with the planktivorous fish stocks (Huse et al., 2012) affects the growth and survival of the salmon feeding in the Norwegian Sea.

The most obvious diagnostic in this instance is an increase in disease/parasite infestation (Table 3). Using the diagram to diagnose the wild salmon results in disease as the most likely mechanism and competition as the second one. For the "increase in disease" flowchart (Fig. 7) the answers would be **Y, High, Y**. This will result in the suggested management action **Disrupt disease vectors**. This is a sensible approach and is in line with current management actions. The industry spends more than $400 million a year on combating salmon lice using various bathing treatments (Rae, 2002; Costello, 2009; Abolofia et al., 2017), motivated to a large degree by the negative effects on wild salmon. The secondary mechanism with competition would yield a path of **Y, N, N, Y.** This would leave us with the question of sufficient data and suggest **Multispecies and SS HCRs adjusted for competition** if the data are adequate and to **gather more information and evaluate multispecies HCRs**.

Northwest Atlantic

Overview

The northwest Atlantic is a highly productive ecosystem, with an extensive continental shelf that has supported major fisheries for centuries (Fogarty & Murawski 1998, Link et al., 2011b). This region merges subtropical-temperate with subarctic biomes and hence has high biodiversity and food web complexity for an ecosystem at this latitude. The fisheries there have had a history of sequential overfishing, going from pelagics to demersal groundfish to elasmobranchs and back to pelagics and invertebrates (EAP, 2012; Fogarty & Murawski, 1998, Fowler, 1999; NEFSC, 2019a, 2019b; Swain & Sinclair, 2000; Baum et al., 2003; Rose, 2004; Link et al., 2011b; Boudreau et al., 2017). This ecosystem has also experienced recent and extreme warming (Pershing et al., 2015), arguably some of the most rapid warming anywhere in the world's oceans. A general polar shift in biomass has been observed (Fogarty et al., 2008; Nye et al., 2009; Pinksy et al., 2013; Bell et al., 2014; Lynch et al., 2015). This all occurs in the context of many other ocean uses (EAP, 2012; Link & Marshak, 2019; NEFSC 2019a, 2019b).

Applying the framework for pelagic fish in the Georges Bank-Gulf of Maine Ecosystem

The diagnostics for Atlantic herring exhibit declines in multiple features of population size, recruitment, and maturity (Table 3; NEFSC, 2018). From these observations that emerged as key diagnostics (Table 3), we contrast them with what could be the causal mechanism (Table 2) and then explore the various flowcharts accordingly. In this instance these diagnostics are indicative primarily of recruitment overfishing (Table 2). Numerous studies have confirmed that this stock has experienced swings in fishing pressure (Fogarty & Murawski, 1998; Link et al., 2011b; Overholtz et al., 2008; Overholtz & Link, 2007), in some instances leading to severe depletion in the late 1970s and early 1980s followed by a recovery in the late 1990s and early aughts (Overhotlz et al., 2008; Overholtz & Link, 2007), with more variable pressures recently (Link et al., 2011b; NEFSC 2018a). Currently this population is facing fishing pressures that oscillate around what is sustainable and is recognized as being close to if not overfished (NEFSC 2018a). Using the Overfishing flowchart (Figure 3), the answer sequence is **Y, Y, N, Y** which results in recommendations of **evaluating multispecies HCRs**, or **reducing total overall effort**. If the evidence for ecosystem overfishing is debatable (which it still can be given the novelty of these measures and philosophical disagreements over this perspective (Link et al., 2011b; Link, 2018)), then the answer sequence becomes **Y, Y, N, N, Y** which results in management suggestions of **reducing F** or **spawning closures**. There is no indication of major shifts in distribution, and most other diagnostics are inconclusive. Growth rates and stomach content diagnostics may indicate an increase in predation. Furthermore, recent assessments indicate that this stock may in fact not be experiencing overfishing (NEFSC, 2018a). Additionally, this population has a well-documented history of experiencing wide-spread predation mortality (Overholtz et al., 2008; Overholtz & Link, 2007; Smith et al., 2015; Deroba, 2018). Thus it is wise to consider predation as another source of mortality. Using the increase in predation flowchart (Figure 5) gives the answer sequence **Y, N, Y, Y** which results in the management suggestion of **modifying F** or **evaluating multispecies HCRs**. Herring in the northwest Atlantic is likely exhibiting population dynamics largely in response to external (to the population and fleet) sources of mortality, with internal dynamics (via recruitment) secondarily present. It would be wise to account for or mitigate those external dynamics accordingly (Overholtz et al., 2008; Tyrrell et al., 2011; Smith et al., 2015; Deroba, 2018). This is consistent with ongoing efforts for this stock (Overholtz et al., 2000, 2008; NEFSC, 2012, 2018; Deroba, 2018; Deroba et al., 2019)

The diagnostics for Atlantic mackerel are similar to those for herring in the northwest Atlantic. There have been declines in measures of population size and individual size and the stock is currently thought to be overfished (NEFSC 2018b). From the observations that emerged as key diagnostics (Table 3), we contrast them with what could be the causal mechanism (Table 2) and then explored the various flowcharts accordingly. In this instance these are indicative of (recruitment) overfishing (Table 2). Similar to herring, there has been a noted history of overfishing this population in this ecosystem (Fogarty & Murawski, 1998; Link et al., 2011b) such that evaluating overfishing is warranted. Using the Overfishing flowchart (Figure 3), the answer sequence is **Y, Y, N, Y** which results in recommendations of **evaluating multispecies HCRs**, or **reducing total overall effort**. Of note is that although mackerel is currently experiencing overfishing, the entire ecosystem also has experienced this level of pressure (Link, 2018), plus the important role of mackerel as a forage fish in this ecosystem will need to be considered in mitigating this overfishing. Again, as ecosystem overfishing is controversial (Link, 2018), the alternate answer sequence becomes **Y, Y, N, N, N, N**, which results in recommendations of **checking other mechanisms**. Similar to herring, and probably the majority of small pelagic fishes (Pikitch et al., 2012; Essington et al., 2015) mackerel also exhibit diagnostics consistent with notable predation (Table 3). This population has a well-documented history of experiencing significant predation from multiple predators in this ecosystem (Link et al., 2011b; Moustahfid et al., 2009; Smith et al., 2015). Using the increase in predation flowchart (Figure 5) gives the answer sequence **Y, N, Y, Y** which results in the management suggestion of **modifying F** or **evaluating multispecies HCRs**. Mackerel population dynamics are likely driven primarily by mortality features, with some consideration of internal dynamics (i.e., recruitment) warranted. In some instances, there may be no specific or advisable management action to mitigate this predation impact, but inclusion in SA modeling and adjustments to BRPs or HCRs seems prudent (Overholtz et al., 2000; Moustahfid et al., 2009; Curti et al., 2013; Smith et al., 2015).

Applying the framework for Atlantic Cod in the Gulf of Maine Ecosystem

The diagnostics for Atlantic cod in the Gulf of Maine have clearly shown lower abundance, lowered recruitment, smaller size metrics, and a shift in distribution (NEFSC 2013, 2017; Palmer, 2014). We contrast these key diagnostics (Table 3) with what could be the causal mechanism (Table 2) and then explored the various flowcharts accordingly. In this instance these diagnostics are indicative of overfishing and a possible shift in location (Table 2). Given our prescribed ordering of use of the flow charts (noted above) and then using the shift in location flowchart (Figure 2), the answer sequence is **Y, N, Y, Y, Y, N, N, N, N** which results in recommendations to **reevaluate stock identification**. The evidence suggests that this stock is not expanding its range or migration, but rather that its distribution is shifting northerly (Fogarty et al., 2008; Nye et al., 2009; Pinksy et al., 2013) in response to warming temperatures in the region (Pershing et al., 2015). That it may cross an international boundary could also speak to allocation concerns. The diagnostics also point to a secondary mechanism of overfishing. This stock is in fact known to be overfished (NEFSC 2013, 2017; Palmer, 2014). Using the overfishing flowchart (Figure 3), the answer sequence is **Y, Y, N, Y** which results in recommendations to **establish ecosystem TAC, reduce total effort, or evaluate multispecies/multifleet harvest control rules**. The evidence for overfishing is consistent with decades of observations for this stock (NEFSC, 2013, 2017; Link et al., 2011b), but the preponderance of overfishing for multiple stocks in this ecosystem suggests that a multispecies approach may be warranted versus stock-specific considerations. As both overfishing and a distribution shift may be occurring, a comprehensive reevaluation of BRPs or HCRs seems prudent (Nye et al., 2009; NEFSC, 2013, 2017; Link et al., 2011b; Palmer, 2014).

Discussion

There is a significant need for a framework like the one proposed here. Largely because we need to change the mind-set when approaching fisheries issues from one of weighing or exploring every potential, optimized outcome to one of identifying workable solutions in the context of such oceanographic, ecological, and socio-economic complexity (Jackson et al., 2001; Ruckelshaus et al., 2008; Halpern et al., 2008; Cheung et al., 2010; Hoegh-Guldberg & Bruno, 2010; Hilborn, 2011; Link et al., 2012a; Micheli et al., 2014; Boyd et al., 2015; Halpern et al., 2015; Tam et al., 2017; Link, 2018; Marshall et al., 2017; Fulton et al., 2019; Link & Marshak, 2019). We propose the first ever framework to systematically, simultaneously, comparatively and relatively explore population diagnostics that link responses to main causal factors. Additionally, this framework then proposes specific management actions tailored to address those mechanisms of population change.

