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Evaluation and optimization of a long-term fish monitoring program in the Hudson River

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ABSTRACT

Long-term monitoring programs are essential for understanding the dynamics of fish populations in freshwater ecosystems, which are threatened by anthropogenic change. Assessment of monitoring programs helps ensure that they continue to meet stated goals, but published assessments are rare. Here we use a power analysis to assess the three surveys that form the core of the Hudson River Biological Monitoring Program, one of the longest-running fish monitoring programs in the United States. All three surveys had substantial power to detect changes in young-of-year abundance for anadromous species of primary management interest and for a variety of other species with diverse life histories and habitat preferences. In particular, the Beach Seine Survey and Fall Juvenile Survey could reliably detect declines in abundance of 15–30% or more over ten years, while the Long River Ichthyoplankton Survey could reliably detect declines of 40–55% or more over ten years. Simulated reduction of sampling intensity to 75–25% of the historical level of effort in these surveys still yielded good power to detect change for many species, particularly for the Beach Seine and Fall Juvenile surveys. Power to detect change varied in freshwater and brackish portions of the river and across different habitat zones, as well as by survey and species. Our results provide guidance for the re-design of fish monitoring programs in the Hudson River following the recent cessation of the historical funding for those programs, and could serve as a useful model for assessing similar programs in large river and estuarine ecosystems around the world.

1. Introduction

Long-term monitoring programs provide the foundation of data needed to understand changes in fish populations and the effects of environmental perturbations and management actions. This is especially important in freshwater ecosystems, as they are some of the most impacted by anthropogenic change, subject to threats including invasive species, changing climate, sedimentation, and other environmental degradation (e.g., Reid et al., 2019). Long-term monitoring of these systems can provide knowledge of baseline conditions (Magurran et al., 2010) as well as provide an understanding of variability inherent in the system (George et al., 2021). However, if the monitoring program is weak or flawed, the data it provides may be unable to support these objectives, and even lead to erroneous conclusions and poor management.

In order to appropriately manage aquatic systems, decision makers need a way to reliably understand fluctuations in species abundance over time. The relationship between fish population dynamics and environmental quality may be highly complex, especially because multiple stressors often impact a population (Rose, 2000). Even without understanding the causal mechanisms behind population dynamics, monitoring can provide important insight into general trends. Long-term monitoring can also reveal the impacts of population change within and across species and evaluate the effectiveness of rehabilitation and restoration efforts on those populations (McClelland et al., 2012; Gibson-Reinemer et al., 2017). A more comprehensive understanding of the key patterns in fisheries can provide managers with the ability to set harvest regulations, schedule fishery openings, and protect or restore important habitat areas.

Regular assessments of monitoring programs are important for evaluating their ability to meet stated goals, but are rarely conducted. It has been suggested that fisheries monitoring programs should have

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explicit goals about the temporal trends they are monitoring and the statistical power at which they can detect those trends (Wagner et al., 2013). While most monitoring programs are designed to meet the specific management goals of the system (Vos et al., 2000), many times, there is no explicit evaluation of those monitoring programs. Indeed, published evaluations of the power of fisheries monitoring data sets are rare (Wagner et al., 2013). A clear, quantitative understanding of the ability of monitoring programs to meet expectations can provide decision makers with tools necessary to adjust the program, including not only scaling down or up, but also realigning the program to better meet expectations while retaining potentially valuable data (Levine et al., 2014). As we increasingly recognize the value of long-term monitoring programs (Lindenmayer et al., 2012), it is important to consider the balance between monitoring costs and meeting stated programmatic goals (Caughlan and Oakley, 2001; Strayer and Smith, 2003).

The Hudson River Biological Monitoring Program (HRBMP) is one of the longest running fish monitoring programs in the United States. The sampling of early life stages of Hudson River fish began in the late 1960 s to determine if the proposed Cornwall pumped storage facility and the Indian Point nuclear generating station cooling system would have an impact on striped bass populations (Barnthouse et al., 1988). This sampling was expanded in 1975 when the United States Environmental Protection Agency issued permits that, in effect, required the retrofitting of cooling towers at several Hudson River power plants (Butzel, 2011). The surveys became an annual requirement in 1980 as a result of a settlement agreement among Hudson River utility companies, state and federal regulators, and Hudson River NGOs. Funded by the electric power generating facilities, this comprehensive monitoring program has provided critical information on the status of Hudson River fish populations and the environmental and biotic factors that influence them. The closure and associated facility upgrades of the power generation facilities to minimize impacts to fish populations in recent decades has resulted in programmatic defunding in 2017 marking the conclusion of more than four decades of biological monitoring for one of the most iconic ecosystems in the United States. Initially, program goals included (1) evaluating the potential impacts power production would have on fish populations and the effectiveness of mitigation measures, (2) monitoring impingement and entrainment of fish at power plants, and (3) monitoring the status of Hudson River fish populations at all life stages (Barnthouse et al., 1988; Young and Dey, 2011). The long-term surveys implemented to address the third goal continued until 2017–2020. The data collected in this monitoring program have been widely used to understand the ecology of the Hudson River. Examples of their use include understanding fish abundance and distribution with regards to salinity and temperature gradients (e.g., Singkran and Bain, 2008), habitat use (e.g., O'Connor et al., 2012a), fluctuations due to climate change (O'Connor et al., 2012b; Strayer et al., 2014a; Nack et al., 2019), movement of eggs and larvae (Boreman and Klauda, 1988; Englert and Sugarman, 1988; Schmidt, 1992; Schultz et al., 2005; Dunning et al., 2006; Dunning et al., 2009), and the impacts of invasive zebra mussels on early life stages of fishes (Strayer et al., 2004; Strayer, 2009; Strayer et al., 2014b).

