<<title>>Improving the communication and accessibility of stock assessment using interactive visualization tools

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<</FOOT;f1>><<altfoot>>[1]All code used to generate this paper, Supplement 1 (getting started dashboard), and Supplement 2 (NCAM explorer) are available at <zurl>https://github.com/PaulRegular/interactive-stock-assessment<zurlx>.</.>

Commented [TC1]: AUTHOR: Please ensure that you thoroughly proofread your galley proofs against this edited copy of the manuscript. (1) Pay particular attention to those areas that are underlined (additions, corrections, or queries) or struck out (deletions). (2) Please address all the questions inserted in this copy (_MS.pdf) but mark all changes on the galley proof file only (_PROOF.pdf). If a question or change is not addressed, the change will be assumed to be correct. (3) Check that Greek letters and mathematical and typographic symbols have been correctly converted. (4) Check the values in the tables against your original manuscript, as errors can be inadvertently introduced during conversion. (5) Check the equations in the proofs against those in your original file. (6) Note that special tagging codes are used in the edited manuscript to accommodate html publishing online (usually in grey-highlighted text; e.g., <xxx>, [lt], etc.), and can be ignored. Please keep a copy of your corrected proofs for reference. Thank you

<<abs>>**Abstract:** Scientists across many fields are faced with the challenge of synthesizing and communicating information from large and complex data sets. The field of stock assessment is no exception as the volume and variety of the data has grown alongside the computational methods used to integrate them. While this growth in data and model complexity has improved many stock assessments, the process of communicating key results to colleagues and stakeholders in a meaningful way has become more daunting. The traditional approach of presenting information across a series of static slides often fails to convey the richness of information available, and, as such, important patterns and details are easily overlooked. Here we contend that this problem can be mediated through the effective use of new open source tools for building interactive visualizations. These tools allow a broader audience to conduct detailed explorations of the results, leading to a deeper and collective understanding of both the data and models used to inform stock assessments. As a consequence, the peer review process is more open and accessible.

<<abs;fr>>**Résumé :** La synthèse et la communication d'information tirée de grands ensembles de données complexes constituent un défi pour les scientifiques de nombreux domaines. Le domaine de l'évaluation des stocks n'y fait pas exception, puisque le volume et la diversité des données ont augmenté parallèlement au développement des méthodes computationnelles utilisées pour leur intégration. Si cette augmentation des données et de la complexité des modèles a amélioré de nombreuses évaluations des stocks, la communication signifiante de résultats clés à des collègues et parties prenantes est de plus en plus compliquée. Bien souvent, l'approche traditionnelle de présentation d'information par une série de diapositives statiques n'arrive pas à transmettre la richesse de l'information disponible, de sorte que d'importants motifs et détails peuvent facilement s'y perdre. Nous arguons que ce problème peut être atténué par l'utilisation efficace de nouveaux outils de source libre pour la production de visualisations interactives. Ces outils permettent à un plus grand auditoire d'explorer des résultats en détail, ce qui se traduit par une compréhension plus poussée et collective des données et des modèles utilisés dans les évaluations de stocks. Le processus d'examen par les pairs s'en trouve ainsi plus ouvert et accessible. [lsqb]Traduit par la Rédaction[rsqb]