We acknowledge that what we propose is a first start, and likely could miss many nuances, may be misinformed with respect to particular mechanisms, may miss other factors, and as such will likely need to be modified over time. One could view as this a prototype to be attempted and improved as it is applied to additional LMR populations. We also acknowledge that even though this proposed framework identifies probable mechanisms, it does not aim to establish and quantify detailed process information nor specific details and nuances of cause-and-effect relationships. Rather, it simply aims to identify general patterns and features, *a la* fisheries autopsies (Smith & Link, 2005) to better assign diagnostics to the most probable, general mechanisms resulting in population change. By analogy, the point is to identify-- using common diagnostics-- that someone has influenza so that the person can be treated, not primarily to identify the causal factors that made the individual susceptible to infection, exposed them to the pathogen, worry about the particular strain of the flu, etc. We also recognize the potential for multiple mechanisms occurring at once, and again propose starting with the flowchart that has the most likely impact and minimization of risk, working through them until sustainable solutions can be obtained. We also recognize that the resulting advice from the flowcharts can still be rather general, and acknowledge that specific values, analyses or reference point modifications would need to be tailored to the local management regime, analytical tools, and ecological context as informed by the data in that situation. Our aim is to see this framework tested on many other LMR populations, adapted for regional implementation accordingly.

An important outcome from the approach proposed here is to rule out causal mechanism and management actions that are not appropriate. For example, there are numerous calls for *carte blanche* spatial closures as a management action (Lauck et al., 1998; Roberts et al., 2001, 2017; Gell & Roberts, 2003; Halpern, 2003; Lester et al., 2009; Watson et al., 2014). In some instances, these are indeed appropriate (Murawski et al., 2000; Halpern & Warner, 2003; Hilborn et al., 2004; Selig & Bruno, 2010). Yet in others such as changing migration or increases in predation, they will not entirely ameliorate the negative factors influencing LMR populations (Allison et al., 1998; Soto, 2002; Hilborn et al., 2004; Keller et al., 2009; Makino et al., 2014) and thus may not be the best intervention. By specifying, with relatively simple diagnostics, what management interventions will be most apt to have a positive impact, we can avoid the inefficiencies of "excessive adaptive management" cycling (i.e., continually trying new, albeit ineffective, management interventions; Walters, 1986; Levin, 1999; Smith et al., 1999; Allan & Curtis, 2005; Walters, 2007; Argent, 2009; Allen & Gunderson, 2011; Rist et al., 2013; Westgate et al., 2013; DeFries & Nagendra, 2017).

In many respects, the framework we propose is a form of ecological engineering (Odum, 1983; Holling, 1996; de la Mare 1998, 2005; Mitsch, 2012). Using the engineering perspective, what we propose aims to increase detection of signals among the noise (Jennings, 2005), thereby suggesting the next suitable set of actions (e.g., Jennings, 2005; Andalecio, 2010; Lockerbie et al., 2018) in a structured decision making manner. The diagnostics and standards for evaluation of them as a suite of decision criteria could also provide efficiencies and improvements in a relatively simple, empirically-based manner that would necessitate an identified range of actions. We certainly are not advocating for curtailment of fisheries-related research in any way, but we do think such an engineering approach could focus from a plethora of process-oriented studies into ones that lead to more refined solutions for LMR management (Lockerbie et al., 2016, 2017; Krug et al., 2017; Link & Marshak, 2019). Often the factors and combinations thereof facing LMR populations can seem so overwhelming that it leads to inaction. The key point from this engineering approach is that we know enough to act now, and given that we will always have imperfect knowledge, the framework we propose provides a rubric to ensure that not only are suitable management interventions explored, but no probable cause of population decline is ignored.

We acknowledge the complexity of the combination of the factors facing just one LMR population, and possible responses thereto, can indeed seem overwhelming. Let alone a full suite of LMRs in a given marine ecosystem. Yet the salient feature of the framework proposed here is to recognize such complexity, prioritize among the most probable factors influencing a population, and then from known linkages and first principles, recommend action. This framework seeks to find diagnostics and actionable solutions rather than optimizing among the myriad possible mechanisms that could be influencing fish populations. Our fear for the fisheries discipline is that there are too many factors influencing LMR populations too rapidly for our normal way of conducting business via detailed, mechanism-by-mechanism process studies to handle them all at once and in adequate time. An approach like the framework we propose here seeks to prioritize and triage those that warrant attention, with suggestions of what the most suitable actions should probably be (de la Mare, 2005; Fletcher, 2005; Hobday et al., 2011; Hare et al., 2016), in a way to ensure sustainable LMR populations.

Another consideration for the application of this framework is who actually makes these determinations and the resultant management decisions? Certainly fisheries management bodies need to start thinking about this. And certainly LMR analysts and population modellers need to start thinking about this as well. But the salient point is that ultimately it does not matter as long as someone begins to do so. Perhaps this framework could be adopted as part of LMR review protocols, or prior to population modelling efforts, as part of LMR analysis scoping common when gauging data needs and availability. Both would ensure that the prominent factors influencing an LMR population would not be overlooked, and might even suggest the best scenarios to test for the condition of a given population. But we do not want to be too prescriptive regarding who needs to execute this approach nor where in any given management process it needs to be inserted. Rather, we simply want to present the approach so the broad community of fisheries scientists and managers are empowered to test the framework and apply it as practitioners in their own local and specific contexts.

Management of risk is an essential part of fisheries management (Table 1-Risk.VI). The negative consequences of LMR population decline are well documented (e.g. Cushing, 1990, 1995; 2011 Smith, 1994; Jennings & Kaiser, 1998; Reno, 1998; Jackson et al., 2001; Hutchings & Reynolds, 2004; Hsieh et al., 2006; Anderson et al., 2008; Cury et al., 2008; Shelton & Mangel, 2011; Essington et al., 2015; Eddy et al., 2017). We certainly have a clear recognition of the risks caused by overfishing (Myers et al., 1994; Rosenberg et al., 1994; Hall 1999; Murawski, 2000; Jackson et al., 2001; Walters & Kitchell, 2001; Pauly et al., 2002; Froese 2004; Hutchings & Reynolds, 2004; Birkeland & Dayton, 2005; Coll et al., 2008; Worm et al., 2009; Hilborn, 2010; Pikitch, 2012). But as the climate and hence oceans continue to change at a rapid pace (Harley et al., 2006; Hoegh-Guldberg et al., 2007; IPCC, 2014; Allen et al., 2018), as fisheries continue to clash with other fisheries (Daan & Sissenwine, 1991; Murawski, 1991; Pomeroy et al., 2016; Rindorf et al., 2017a, 2017b) and other ocean-uses (Sanchirico et al., 2010; Yates et al., 2015; Rudd et al., 2018), and as ecosystem dynamics shift (e.g., Francis & Hare, 1994; Scheffer et al., 2001; Casini et al., 2008; deYoung et al., 2008; Möllmann et al., 2008; Johnson et al., 2011; Lockerbie et al., 2018), the need to account for and manage risk from a wider array of factors is heightened. There are many extant methods and approaches to identify and evaluate this risk (Table 1-Risk.VII), and in many ways they are quite compatible with and actually informative to the approach noted here. Among these risk-based approaches that identify major concerns, very few actually prescribe recommended management actions. We hope that the framework provided here bridges the gap between identification of risk to specific and appropriate management measures.

There are other works that have attempted to provide decision trees for managing LMRs beyond the risk assessments noted above. For instance, changes to migration (Link et al., 2011a; Pinnegar et al., 2013; Karp et al., 2018), changes due to climate change (Allison et al., 2009; Cinner et al., 2012; 2013; Hare et al., 2016; Karp et al., 2018), overfishing (Fletcher, 2005; Cope & Punt, 2009; Dunn et al., 2011), or changes due to predation (Rochet et al., 2005; Shannon et al., 2014) have all in many ways served as precursors to the framework noted here. Yet none of those has attempted to tackle the full range of factors that influence LMR populations simultaneously. The challenge among all of these prior approaches has been to note where in the science-to-management decision process is appropriate to insert the additional information or intervention. If one generally accepts the Monitoring/Data → Modeling/Assessment →Management Advice/BRPs → Management Action/HCRs rubric as the generic process for executing LMR management (Caddy & Mahon, 1995; Mace et al., 2001; Caddy, 2004; Punt, 2010; NMFS, 2016; Karp et al., 2018; Lynch et al., 2018), it is clear from this generic management process that the science-to-management decision process has multiple insertion points. Each of the steps in that process could potentially be a place to account for the factors influencing LMR populations, and it may be wise to include some level of redundancy to ensure the mechanism is addressed, as it is in engineering systems (Odum, 1983; Holling, 1996; de la Mare 1998, 2005; Mitsch, 2012). In fact, many of the recommendations from the flowcharts result in recommendations that indeed capture both this need for redundancy and the reality of multiple insertion points. This built-in optionality leading to redundancy is important primarily as a means to address imperfect knowledge among these factors in a given marine ecosystem.