In this paper, we assess the ability of one of the longest running fish monitoring programs in the United States to meet one of its primary goals: detecting changes in fish abundance. As the funding from the utilities for this monitoring program has recently concluded, there is a critical need to evaluate and optimize the HRBMP to provide guidance to sustain this valuable monitoring program. We used a power analysis method to assess the ability of long-term data to meet the goal of detecting changes in fish abundance. Specifically, we assessed the ability of three major components of the HRBMP, the Beach Seine Survey (BSS), the Fall Shoal Juvenile Survey (FJS), and the Long River Ichthyoplankton Survey (LRS) to detect declines in abundance. We further used the spatially explicit data to understand the role that sample distribution plays in the ability to detect changes in abundance. Finally, in all monitoring programs, there is a need to understand the balance between costs of monitoring and long-term benefits. To address this, we evaluated the effectiveness of decreasing sampling effort in meeting monitoring goals through simulated subsampling. This exercise allowed for exploration of potential aspects of the HRBMP that can be optimized to decrease overall costs while maintaining the ability to detect changes in species abundance.

2. Methods

For this analysis, we considered four 'focal' species of direct management interest (Striped Bass *Morone saxatilis*, American Shad *Alosa sapidissima*, Alewife *Alosa pseudoharengus*, and Blueback Herring *Alosa aestivalis*), and six 'non-focal' species that are important in the river but not of primary management interest (Atlantic Tomcod *Microgadus tomcod*, Bay Anchovy *Anchoa mitchilli*, Channel Catfish *Ictalurus punctatus*, Spottail Shiner *Notropis hudsonius*, White Catfish *Ameiurus catus*, and White Perch *Morone americana*). Non-focal species were selected to allow us to evaluate the monitoring program across a variety of life histories and distributions. With the exception of Channel Catfish, all of the species that we considered are native to the Hudson River Estuary (Waldman et al., 2006).

2.1. Study site

Sampling was conducted by the HRBMP on the tidal portion of the Hudson River which extends south from the Federal Dam at Troy, NY to the Battery in Manhattan (Fig. 1; Barnthouse et al., 1988; Young and Dey, 2011). The monitoring program divided a 240 km section of river into 13 regions and each region was further divided into strata (shore, shoal, channel, bottom) based on geomorphology and river depth. The program defined the shore as the portion of the river from the shoreline to a depth of 10-ft (3.1 m), the shoal as the area extending from the shore to a depth of 20-ft at mean low tide, the bottom as the area from the river

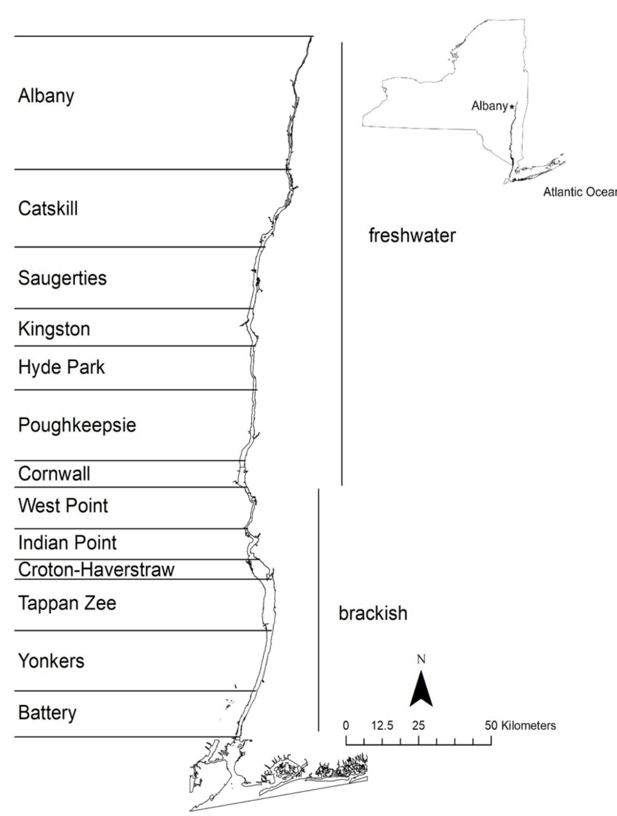

Fig. 1. Location of the Hudson River and sampling regions as defined by the Hudson River Biological Monitoring Program.

bottom to 10-ft above the bottom in those areas where river depth is greater than 20-ft at mean low tide, and the channel as the area that is not considered bottom where river depth is greater than 20-ft at mean low tide. The Hudson River has a moderate salinity gradient which is influenced by freshwater flow and to a smaller extent by spring and neap tides (Wells and Young, 1992; Geyer et al., 2006). The location of the salt front (where chloride concentration = 100 mg/L) fluctuates seasonally; the river is generally considered brackish downstream of West Point.