<<hd1>><foot;fu;10>Introduction

<mc>Quantitative stock assessment plays a central role in modern fisheries management (<zharv;23>Hilborn and Walters 1992<zharvx>). Over time, and as new methods are developed, there is an increasing amount of data available to inform stock assessments. These data might be richer information on stock structure using an increasing array of markers and biomarkers, and (or) the continued lengthening of population status and catch time series. Concurrently, analytical methods are now able to integrate many data sources into one stock assessment model (<zharv;37>Maunder and Punt 2013<zharvx>). While these advances have surely improved the advice provided on stock status, it has become more difficult to communicate the basis of this advice in a meaningful way. Visualizations play a critical role in communicating this information to stakeholders (<zharv;32>Levontin et al. 2017<zharvx>). However, traditional formats (e.g., slides) are often insufficient to convey the richness of information available, and the static and sequential nature of these formats can stifle meaningful discussions. A solution to this problem is the effective use of interactive visualization tools (<zharv;27>Keena et al. 2016<zharvx>). These are common tools we use every day on a range of web sites, but their use is no longer restricted to web site developers, as these tools are being integrated into software commonly used by the research community (<zharv;43>Perkel 2018<zharvx>). As a result, an increasing number of scientists across a wide range of disciplines are starting to apply interactive visualization tools to explore and communicate their results (e.g., <zharv;26>Jones et al. 2016<zharvx>; <zharv;31>Letcher et al. 2018<zharvx>; <zharv;54>Yeatman et al. 2018<zharvx>).

<mc>Fisheries scientists are a part of this trend, and, as such, there are a growing number of interactive tools available that facilitate the exploration and communication of fisheries science. For instance, they can be used to disseminate real-time information for

dynamic ocean management (<zharv;38>Maxwell et al. 2015<zharvx>; <zharv;22>Hazen et al. 2018<zharvx>), explore hindcasts and projections from various habitat suitability models (<zharv;39>McHenry et al. 2019<zharvx>), and evaluate different fisheries management approaches (<zharv;18>Goethel et al. 2019<zharvx>; <zharv;41>Miller et al. 2019<zharvx>) (see Appendix A for more examples). Such tools complement static documentation, as they allow audiences to explore data and models in ways not amenable to static formats, and, in the process, they improve accessibility and augment communication efforts. These will be helpful tools to utilize as we proceed through an age of heightened scientific scrutiny (<zharv;40>McInerny et al. 2014<zharvx>), and here we aim to promote their use in fisheries science by demonstrating a series of interactive visualization tools built to aid in the peer review of stock assessments.

<mc>We first demonstrate the application of interactive tools to data that are commonly presented in stock assessments to show how they can simplify the detailed exploration of data from long-term monitoring programs. Second, we focus on the modeling aspect of stock assessment and demonstrate how interactive tools can be used to explore, diagnose, and communicate results from an integrated assessment model. This structure corresponds to two important steps in the stock assessment process: (*i*) data exploration, and (*ii*) data modeling. In both cases interactive visuals are nested inside dynamic documents called "dashboards". The concept of using a dashboard was borrowed from the business community where they are frequently used to group a series of interactive visuals and tables to provide at-a-glance views of key performance indicators. These dashboards were constructed within the framework of the R programming language (<zharv;45>R Core Team 2017<zharvx>) and the RStudio IDE (<zharv;48>RStudio Team 2015<zharvx>) using three or more of the packages listed in Table<usb> 1<pick;t1;0>. See the online link for Supplement 1 for a "getting started" tutorial that highlights one approach to constructing a dashboard using R.[1]<foot;f1;10> Using this as a guide, an R user can start constructing basic dashboards within a day.

<<hd1>>Data exploration

<<texp>>The data sets used in stock assessments are constantly growing due to the continuation of long-term monitoring efforts, the addition of new monitoring programs, or both. As such, stock assessment biologists need to manage large volumes of data from a variety of sources. Time series of reported landings and catch-at-age are often analyzed in conjunction with data from "fishery-independent" surveys that track changes in relative abundance and, in many cases, also monitor trends in biological factors, such as age composition, growth rates, sex ratios, and maturation stages. For some data-rich stocks, mark and recapture studies are also carried out to estimate movement, migration, growth rate, natural mortality, and discard mortality. All of the above-mentioned data sets are complex, and, as the volume and variety of these data increases, it becomes more difficult to be aware of the details of each data set and discover key patterns within each. It has long been recognized that this challenge can be mediated, to a degree, by the application of interactive visualization tools, as they allow detailed exploration of the data behind a plot (<zharv;53>Tukey and Tukey 1985<zharvx>; <zharv;14>Fisherkeller et al. 1988<zharvx>). For instance, the ability to zoom in on features or areas of interest, turn off layers, and hover over specific points to reveal more information creates an interactive, user-driven experience that expedites explorations of data. These abilities are illustrated by two recently developed interactive tools: (*i*) a tool designed to quickly examine fishery-independent survey data; and (*ii*) an interactive mapping tool developed for the exploration of a long-term tagging study.