Almost all of the proposed management measures noted here (Figure 1) are not novel LMR management options (Table 1-EAFM.VI). They are simply reconfigured or used with respect to specific causal mechanisms of population responses. This is beneficial for at least two reasons. First is that the management measures to address the factors facing LMR populations are already extant, and we do not need to develop even further solutions (Table 1-EAFM.VI). And second, that these measures are extant affords some modicum of familiarity, which should enhance their ongoing uptake and use (Riechers et al., 1993; Smith et al., 2007; Rice, 2011). For those that are mildly novel or proposed for use in an atypical fashion, the use of management strategy evaluations (MSE) as a simulation and testing tool should be able to better assuage concerns about those measures (Smith et al., 1999; Sainsbury et al., 2000; Bunnefeld et al., 2011; Fulton et al., 2011, 2014; Punt et al., 2014, 2016; Cummings et al., 2017; Lynch et al., 2018). More so, it is the combination of measures, with some built-in redundancy as noted above, along with their specificity to the particular mechanism influencing LMR populations that should increase even further their efficacy for achieving sustainable LMR populations.

The need to compare and coordinate across species emerges from this proposed framework. Many of the factors revolving around ecological or habitat or disease interactions imply factors that impact more than one taxa. Additionally, an important thing to note about this framework is that many of the management recommendations result in multispecies HCR, reduce bycatch, restore habitat, or ecosystem-level BRP types of actions that impact more than one targeted species. Clearly the need to further advance multi-taxa approaches has merit, and in many ways is an important feature of enhanced fisheries management (Fogarty, 2014; Collie et al., 2016; Holsman et al., 2017, 2018; Holsman et al., 2018; Link, 2018;

Weijerman et al., 2018; Fulton et al., 2019). We acknowledge that ecosystem reference points are still controversial (Link, 2018) but assert that they need to be given additional consideration; initial instances of doing so exhibit significant improvements (Link, 2018; Fulton et al., 2019). The framework we propose here is decidedly single-population in orientation, but it is clear that ancillary information will benefit this framework. We assert that at least having extant, multispecies MSEs is advisable given the range of HCR that will likely need to be explored (Punt, 2010; Fulton et al., 2014; Punt et al., 2014; Grüss et al., 2016; Ono et al., 2017; Rindorf et al., 2017a, b; Holsman et al., 2018; Fulton et al., 2019).

We offer this proposed framework as a way to enhance and improve sustainable management of LMR populations. We also offer it as a way to further implement EAFM (Table 1-EAFM.VIII). In many ways, we view the two as synonymous. The benefits of EAFM have been well stated but are rarely realized (Table 1-EAFM.III). In many ways they embody the objectives of sustainable LMR management, are in many ways necessary to do so, and in many ways address the competing objectives as doing so occurs (Table 1-EAFM.IV). We acknowledge that the lack of clear operational guidance has hindered the wide adoption of EAFM and EBFM (Table 1-EAFM.V). We trust that the approach proposed here provides at least the rudiments of an operational framework for executing EAFM. By better diagnosing factors influencing LMR populations, suggestive of more appropriate management interventions, and ultimately leading to improved fisheries, we trust that sustainable LMR management using an EAFM will become increasing realized.

Acknowledgements

This work was conceived, initiated, and partly executed during a scientific exchange with GH visiting Woods Hole. GH thanks the National Marine Fisheries Service for kindly providing a workspace and a stimulating work environment. SG and JL thank the Institute of Marine Research and the Norwegian Research Council for institutionally and fiscally supporting GH's visit. This resulting work is an example of an useful outcome from the long-standing MOU between both organizations. The authors declare no conflict of interest. We all also thank Erik Olsen, Laurel Smith, Kenric Osgood, Kevin Craig, Scott Large, Jon Deroba, Kiersten Curti, Mike Palmer, Patrick Lynch, John Field and anonymous reviewers for their constructive comments on earlier versions of this manuscript.

Data Availability Statement

All data herein are publicly available.

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Table 1. Summary of the literature for major mechanisms impacting living marine resource (LMR) populations, with detailed mechanisms or specific effects noted. With some summarizations of EAFM, Monitoring, and Risk considerations. LMR = living marine resource, BRP = biological reference point, F = fishing mortality rate, HCR = harvest control rule.

Major Mechanism Impacting LMR	#	Detailed Mechanism or Specific Effect	References
Migration/ Movement/ Location			
	I	Important to LMR populations if location/migration/ movement changed	Perry et al., 2005; Nye et al., 2009; Cheung et al., 2010, 2015; Pinsky & Fogarty, 2012
	II	Changes to migration route worth tracking	Tiews, 1978; Fromentin & Powers, 2005; Jørgensen et al., 2008; Nye et al., 2009; Opdal, 2010
	III	Changes in range & distribution can be important diagnostics	Kirkpatrick & Barton, 1997; Pearson & Dawson, 2003; Guisan & Thuiller, 2005; Nye et al., 2009
	IV	BRPs inaccurate if not included	Caddy & Mahon, 1995; Mace et al., 2001; Caddy, 2004; c.f. Link et al., 2011a; Karp et al., 2018; Pinsky et al., 2018
	V	Lowering buffers or increasing F worth considering if range exapnds	Caddy, 1999; Babcock et al., 2007; Dankel et al., 2008; Prager & Shertzer, 2010; Crosson, 2013; Methot et al., 2014; Lynch et al., 2018
	VI	Spatial seasonal closures can be useful	Myers et al., 2000; Halpern, 2003; Babcock et al., 2005; Eero et al., 2012; Little, et al., 2015; Hazen et al., 2018
	VII	Spatial stock assessment models, or reevaluation of stock identification important options	Booth, 2000; Goethel et al., 2011; Link et al., 2011a; Eero et al., 2012; Pinsky & Mantua, 2014; Berger et al., 2017; Karp et al., 2018; Pinsky et al., 2018; Thorson & Haltuch, 2018; Dubik et al., 2019; Thorson, 2019
Overfishing			
	I	Importance of lowering fishing pressure	Hall, 1999; Restrepo & Powers, 1999; Murawski, 2000; Pauly et al., 2002; Hutchings & Reynolds, 2004; Birkeland & Dayton, 2005; Worm et al., 2009

II	lowering F alone may not be sufficient to maintain or recover stocks	Murawski, 2000; Caddy & Agnew, 2004; NRC, 2014; Tyrrell et al., 2011; Walsh et al., 2006, Worm et al., 2009
III	Increasing Fishing Mortality leads to overfishing and population decline	Beverton & Holt, 1957; Gulland, 1970; Myers et al., 1994, 1997; Smith, 1994; Caddy & Mahon, 1995; Restrepo & Powers, 1999; Hutchings, 2000; Murawski, 2000; Jackson et al., 2001; Babcock et al., 2007; Dankel et al., 2008; Methot et al., 2014
IV	Recruitment overfishing described	Sissenwine & Shepherd, 1987; Myers et al., 1994; Rosenberg et al., 1994; Walters & Kitchell, 2001; Froese et al., 2008; Hilborn, 2010
V	Growth overfishing described	Rosenberg et al., 1994; Pauly, 1989, 1994; Froese 2004; Froese et al., 2008; Diekert, 2012
VI	Ecosystem overfishing described	Pauly, 1994; Yachi & Loreau, 1999; Murawski, 2000; Loreau et al., 2001; Link, 2005; Coll et al., 2008; Link & Watson, 2019
VII	Main measures of overfishing	Gulland, 1970; Murawski, 1991; Coleman et al., 2004; Froese, 2004; Maunder & Punt, 2004; Dankel et al., 2008; Cordue, 2012; Methot et al., 2014
VIII	Bycatch or mutlispecies HCRs important	Daan & Sissenwine, 1991; Vinther, 2001; Smith et al., 2008; Worm et al., 2009; Punt, 2010; Gaichas et al., 2012; Fulton et al., 2014; Punt et al., 2014; Grüss et al., 2016; Ono et al., 2017; Rindorf et al., 2017a, b; Holsman et al., 2018
IX	Bycatch mitigation	Witherell & Pautzke, 1997; Broadhurst, 2000; Witherell et al., 2000; Johnson, 2010; Bellido et al., 2011; Little et al., 2015; O'Keefe et al., 2014
X	Multifleet considerations could minimize bycatch	Murawksi, 1991; Ulrich et al., 2002; Hutton et al., 2010; Gaichas et al., 2016
XI	Reduce F if overfishing/overfished	Caddy & Mahon, 1995; Restrepo & Powers, 1999; Murawski, 2000; Babcock et al., 2007; Dankel et al., 2008
XII	Protect stock structure and genetic diversity	Enberg et al., 2009; Hutchings, 2009; Jørgensen et al., 2009; van Overzee & Rijnsdorp, 2015