2.2. Monitoring program

While the overarching goals of the monitoring program were to monitor distribution and abundance of fish in the Hudson River, each individual survey had specific stated goals and methods. All surveys used a stratified random design with sampling locations allocated by region and available strata.

The goal of the Beach Seine Survey (BSS) was to monitor the distribution and abundance of juvenile fish in shallow near-shore areas in the Hudson River. The BSS occurred annually in the mid-summer and fall, with sampling occurring every other week, for a total of 10 weeks. Each sampling week included 100 samples collected from the shore stratum with a 100′ (30.48 m) beach seine.

The goal of the Fall Juvenile Survey (FJS) was to monitor the distribution and abundance of juvenile fish in off-shore habitats in the Hudson River. The FJS occurred annually in the mid-summer and fall, with sampling occurring every other week, for a total of about 11 weeks, with some variance across years. Each sampling week included 200 samples collected from shoal, bottom, and channel strata. The channel stratum was sampled with a 1 m^2 Tucker trawl (3.0 mm mesh), while the shoal and bottom strata were sampled with a 3 m beam trawl (3.8 cm mesh with 1.3 cm mesh codend).

The goal of the Long River Ichthyoplankton Survey (LRS) was to monitor the distribution and abundance of fish eggs and larvae in the Hudson River. This survey occurred every other week beginning early in the year, weekly from mid-spring to early-fall, and every other week into late-fall annually (around 23 weeks per year). Each sampling week included 100–200 samples collected in shoal, bottom, and channel strata. Gear used for this survey included 1 m^2 epibenthic sled used to sample the bottom strata and a 1 m^2 Tucker trawl for the channel and shoal strata, both of which were equipped with a 0.5 mm mesh. Samples were then processed in the laboratory for larval identification.

2.3. Statistical analysis

We used power analyses to determine the ability of the surveys to detect changes in population abundance through time for the focal and non-focal species, using the powertrend function in R (Gerrodette, 1987; R Development Core Team, 2018). We used a power level of 80 (as in Wagner et al., 2013), a significance level of $\alpha = 0.05$ for a one-tailed test, and a time span of 10 years (as in ASMFC, 2020); that is, we sought to identify the smallest decrease in abundance over 10 years that could be detected 80% of the time at $\alpha = 0.05$. Power to detect increases in abundance was consistently slightly worse than power to detect declines in abundance, but the qualitative patterns were similar, so for simplicity, we only present results of analyses considering declines in abundance. Our power analysis assumed additive errors and variance proportional to the mean (i.e., pserel = 1), as is recommended for CPUE-type data (Gerrodette, 1987). To avoid issues related to changes in survey methodologies over time, we restricted the set of years over which we made these calculations to 1989–2013 for the BSS and to 1979–2013 for the FJS and LRS. We considered the ability to reliably detect a 50% decline in abundance over 10 years as a minimum threshold for acceptable power, and use this threshold as a reference in reporting results.

The raw data for the power analysis are sample-level counts of fish abundance per cubic meter for the FJS and fish abundance per haul for the BSS. For the LRS, field samples were aggregated before lab processing and split into subsamples based on volume. A minimum of 6 subsamples per region and habitat stratum for each week were assessed, and then individuals were identified and counted from this subsample of the aggregated sample. For each species in each survey, we calculated the mean abundance in each year by averaging the volume/haul standardized fish counts, and the coefficient of variation (CV) in each year as the standard error of all the samples divided by the mean. We then determined the median of the set of interannual CVs, to get the "proportional standard error", the measure of variability that is used in the power analysis. The median interannual CV was used to describe interannual variability in abundance across the survey (as in ASMFC, 2020).

We focused our analyses on young-of-year fishes. The BSS and FJS target both young-of-year and yearling fishes, but young-of-year comprise the majority of the total catch. The LRS targets early life stages including eggs, yolk-sac larvae, and post-yolk-sac larvae, and also catches young-of-year and yearling. Our preliminary analyses demonstrated very little ability to detect changes in abundance in the early life stages (i.e., eggs and yolk-sac larvae), due to high intra-annual variation in those life stages (see also Klauda et al., 1988, Appendix B). Therefore, we focused our analyses of the LRS data on the young-of-year age class, as in our analyses of the other surveys.

As one of the stated goals of the monitoring program was to understand patterns of fish distribution, we conducted a coarse distribution power analysis to look at different sections of the river. Data were split into freshwater and brackish water, and power analyses run on these individual portions of the river. We divided the freshwater portions of the river (Albany to Cornwall) and brackish water (West Point to Battery) at RKM 88.5. We additionally split the data for the FJS by habitat stratum sampled (channel, shoal, and bottom) to understand the physical space in the river in which fish reside. For this analysis, we used the same power analysis methods as above with the subset of data.

2.4. Subsampling and optimizing

We simulated reductions in sampling effort to understand the impact of such reductions on the ability to detect changes in abundance for both focal and non-focal species. Decreased sampling effort was simulated for reductions of 25%, 50% and 75% of historical effort. Reduced sampling was simulated by bootstrapped subsampling (iterations = 1,000) using the total number of samples (with replacement) constrained by river region and year. In essence, this exercise allowed us to retain the overall structure of the surveys (i.e., timeframe, sample distribution, etc.) while decreasing overall number of samples proportionally within each river region. This allowed for incorporation of intra-annual variation within the data while retaining the stratified random design based on the number of sampling locations per region. Power analyses were then conducted using the procedure described above on the bootstrapped data.