	XIII	Ecosystem catch quota or mutispecies HCR important	Witherell et al., 2000; Mueter & Megrey, 2006; Smith et al., 2008; Worm et al., 2009; Punt, 2010; Gaichas et al., 2012; Fulton et al., 2014; Kang et al., 2018; Ono et al., 2017; Rindorf et al., 2017a, 2017b; Link, 2018; Link & Watson, 2019
	XIV	Dealing with Recruitment overfishing	Sissenwine & Shepherd, 1987; Myers et al., 1994; Bohnsack & Ault, 1996; Restrepo et al., 1998; Shepherd et al., 1998; Froese, 2004
Physiology			
	I	Growth rate a key diagnostic	Pauly, 1994; Froese, 2004; Bakun, 2006; Rochet et al., 2005; Froese et al., 2008; Enberg et al., 2012
	II	Condition factor a key diagnostic	Handford et al., 1977; Amarasinghe, 1988; Rosenberg et al., 1994; Lambert & Dutil, 1997; Ballón et al., 2008; Enberg et al., 2012; Ba et al., 2016
	III	Fecundity a key diagnostic	Ennis, 1981; Sissenwine & Shepherd, 1987; Pollock, 1993; Shepherd et al., 1998; Sadovy, 2001; Froese, 2004
	IV	Maturity a key diagnostic	Sissenwine & Shepherd, 1987; Pauly et al., 1989; Pollock, 1993; Musick, 1999; Froese, 2004; Usseglio et al., 2016
	V	If change not accounted for, can misrepresent population functioning	Young et al., 2006; Keyl & Wolff, 2008; Horodysky et al., 2015
	VI	Change in model parameterization or management measure needed if change in physiology	Sissenwine & Shepherd, 1987; Myers et al., 1994; Caddy & Mahon, 1995; Bohnsack & Ault, 1996; Restrepo et al., 1998; Restrepo & Powers, 1999; Babcock et al., 2007; Young et al., 2006; Froese et al., 2008; Jørgensen et al., 2009; Johnson, 2010; Little et al., 2015; Horodysky et al., 2015, 2016
	VII	Need to lower BRP due to lower growth	Pauly et al., 1989; Caddy, 1999; Caddy, 2004; Froese et al., 2008; Prager & Shertzer, 2010; Methot et al., 2014; Lynch et al., 2018
	VIII	Debate over including environmental parameters	Skud, 1975; Smith, 1994; Walters & Collie, 1998; Rose, 2000; Punt et al., 2014, Szuwalski et al., 2015

	IX	Thermal conditions known to drive population dynamics via physiological mechanisms	Pauly, 1980; Loeng, 1989; Regier et al., 1990; Gislason et al., 2010
	X	Adding thermal conditions may not always be helpful	Myers, 1998; Robin & Denis, 1999; Rose, 2000; Mickelsen & Petersen, 2004; Kempf et al., 2009; McClatchie et al., 2010; Carscadden et al., 2013
	XI	Adding thermal conditions can be benefitial	Young et al., 2006; Keyl & Wolff, 2008; Horodysky et al., 2015, 2016; Munroe et al., 2016; Marshall et al., 2019
Predation			
	I	Predation incresase natural mortality rates leading to population declines	Sparre, 1991; Bax, 1998; Hollowed et al., 2000a; Köster & Möllman, 2000; Bundy, 2001; Whipple et al., 2001; Read & Brownstein, 2003; Moustahfid et al., 2009; Tyrrell et al., 2011
	II	Predators tend to target smaller fish prey	Scharf et al., 1997; Scharf et al., 2000; Friedlander & DeMartini, 2002; Blanchard et al., 2009
	III	Changes in stomach (contents) weight important to track	Hyslop, 1980; Carl, 2008; Garrido et al., 2008; Donelson et al., 2010; Link & Auster, 2013; Whitley & Bollens, 2014
	IV	BRPs inaccurate if not included	Hollowed et al., 2000a; Mace et al., 2001; Tsou & Collie, 2001a; b; Caddy, 2004; Tyrrell et al., 2008, 2011; Barnett et al., 2017
	V	Forage predation considerations important to consider	Eero et al., 2012; Pikitch et al., 2012; Peck et al., 2014; PFMC, 2014; Essington et al., 2015
	VI	Handling predation directly as predation mortality in assessment model can be useful	Bundy, 2001; Hollowed, et al., 2000b; Whipple et al., 2001; Moustahfid et al., 2009; Tyrrell et al., 2011
	VII	Predation can alter magnitude of population estimates	Christensen, 1996; Hollowed et al., 2000a; Köster & Möllman, 2000; Read & Brownstein, 2003; Gaichas et al., 2010
	VIII	Predation can alter magnitude of BRPs	Caddy & Mahon, 1995; Collie & Gislason, 2001; Mace et al., 2001; Caddy, 2004; Overholtz et al., 2008; Tyrrell et al., 2011

	IX	Predation can alter fishing management recommendations	Fritz et al., 1995; Punt & Butterworth, 1995; Caddy, 1999; Sainsbury et al., 2000; Butterworth & Punt, 2003; Read & Brownstein, 2003; A'mar et al., 2010
Competition			
	I	Competition among fishes can impact LMR populatoins	Murawski, 1991; Link, 2002b; Stergiou, 2002; Munday et al., 2001; Hixon & Jones, 2005; Ward et al., 2006; Hilborn, 2011; Link & Auster, 2013
	II	BRPs inaccurate if not included	Hollowed et al., 2000b; Mace et al., 2001; Caddy, 2004; Mangel & Levin, 2005; Baskett et al., 2006, 2007; Ward et al., 2012
	III	Invasive species (blooms) can impact food webs	Walton et al., 2002; Strayer et al., 2004; Geiger et al., 2005; Byrnes et al., 2007; Blamey et al., 2010; Pinnegar et al., 2014; Arndt et al., 2018; Pedersen et al., 2018
	IV	Invasive species control measures can be useful	Taylor & Hastings, 2004; Anderson, 2005; Simberloff et al., 2005; Hastings et al., 2006; Williams & Grozholz, 2008; Clout & Williams, 2009; Pyšek & Richardson, 2010; Buhle et al., 2012; de Leon et al., 2013; Green et al., 2014; Januchowski-Hartley et al., 2018
	V	Consider spatial management or adjusted BRPs/assessment models if competition suspected	Booth, 2000; Punt, 2010; Froese et al., 2011; Goethel et al., 2011; Fulton et al., 2014; Punt et al., 2014; Grüss et al., 2016; Ono et al., 2017; Rindorf et al., 2017a, b; Holsman et al., 2018; Thorson & Haltuch, 2018; Thorson, 2019
	VI	Multispecies HCR to deal with competing species	Witherell et al., 2000; Mueter & Megrey, 2006; Smith et al., 2008; Worm et al., 2009; Punt, 2010; Gaichas et al., 2012; Fulton et al., 2014; Kang et al., 2018; Ono et al., 2017; Rindorf et al., 2017a, 2017b; Link, 2018
Disease/Parasite			
	I	Presence of disease/parasites usually quite definitive diagnostics	Meyer, 1991; Kuris & Lafferty, 1992; Reno, 1998; Wahle et al., 2009; Wilberg et al., 2011; Lafferty et al., 2015
	II	Disrupt disease vector an option	Kuris & Lafferty, 1992; Chai et al., 2005; Bricknell et al., 2006; Torrissen et al., 2013
	III	Disrupt parasite life history an option	dos Santos et al., 2011; Cable et al., 2017
	IV	Fish consumption moratoria due to metals or organochlorines	Cunningham et al., 1994; Suedel et al., 1994; Kennish & Ruppel, 1996; Kennish & Ruppel, 1998; Gray, 2002; Jakus et al., 2002; Knap et al., 2002; Basra et al., 2018

	V	Fish consumption moratoria due to disease outbreaks	Watkins et al., 2008; Pintó et al., 2009; Etheridge, 2010; Polo et al., 2010; Fleming et al., 2011; Froelich & Noble, 2016
	VI	Accounting for disease mortality in LMR population dynamics can be advisable	Francis, 1992; Kuris & Lafferty, 1992; Patterson, 1996; Marty et al., 2003; Deriso et al., 2008; Wilberg et al., 2011; Ben-Horin et al., 2016; Legault & Palmer, 2016; Hoenig et al., 2017; Schulte, 2017
Habitat			
	I	Site fidelity of taxa important to determine effect of any habitat change on LMR	Langton et al., 1996; Gregory & Bisson, 1997; Rogers & Beets, 2001; Armstrong & Falk-Petersen, 2008; Wilson et al., 2008b; Wilson et al., 2010
	II	Habitat importance less pronounced for taxa with low site fidelity	Fahrig 1998; Wilson et al., 2006; Lederhouse & Link, 2016; Pandit et al., 2009
	III	Specific habitat requirements can create populationbottlenecks	Gregory & Bisson, 1997; Halpern et al., 2004; Wilson et al., 2006, 2008a; Pandit et al., 2009
	IV	Misspecfied population dynamics possible if not included	Barbier, 2000; Armstrong & Falk-Petersen, 2008; NMFS, 2010; Peters et al., 2018; Thorson, 2019
	V	Consider spatial management or spatial stock assessment	Turner et al., 1999; Booth, 2000; Rogers & Beets, 2001; Cadrin & Secor, 2009; Goethel et al., 2011; Eero et al., 2012; Kritzer & Liu, 2014; Little et al., 2015; Hazen et al., 2018; Dubik et al., 2019; Thorson, 2019
	VI	Reducing habitat pressure or restoration	Langton et al., 1996; Gregory & Bisson, 1997; Turner et al., 1999; Berkes et al., 2001; Rogers & Beets, 2001; McHugh et al., 2004; Fletcher, 2005; Mora et al., 2009; Beck et al., 2011; Dunn et al., 2011; Beechie et al., 2013; Lederhouse & Link, 2016
	VII	Consider habitat-linked assessment model	Hayes et al., 1996; Jones et al., 1996; McHugh et al., 2004; Goethel et al., 2011; Kritzer & Liu, 2014
	VIII	Broader benefits of habitat restoration	Rozas et al., 2005, 2007; Elliott et al., 2007; Grabowski & Peterson, 2007; Beck et al., 2011; Scyphers et al., 2011; Lederhouse & Link, 2016