3. Results

The three surveys provided qualitatively similar descriptions of trends in abundance for most of the species that we considered (Fig. 2). The only notable exception to this pattern was the Bay Anchovy, for which the FJS and LRS showed opposite trends in abundance, while the BSS showed high levels of variance and no strong trend. The abundance of American Shad, Atlantic Tomcod, and Blueback Herring declined over the study period, while the abundance of Channel Catfish increased. Most other species, though they exhibited substantial interannual variation in abundance, did not exhibit long-term increasing or decreasing trends.

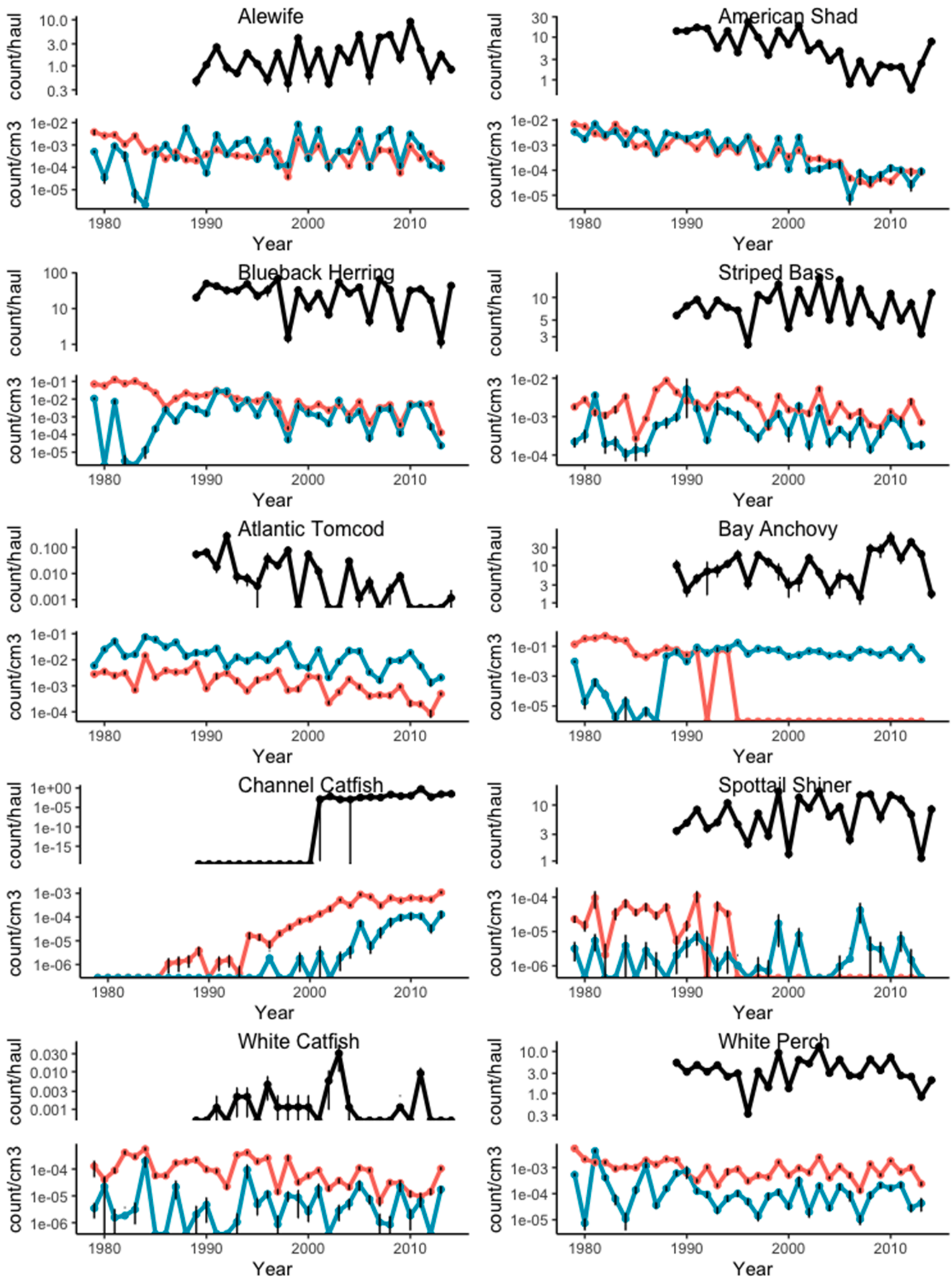

Fig. 2. Mean (±SE) young-of-year sampling abundance over time for the four focal species and six non-focal species for the Beach Seine Survey (BSS; black), the Fall Juvenile Survey (FJS; red), and the Long River Ichthyoplankton Survey (LRS; blue). For the BSS, mean sampling abundance is estimated as the mean catch per haul while for the FJS and the LRS sampling abundance is estimated as mean catch per cubic centimeter. Note that the y-axis is on a logarithmic scale and varies across species. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

3.1. Abundance monitoring

The BSS, at its full historical sampling intensity, could reliably detect decreases in abundance as small as 15–25% over a decade for our focal species (Fig. 3A). It performed similarly well for White Perch, Spottail Shiner, and Bay Anchovy, but for the other non-focal species declines had to be quite large to be reliably detectable (75% for Atlantic Tomcod) or were not reliably detectable at any level (Fig. 3B).

The FSS, at its historical sampling intensity, could reliably detect decreases in abundance as small as 20–30% over a decade for our focal species (Fig. 3B). It performed similarly well for most of the other species that we considered, with the exception of Spottail Shiner and to a lesser extent Channel Catfish, for which declines had to be 65% over a decade to be reliably detectable.

The LRS, at its historical sampling intensity, could reliably detect decreases in abundance as small as 40–55% over a decade for our focal species (Fig. 1C). It performed similarly well or even better for some of the non-focal species, like Atlantic Tomcod, Bay Anchovy, and White Perch, but very poorly for others. The species for which the smallest change in abundance was detectable was Bay Anchovy, where a 27% decrease in abundance was detectable. The LRS rarely sampled species such as White Catfish and Spottail Shiner, and consequently was unable to detect changes in abundance in those species.

In comparing the three surveys, we found fairly consistent patterns in their ability to detect changes in abundance, with some notable exceptions (Fig. 3). For example, the FJS is better at detecting changes in abundance for species such as Alewife, Atlantic Tomcod, and Bay Anchovy. However, this trend is not consistent for all species, with small changes in abundance being detectable in the BSS for species such as American Shad and Spottail Shiner. For some species, such as Atlantic Tomcod and Bay Anchovy, the LRS outperforms the BSS in ability to detect changes in abundance.

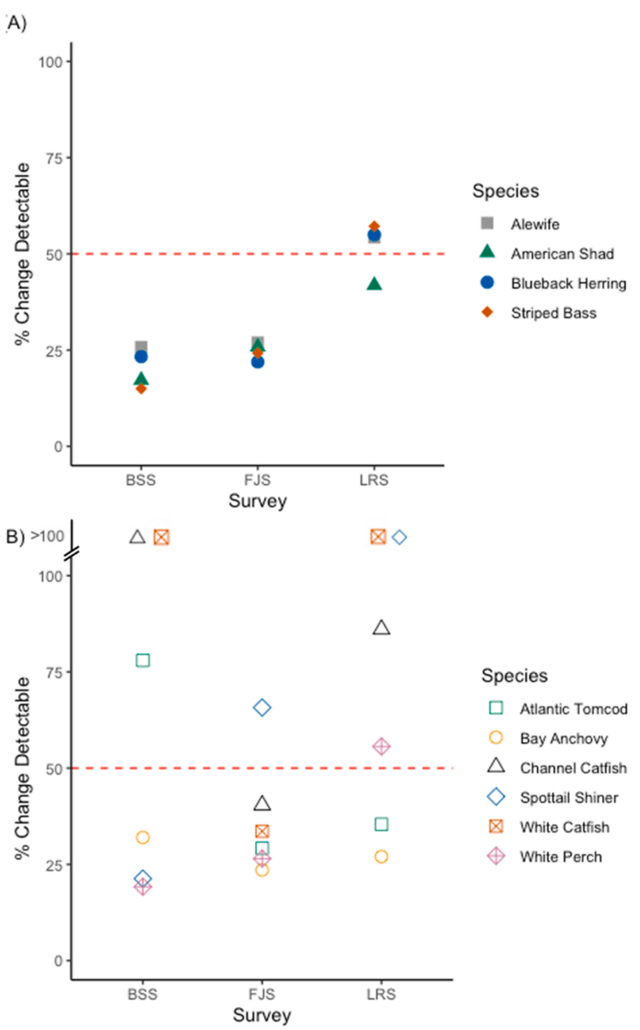

Fig. 3. Ability to detect decreases in abundance at full sampling effort for (A) focal species and (B) non-focal species across three surveys: The Beach Seine Survey (BSS), Fall Juvenile Survey (FJS), and Long River Ichthyoplankton Survey (LRS). Plots show the smallest change in abundance over ten years that is detectable with a power level of 80% at $\alpha = 0.05$. For some non-focal species-survey combinations, power analysis indicated that only a greater than 100% decline in abundance would be detectable. Dashed red line indicates a 50% decline in abundance. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

3.2. Species distributions

To evaluate the effectiveness of monitoring species that span different life histories and distributions, we sought to understand the ability of these surveys to capture variation across fresh and brackish portions of the river, as well as across the different strata sampled. In general, data from the freshwater reach were better able to detect trends in abundance for White Catfish, Channel Catfish, White Perch, and Spottail Shiner than the brackish reach. In the brackish reach of the river, changes in abundance were more readily detectable for Atlantic Tomcod and Bay Anchovy than the freshwater reach (Tables A.1–3). For the FJS, there is no ability to detect changes in abundance for Channel Catfish and Spottail Shiner in the brackish reach of the river. In our evaluation of distribution within the water column (i.e., evaluation among strata), we found that the stratum in which the FJS has the strongest ability to detect changes in abundance was the bottom (Fig. 4). Within the channel strata, there were only two species for which we could detect a decrease in abundance of less than 50% (Alewife and Blueback Herring). In the shoal, the FJS can only detect decreases in abundances of less than 50% for two species, American Shad and Striped Bass.