Major Consideration	#	Detailed Consideration or Specific Effect	References
EAFM			
	I	Many factors impact LMR populations	Patin, 1982; Clark et al., 1989; Edwards & Richardson, 2004; Harley et al., 2006; Halpern et al., 2008; Cheung et al., 2010; Hoegh-Guldberg & Bruno, 2010; Link et al., 2012a; Boyd et al., 2015; Halpern et al., 2015
	II	General EAFM/EBFM descriptions	Larkin, 1996; Link, 2002a; Pikitch et al., 2004; Garcia & Cochrane, 2005; Francis et al., 2007; Fogarty, 2014
	III	EAFM/EBFM has benefits	Botsford et al., 1997; Hall & Mainprize, 2004; Pikitch et al., 2004; Essington & Punt, 2011; Fogarty, 2014; Fulton et al., 2014; Patrick & Link, 2015; Ballesteros et al., 2018; Link, 2018; Fulton et al., 2019
	IV	Many objectives face fisheries	Botsford et al., 1997; Link 2002b, 2010; Hilborn, 2011; Fogarty, 2014; Fulton et al., 2014; Micheli et al., 2014; Andersen et al., 2015; Patrick & Link, 2015; Marshall et al., 2017; Link, 2018; Link & Marshak, 2019
	V	EAFM needs operational guidance	Garcia & Cochrane, 2005; Appeldoorn, 2008; Pitcher et al., 2009; Hilborn, 2011; Cowan et al., 2012; Levin et al., 2013; Fulton et al., 2014; Long et al., 2015; NMFS, 2016a, b; Skern-Mauritzen et al., 2016; Ballesteros et al., 2018; Marshak et al., 2017; Levin et al., 2018; Link et al., 2018; Marshall et al., 2017, 2018; Rudd et al, 2018; Skern-Mauritzen, et al., 2018; Link & Marshak, 2019
	VI	Common LMR management measures	Caddy, 1999; Restrepo & Powers, 1999; Smith et al., 1999, 2007; Sutinen, 1999; Charles, 2001; Mace et al., 2001; Babcock et al., 2007; Dankel et al., 2008; Punt, 2010; Hilborn, 2011; Crosson, 2013; Methot et al., 2014; Hilborn et al., 2015; Lynch et al., 2018
	VII	Sustainable fisheries result from appropriately lowering BRPs	Caddy & Agnew, 2004; Rosenberg et al., 2006; Hilborn, 2010; Methot et al., 2014; Rindorf et al., 2017a, b

	VIII	Options to further implement EAFM	Garcia & Cochrane, 2005; Smith et al., 2007; Appeldoorn, 2008; Pitcher et al., 2009; Hilborn, 2011; Cowan et al., 2012; Fulton et al., 2014; Link & Browman, 2014; Long et al., 2015; NMFS, 2016a; b; Ramirez-Monsalve et al., 2016; Marshak et al., 2017; Levin et al., 2018; Link et al., 2018; Marshall et al., 2017, 2018; Rudd et al, 2018; Link & Marshak, 2019
Monitoring			
	I	Basic fishieres monitoring needed	Gulland, 1970; Smith, 1994, 2002; Stefansson, 1996; Maunder & Punt, 2004; McClatchie et al., 2014; Hughes et al., 2017
	II	Biological sampling needed	Gunderson, 1993; Murphy & Willis, 1996; Pennington & Strømme, 1998; Anderson, 2002; Smith, 2002; ICES, 2004; Kimura & Somerton, 2006
	III	Multidisciplinary sampling needed	Smith, 2002; Nicholson & Jennings, 2004; Link et al., 2008; McClatchie et al., 2014; Lynch et al., 2018
	IV	Other physcial measures to consider as part of monitoring/observing system	Mugo et al., 2010; Manderson et al., 2011; Kohut et al., 2012; Borja et al., 2013; Malone et al., 2014; McClatchie et al., 2014; Alin et al., 2015; NOC, 2016; Benson et al., 2018; Miloslavich et al., 2018; Muller-Karger et al., 2018
Risk (based approaches)			
	I	Assessing risk to LMRs due to fishing	Francis, 1992; Rosenberg & Restrepo, 1994; Peterman & Anderson, 1999; Hilborn et al., 2001; Stobutzki et al., 2001; Peterman, 2004, 2009; Hobday et al., 2004, 2007, 2011; Fletcher, 2005; Smith et al., 2007; Patrick et al., 2010; Collie et al., 2012; Cormier et al., 2013; Micheli et al., 2014; Holsman et al., 2017; Lockerbie et al., 2017; Stelzenmuller et al., 2018; Lynch et al., 2018
	II	Assessing risk to LMRs due to climate change	Williams et al., 2008; Cochrane et al., 2009; Preston et al., 2011; Foden et al., 2013; Gaichas et al., 2014, 2016; Hare et al., 2016
	III	Assessing risk to ecological dynamics	Kolar & Lodge, 2002; Forbes et al., 2011; Hobday et al., 2007, 2011; Le Quesne & Jennings, 2012; Lockerbie et al., 2018

IV	Assessing risk to habitat loss	Penney & Guinotte, 2013; Arkema et al., 2014; Seitz et al., 2014; Gaichas et al., 2016
V	Broader risk considerations for LMRs	Parent & Schriml, 1995; Dulvy et al., 2004; Graham et al., 2011; Burgess et al., 2013; Cormier et al., 2013; Zhou et al., 2016; Holsman et al., 2017; Lynch et al., 2018
VI	Management of risk an imporant part of fisheries management	Francis, 1992; Smith et al., 1993; Peterman & Anderson, 1999; Hilborn et al., 2001; Stobutzki et al., 2001; Peterman, 2004, 2009; Hobday et al., 2004, 2007, 2011; Fletcher, 2005; Smith et al., 2007; Patrick et al., 2010; Collie et al., 2012; Cormier et al., 2013; Hare et al., 2016; Holsman et al., 2017; Lockerbie et al., 2018; Stelzenmuller et al., 2018
VII	Many extant methods to evaluate risk for LMRs	Dulvy et al., 2004; Fletcher, 2005; Jiao et al., 2005; Hobday et al., 2011; Burgess et al., 2013; Cormier et al., 2013; Hare et al., 2016; Zhou et al., 2016; Holsman et al., 2017; Lockerbie et al., 2018

Table 2. Diagnostic table listing population features (rows) indicative of possible mechanisms (columns) influencing LMR populations. A minus sign indicates a negative effect, a plus sign indicates a positive effect, a zero indicates no effect, and a question mark indicates that the effect is unknown relative to the possible mechanism. Different signs are also similarly shaded to facilitate comparison across mechanism. Those cells circled indicate population features that can particularly distinguish among mechanisms. In = increase, De = decrease.

	Potential mechanisms																		
Population feature	Overfishing			Location	Migration & Movement		Habitat quality		Habitat quantity		Competition		Prey abundance		Physiology		Predation		Disease and Parasites
	Recruitment	Growth	Ecosystem		Route	Timing	In	De	In	De	In	De	In	De	In	De	In	De	
Abundance	-	-	-	0	?	0	+	-	+	-	-	+	+	-	0	0	-	+	-
Biomass	-	-	-	0	0	0	+	-	+	-	-	+	+	-	+	-	-	+	-
Abundance at age	-	-	-	0	0	0	+	-	+	-	-	+	+	-	?	?	-	+	-
Size at age	0/-	-	-	0	0	0	+	-	+	-	--	+	+	--	+	-	+	-	0
Weight at length	0/-	-	-	0	0	0	+	-	+	-	-	+	+	-	+	-	+	-	0/?
Length frequency	-	-	-	0	0	0	+	-	+	-	-	+	+	-	?	?	+	+	-
Max L/ L infinity	-	-	-	0	0	0	+	-	+	0/-	-	+	+	-	?	-	0	+	-
Growth rate	0	-	-	0	0	0	+	-	+	-	-	+	+	-	+	-	+		-
Condition factor	0	-	-	0	+	0	+	-	+	-	-	+	+	-	+	-	0	0	-
Liver weight/HSI	0	-	-	0	?	0	0	-	0	-	-	+	+	-	+	-	0	0	-
Stomach weight	0	0	?/0	0	0	?	+	-	+	-	-	+	+	-	+	-	0	0	0
Diet composition	0	0	0/?	0	0	+	?	?	?	?	?	?	?	?	0	0	?	?	?
Median Age	-	-	-	0	0	0	+	-	+	-	-	+	+	-	?	?	-	+	-
Fecundity	+	0	-	0	0	0	+	-	+	-	-	+	+	-	+	-	0/+	0	-
Maturatiy (ogives)	-	0	-	0	0	0/-	0	-	0	-	-	+	+	-	+	-	0/+	0	-
Recruitment	-	-	-	0	0	0	+	-	+	-	-	+	+	-	+	-	-	+	-
Pathogen/parasite prevalence	0	0	-	?	?	?	?	-	?	-	0/+	-	-	0/+	?	?	0	0	+
Distribution	0	-	-	+/-	-	+	+	-	+	-	-	+	+	-	+	-	-	+	0
Range	-	-	-	+/-	-	0	+	-	+	-	++	-	-	+	+	-	-	+	+
Spawning initiation time	-	0/-	0	?	+	+	?	?	?	?	?	?	0	0	?	?	0	0	?
Spawning duration	-	0/-	0	?	+	0	+	-	+	-	-	+	+	-	-	+	0	0	-

Table 3. Case studies of example populations from the Northeast and Northwest Atlantic. Values indicate actual observed population responses in each situation. A minus sign indicates a negative effect, a plus sign indicates a positive effect, a zero indicates no effect, and a question mark indicates that the effect is unknown. Cells highlighted in shading indicate particularly distinguishing diagnostics.