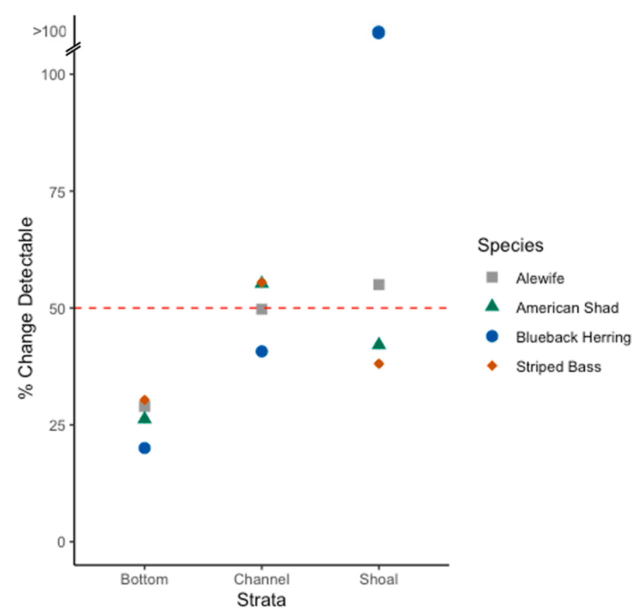

Fig. 4. For the FJS strata, smaller decreases in abundance are detectable in the bottom stratum than in the channel or shoal. For the shoal, there is no ability to detect a less than 100% decrease in blueback herring abundance. Plot shows the strata subset for the FJS for the entire river for the four focal species. Dashed red line indicates a 50% decline in abundance. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

3.3. Optimization

Simulated reductions in sampling intensity revealed that it would be possible to reduce sampling intensity (in some instances by up to 75%) without greatly limiting the ability to detect decreases in abundance. For the BSS, a 50% or less decline in abundance was reliably detectable for all focal species when we reduced sampling intensity to half of its historical level, and was still detectable for American Shad, Blueback Herring, and Striped Bass even when sampling intensity was reduced to 25% of its historic level (Fig. 5A). Among non-focal species in the BSS, a 50% decline was only detectable for White Perch, Spottail Shiner, and Bay Anchovy when sampling intensity was reduced to half of its historical level (Fig. 5E). For the FJS, a 50% or less decline in abundance in any of the focal species was reliably detectable when we reduced sampling intensity to 25% of its historical level, the lowest level of sampling intensity that we considered (Fig. 5B). A 50% decline in abundance of most of the focal species for the LRS was not reliably detectable when we reduced sampling intensity even to 75% of its historical level (Fig. 5C).

4. Discussion

Regular assessment of existing fisheries monitoring programs can help ensure that they continue to meet their objectives, assess those objectives, and address important questions in science and management (Vos et al., 2000; Lindenmayer and Likens, 2009; Lindenmayer and Likens, 2010). Yet such assessments are relatively rare, particularly in the peer-reviewed literature. Indeed, Wagner et al. (2013) found only nine studies which quantitatively assessed the ability of fisheries monitoring programs to monitor changes in abundance. Assessing a monitoring program requires time and money, and implies an institutional willingness and ability to make potentially substantive changes in priorities and procedures. Both of these requirements probably limit the frequency with which monitoring programs are assessed.

Our assessment in this paper was catalyzed by the impending termination of the funding for the HRBMP after more than four decades. As stakeholders considered how to design and fund a continuation of the HRBMP, there was a clear need to assess the existing program. Our analysis highlights some of the strengths and limitations of the HRBMP for meeting its objective of detecting changes in fish abundance, which we discuss below. Building from this discussion, we then reflect more broadly on possible modifications to the program's design and objectives in the context of changes in the natural environment and the funding environment.

4.1. Detecting changes in abundance: Strengths and limitations of the historical monitoring

All three of the HRBMP surveys that we considered have substantial power to detect changes in abundance of young-of-year fishes. This level of power seems to be rare in freshwater fisheries monitoring programs. Wagner et al. (2013) summarized the statistical power to detect change in biological indicators of seven freshwater fishery surveys. They found that power to detect trends in abundance relied more on among-year variation and number of years sampled than among-site variation and number of sites sampled, providing valuable insight into understanding how decreased sampling can still result in an effective monitoring program. The surveys reviewed in Wagner et al. (2013) were all found to have reduced or similar power when compared to the ability to detect change we found in the HRBMP surveys. The high power of the HRBMP surveys stems from the length of the program coupled with intensive