Population feature	**Stocks/Regions**						
	Norwegian spring spawning herring	Northeast Atlantic mackerel	Blue whiting	Salmon	Northwest Atlantic herring	Northwest Atlantic mackerel	Gulf of Maine Cod
Ecosystem	**Norwegian Sea**	**Norwegian Sea**	**Norwegian Sea**	**Norwegian Sea**	**Northeast US Shelf**	**Northeast US Shelf**	**Northeast US Shelf**
Abundance	-	+	0	-	-	-	-
Biomass	-	+	0	-	-	-	-
Abundance at age	-	0/+	0	-	-	-	-
Size at age	-	0	-	+/-	0/-	-	-
Weight at length	0	-	0	0	0	0	-
Length frequency	+	0	+	0	0	-	-
Max L/ L infinity	0/+	0	0/+	0	0	-	0
Growth rate	?	0	+	+/-	?	?	-
Condition factor	-	0	-	+/-	0	0/-	-
Liver weight/HSI	0	?	?	0	?	?	?
Stomach weight	-	0/+	-	+/-	0	0	0
Diet composition	-	?	?	0	?	?	0
Median Age	-	0	-	0	-/0	-	-
Fecundity	-	0	?	0	?	?	?
Maturatiy (ogives)	-	0	-	0	-	-	?
Recruitment	-	+	+	-	-	-	-
Pathogen/parasite prevalence	0	0	0	+	?	?	?
Distribution	0	+	0	0	0	0	+
Range	0	+	0		0	0/-	0/+
Spawning initiation time	-	?	?	0	?	0	?
Spawning duration	-	?	?	0	?	0/-	?
Likely mechanism/Flow chart number	Prey Availibility/Competition, Predation, OF	Movement, Competition	Competition, Predation	Disease and Parasites	Predation, OF	Predation, OF	Shift in Location, OF

Figure Legends

Figure 1. Schematic of how major factors can impact key features of LMR populations. Which when diagnosed, suggest particular LMR management actions and options. LMR= living marine resource, HCR= harvest control rules, BRP= biological reference point, TAC= total allowable catch, SA = stock assessment, ID = identification, p*= probability of overfishing. We use the term Living Marine Resources (LMR) largely as a fish stock or population, but recognize that there can be other taxa that are harvested. Here we use the term "factors" as those facets of a marine ecosystem that respond to some larger-scale driver, but functionally can be thought of as synonymous to a "mechanism" or "process" that influences LMR populations. In the sense they negatively influence a population, we synonymously use the term "pressure." We use the term "features" as representative of those aspects of LMR populations that can be tracked to understand the potential causality of a population change, here used synonymously as "diagnostics". We use the term Living Marine Resources (LMR) largely as a fish stock or population, but again recognize that there can be other taxa that are harvested.

Figure 2. Change in movement and location. Flowchart for suggesting management or assessment action given changes in migration of a LMR population. Semicolons indicate alternative management actions.

Figure 3. Overfishing. Flowchart for suggesting management or assessment action given overfishing of a LMR population. Semicolons indicate alternative management actions.

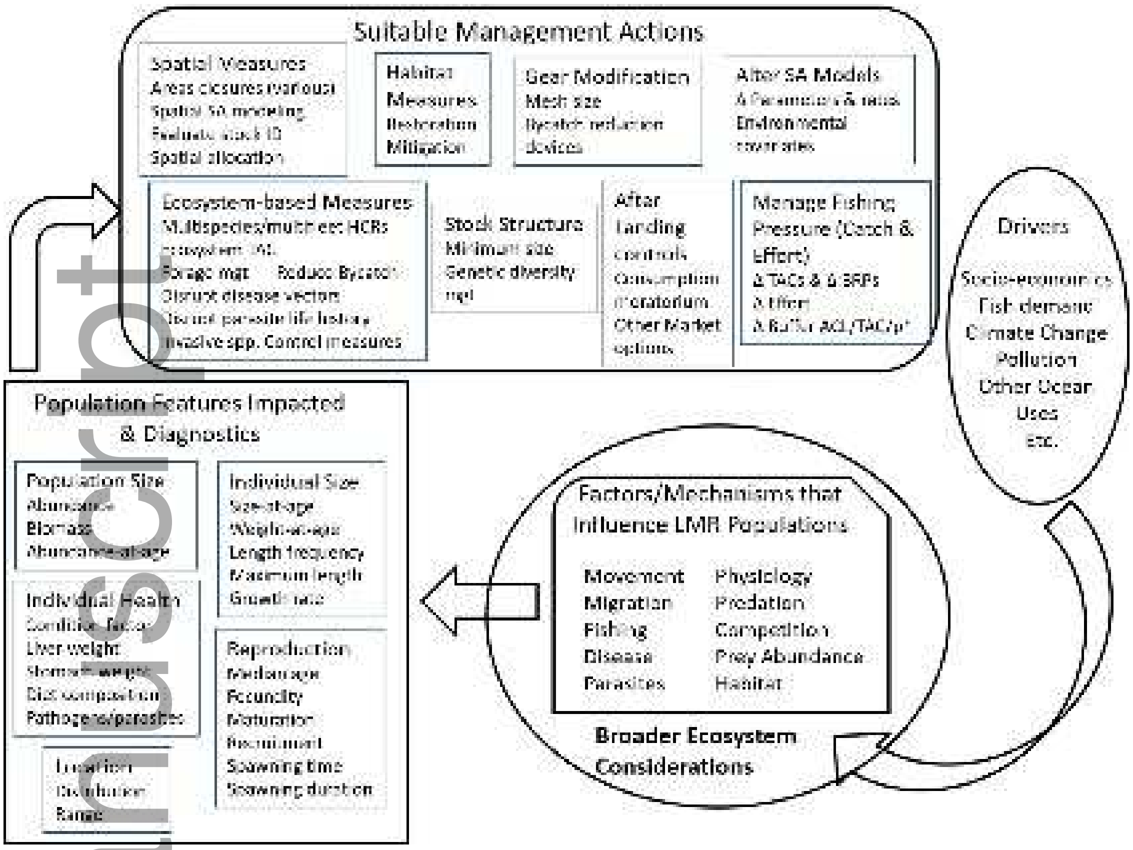
Figure 4. Change in physiology. Flowchart for suggesting management or assessment action given change in physiology of a LMR population. Semicolons indicate alternative management actions. Change in bold in the flowchart could either indicate decrease or increase depending on whether it relates a decline or an increase in physiological rates. Management actions in italic only refer to the cases where there is a decline in physiology.

Figure 5. Increase in predation. Flowchart for suggesting management or assessment action for increased predation on LMR populations. Semicolons indicate alternative management actions.

Figure 6. Increase in competition or decrease in prey. Flowchart for suggesting management or assessment action given competition and/or prey base of a LMR population. Semicolons indicate alternative management actions.

Figure 7. Increase in disease or parasitism. Flowchart for suggesting management or assessment action for disease outbreaks in LMR populations. Semicolons indicate alternative management actions.

Figure 8. Habitat change. Flowchart for suggesting management or assessment action given changes in habitat of a LMR population. Semicolons indicate alternative management actions.



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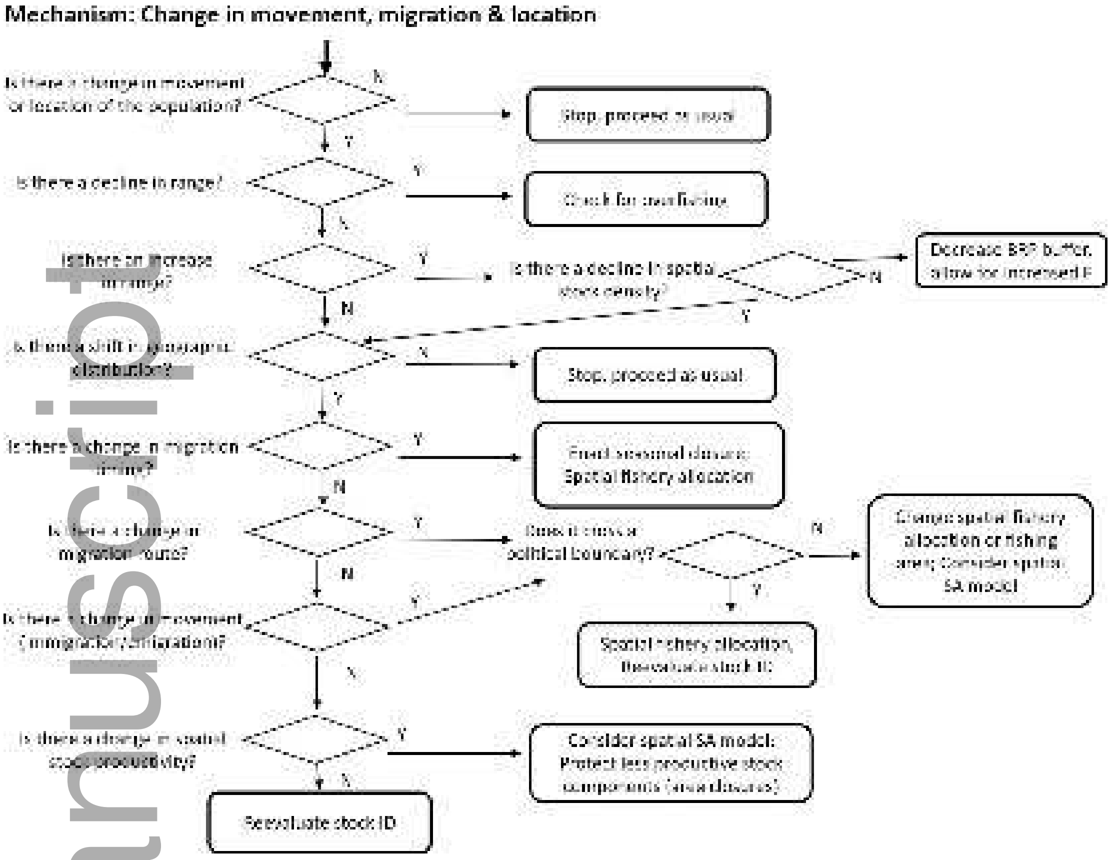

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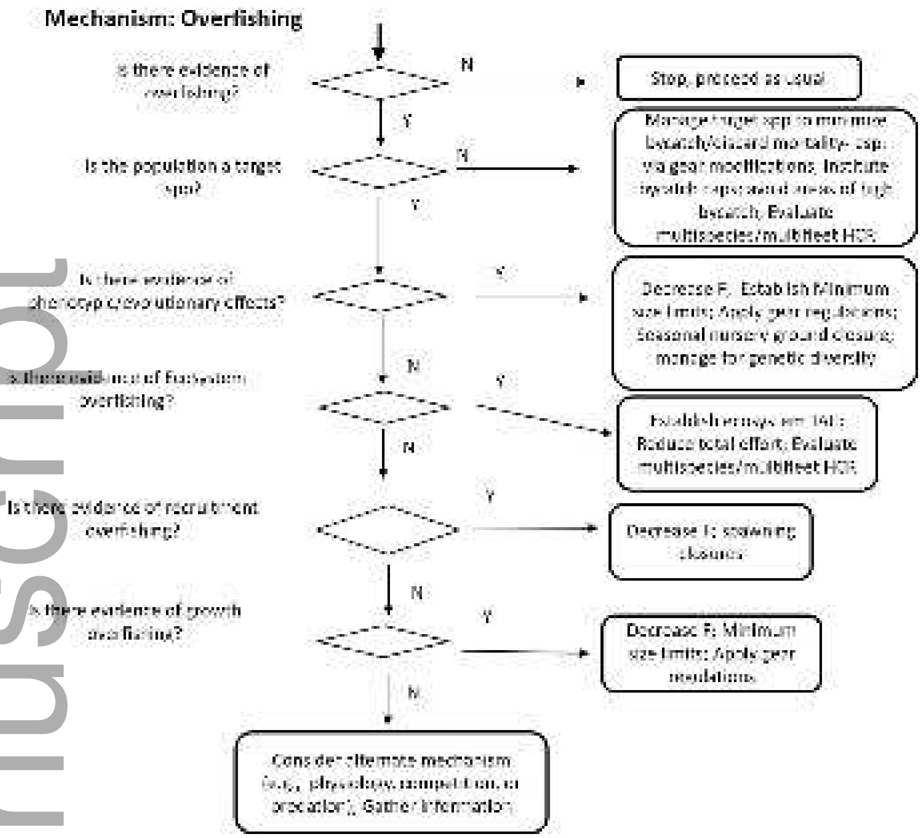

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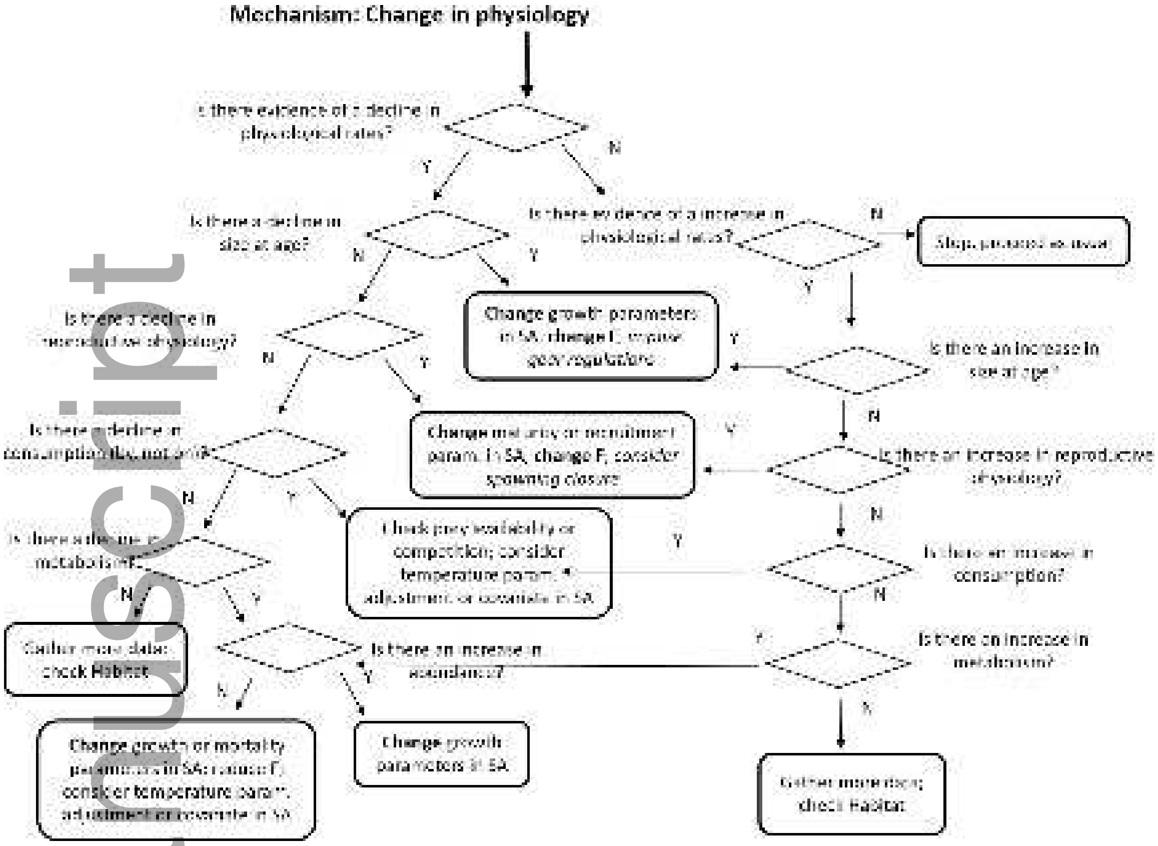

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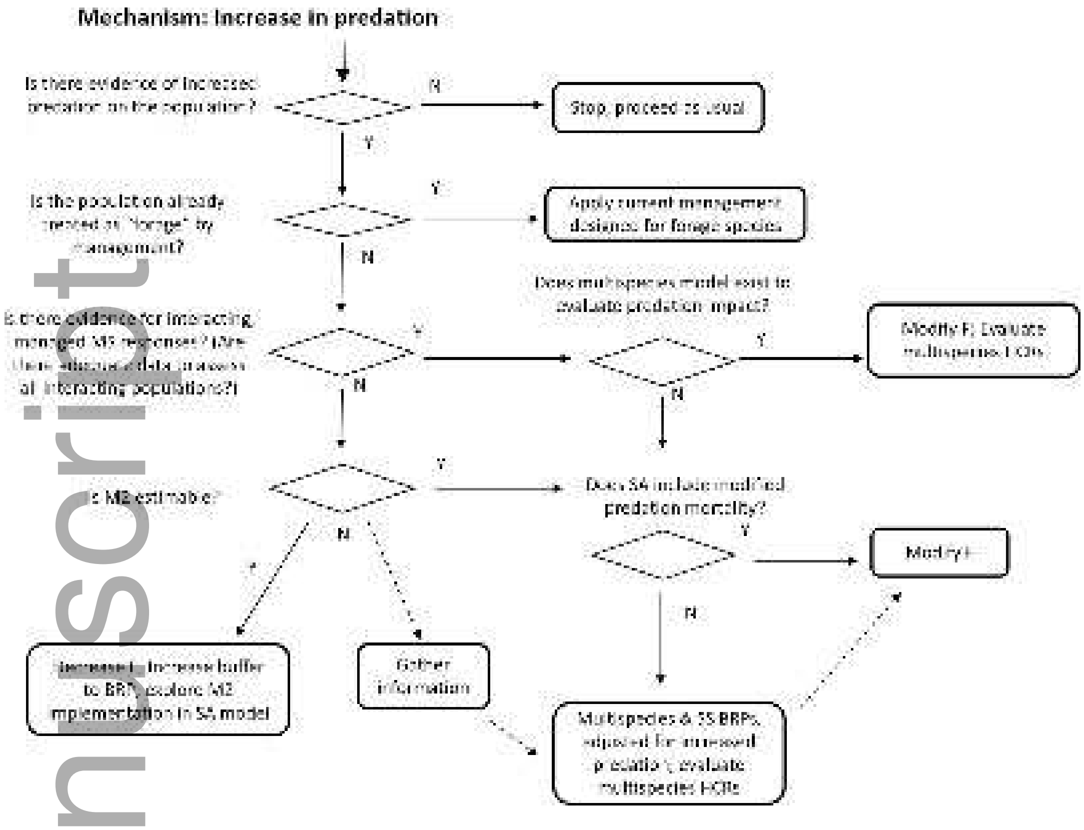