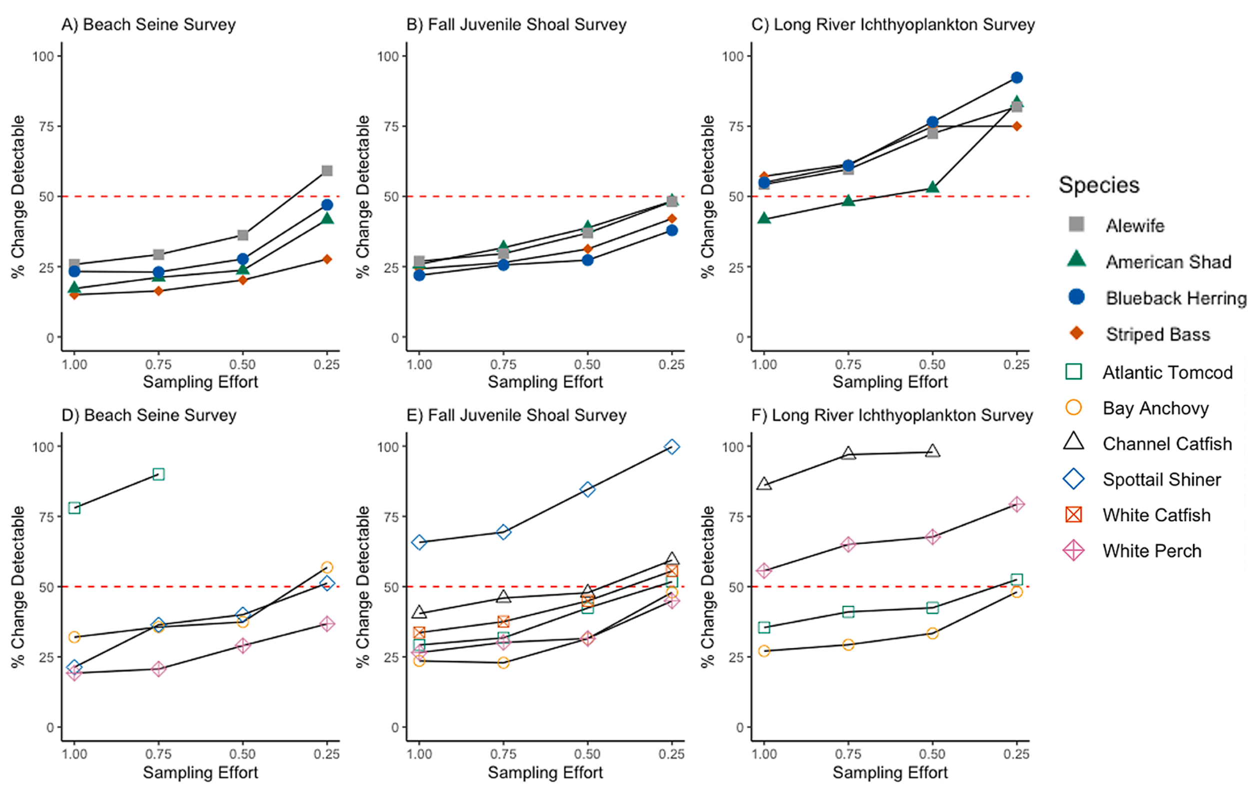

Fig. 5. Summary of subsampling power analysis of the three HRBMP surveys for focal species: (A) Beach Seine Survey (BSS); (B) Fall Juvenile Survey (FJS); (C) Long River Ichthyoplankton Survey (LRS) and non-focal species: (D) BSS, (E) FJS, (F), LRS. Plots show, for each of the focal species, the minimum decline in young-of-year abundance over 10 years that is reliably detectable, given a survey conducted at sampling intensities ranging from 100% (left end of x-axis) to 25% (right end of x-axis) of the historical level. Species that do not appear for a specific survey indicates >100% decline in abundance is necessary to detect change over a ten-year period. Red dashed line indicates the threshold of being able to reliably detect a decline in abundance of 50% or less. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

sampling; sample size, along with the underlying variability in the observed abundances, is a primary determinant of power. While the sampling intensity of many fisheries monitoring programs is strongly constrained by the budgetary limitations of management agencies, the origin of the HRBMP as a court mandate to large commercial entities has largely shielded it from budgetary pressure. As the funding landscape changes for the HRBMP, tradeoffs must be considered between maintenance of the unique level of power of this monitoring program, meeting programmatic goals, and costs associated with monitoring.

The range of locations and times that the HRBMP samples, and the range of gears that it uses, are another strength of the design that is somewhat separate from sampling intensity per se. This diverse sampling provides complementary information on trends in different combinations of habitats, species, and life stages. For example, the combination of a beach survey and trawling surveys allow for the capture of fishes with different life histories and distributions. Channel and White Catfish, both of which are found primarily on the bottom stratum are not frequently captured in the BSS, and are therefore best represented in the FJS (Fig. 3B). Alternatively, species such as Spottail Shiner, which are found primarily in nearshore environments, are best represented in the BSS (Fig. 3B). Further, there is some evidence that the use of known species distributions within the river (e.g., freshwater vs. brackish areas of the river), we can target species better within certain segments of the river. By combining information gleaned in each of the surveys, we are better able to understand not only variance in abundance, but also capture the nuance in distribution found in riverine environments, particularly those that also have the added complexities of harvested diadromous fishes.

Even with a sampling effort as intensive as the HRMBP, detecting changes in the abundance of fish eggs and larvae is difficult. Of the surveys that we considered, only the LRS was designed to sample these earliest life stages. It is important to note that the LRS targets these life stages in particular; the older young-of-year fishes on which we focused most of our analyses are to some extent bycatch in this survey. The benefits of monitoring early life stages include increased ability to quantitatively measure relationships between global change variables and early life stages (e.g., Nack et al., 2019). Here, we found very little power to detect changes in abundance of early life stages, one of the stated goals of the LRS. While the distribution of fishes at any life stage varies in space and time, egg and larval abundances are particularly variable, in part because of the brief duration of these early life stages. This high variability leads to low power; we found that for most species that ability to detect changes in abundance was strongest for young-of-year and post-yolk sac larvae (Appendix B, Tables B.2–4), while there was little power to detect changes in abundance for eggs and yolk-sac larvae. For example, the ability to detect change in American Shad young-of-year was 4x greater than the ability to detect change in egg abundance (Fig. B.2).

4.2. Redesigning monitoring for a changing world

If monitoring the abundance of focal fish species remains a core objective of a revised monitoring program for the Hudson River, our analysis suggests two important ways in which the existing HRBMP might be modified to maximize its cost-effectiveness. We assume here that monitoring should, at a minimum, be reliably able to detect a decline in abundance of 50% over 10 years in any of the focal species (ASMFC, 2020), but the general ideas hold for alternative specifications of the minimum acceptable power. In this assessment, we found that the LRS did not have the ability to detect decreases in abundance to that 50% threshold, and therefore is potentially not meeting its stated goals. The high variability of catches in this survey makes it hard to use the data to detect changes in abundance through time, whether for young-of-year or for eggs and larvae (Fig. B.1-4). Furthermore, the time-consuming and labor-intensive process of identifying and enumerating ichthyoplankton samples means that this survey, as it was historically conducted, was by far the most expensive of the three core HRBMP surveys that we examined here (roughly 75% of total monitoring program costs). Second, the sampling intensity of both the FJS and the BSS could be reduced substantially; both are capable of detecting 50% declines in abundance of the focal species over 10 years even at 25–50% of their historical intensity (Fig. 5). These reductions could take the form of reductions in the number of sampling locations (as demonstrated here) or through decreasing sampling dates or through pooling of field samples in the laboratory for the LRS. The BSS and the FJS sample different habitats, so retaining both provides complementary information among species that utilize multiple habitats.

On the other hand, there are at least two reasons to be cautious about reducing the sampling intensity of the HRBMP. As detecting changes in abundance is likely to remain an important objective of the monitoring program moving forward, it may require careful, strategic thinking to balance decreasing costs and retaining statistical power. Maintaining statistical power in the face of uncertainty and environmental change remains a major challenge of monitoring program design, and must integrate cost-effective monitoring coupled with careful thinking of potential sources of ecological variation and change. Further, in evaluation and redesign of monitoring programs, it is important to retain the benefits of the current program, even as they may lie outside stated objectives. For example, the LRS has been used to provide insight into a wide variety of ecological processes, including fish development, growth, predator–prey dynamics, and habitat use, and how these are influenced by large-scale changes like climate and invasive species (e.g., O'Connor et al., 2012b; Strayer et al., 2014a; Nack et al., 2019).

These considerations emphasize the importance of assessing the objectives of the monitoring program, not just the design (Caughlan and Oakley, 2001; Lindenmayer and Likens). A clear understanding of the objectives provides a strong foundation for optimizing program design and making difficult decisions about what to retain, add to, or remove from an existing design. Setting objectives is a policy discussion, not strictly a science one, though science certainly can and should inform the discussion. This is particularly true when monitoring is motivated by a need to answer particular questions, rather than by a government mandate or simple curiosity (Lindenmayer and Likens, 2009).

Government mandates will continue to play an important role in setting the objectives of monitoring programs in fisheries systems like the Hudson River. For instance, the State of New York is required by the Atlantic States Marine Fisheries Commission to develop an annual abundance index for juvenile fish for species like American Shad and Striped Bass. The historical HRBMP provides the only annual measure of young-of-year fish for these species in non-shore habitats. These data are critical for calculating an annual juvenile index that samples fish in all Hudson River habitats. Yet beyond mandated documentation of fisheries status or trends, it may also be useful to consider explicitly setting monitoring objectives to answer research questions. A question-driven approach can focus effort on testing and refining conceptual models of the system, and so help to advance basic and applied understanding of ongoing change and its implications (Lindenmayer and Likens, 2009). It may also serve to build into the program a need for regular assessment; as answers emerge, the need for new questions (and thus new objectives) becomes clear. The responsiveness of such a monitoring program may be further improved by setting aside funding for a linked research program with an explicit charge to explore new hypotheses (Paukert et al., 2016). Once the objectives of a monitoring program are defined, analyses such as the one we conducted here can help to determine whether a given program design is meeting, or will be able to meet, its objectives.

CRediT authorship contribution statement

Chelsey L. Nieman: Conceptualization, Methodology, Validation, Writing – original draft. **Richard M. Pendleton:** Conceptualization, Methodology, Validation, Writing – review & editing. **Gregg H. Kenney:** Conceptualization, Methodology, Writing – review & editing. **Christopher T. Solomon:** Conceptualization, Methodology, Writing –

review & editing.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Data Availability

Data are available, by request, from Stony Brook University's School of Marine and Atmospheric Sciences.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.ecolind.2021.108344.

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