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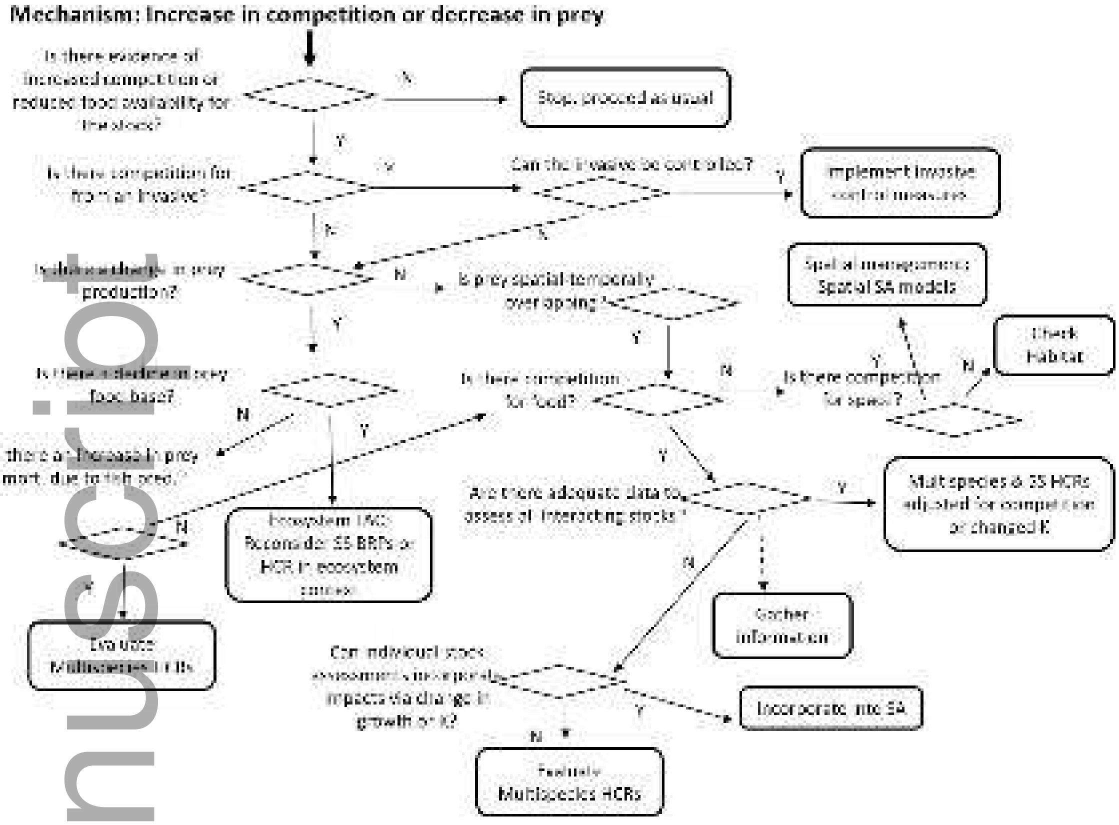

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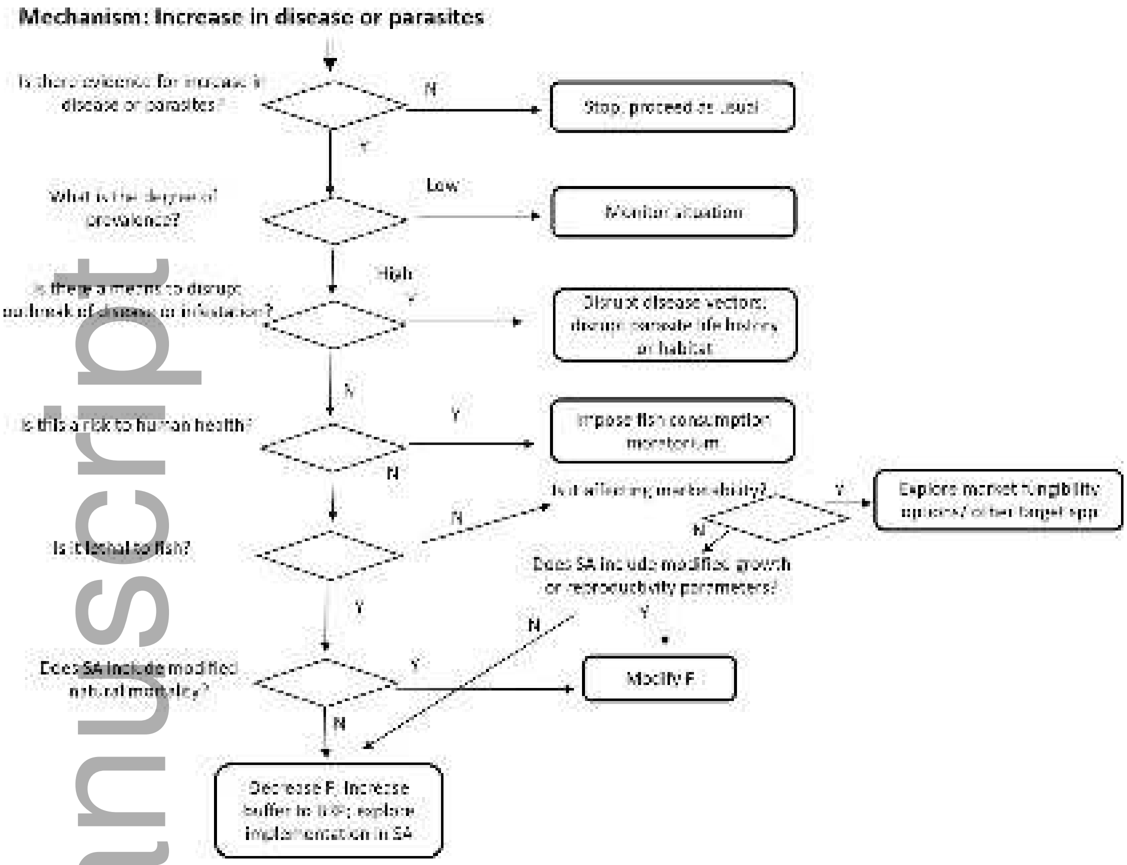

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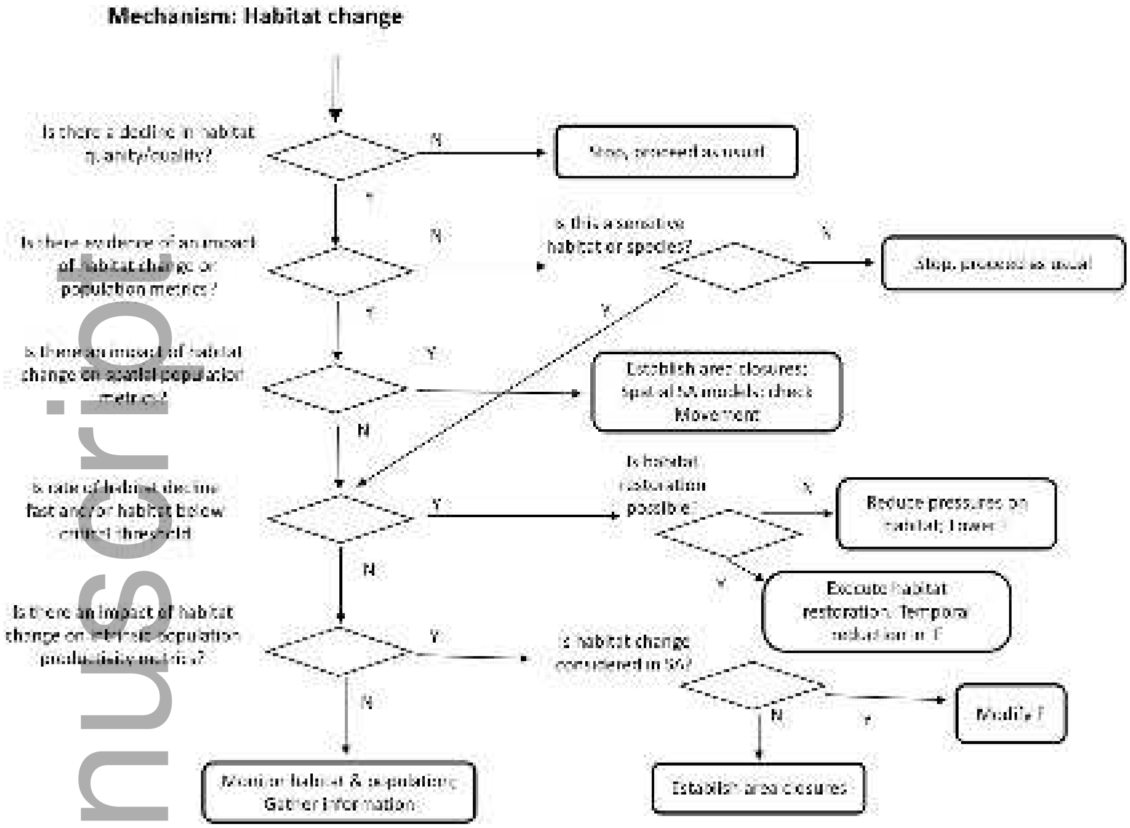

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