<<hd2>>Survey data

<<texp>>Fisheries and Oceans Canada (DFO) has been conducting a multi-species stratified-random survey across the Newfoundland and Labrador shelf since the 1970s (<zharv;47>Rideout and Ings 2018<zharvx>). These data are analyzed using a standard stratified analysis via a local R package called RStrap (for details on methodology, see <zharv;50>Smith and Somerton 1981<zharvx>). Both the inputs and outputs from RStrap analyses are very large and, depending on the species, may include >40<usb> years and span the majority of the Newfoundland and Labrador shelf. In order for fisheries scientists to quickly and reliably explore these data without iteratively modifying R

scripts one species at a time, an application (hereinafter called RStrap Explorer) was built using a combination of shiny, crosstalk, flexdashboard, plotly, and R markdown (Table<usb> 1). RStrap Explorer started as a way to visualize estimates of biomass and abundance trends of specific species by supplying RStrap output to a flexdashboard file designed to organize and visualize the results. The shiny package was latter applied, as it allows RStrap to be run in the background and therefore allows the user to dynamically explore abundance and biomass estimates from multiple species in one session. Both crosstalk and plotly were incorporated to allow the user to interact with the data.

<mc>RStrap Explorer contains four primary tabs: (*i*) "Survey Indices" contains stock-level estimates of biomass and abundance (Fig.<usb> 1<pick;f1;0>); (*ii*) "Age and & Length Distributions" contains length and age frequency plots (Fig.<usb> 2<pick;f2;0>); (*iii*) "Recruitment" displays recruitment indices; and (*iv*) "Help" provides additional context to the survey data and analysis. The input interface for RStrap Explorer is divided into two parts: basic and advanced inputs. Basic inputs are those like species, season, and survey year(s). Advanced inputs allow the user to define the length or age of recruitment, select whether they would like analyses conducted by length and (or) age, and so on. This application was built for data exploration and allow the user to obtain quick and easy visualization of survey data, before the thorough data checking and analysis required for formal stock assessment begins.

<<hd2>>Tagging data

<<texp>>Northern cod (NAFO Divisions 2J3KL) has a rich history of tagging, starting as a dedicated program in 1954 (<zharv;51>Taggart et al. 1995<zharvx>) and continuing to this day. The tagging and recovery data are captured in a standardized database, with fields typical of most tagging programs. This database has over 600<ths>000 records as of early 2019, with 2000–10<ths>000 tags deployed annually in recent decades. The tagging and recovery data are used in the current assessment model for this stock (<zharv;7>Cadigan 2016<zharvx>), but tools to explore this extensive data set were limited, especially from a spatial perspective. To begin to explore and understand this large data set, we built a

simple application using shiny and leaflet (Table<usb> 1) that allows a user to quickly and dynamically subset the data (e.g., ranges of tag release and tag recovery years, specific geographic locations). As the application developed, it was incorporated into shinydashboard, to take advantage of the number of layout options available in shinydashboard (Table<usb> 1). Given the large number of tags released, often at nearby sites, visualizing the data with static mapping was particularly challenging. The markercluster (<zurl>https://github.com/Leaflet/Leaflet.markercluster<zurlx>) function available in leaflet was particularly useful as a means to dynamically scale the level of pooling of spatial points (Fig.<usb> 3<pick;f3;0>). This basic mapping tool allowed us to quickly become familiar with the data, identify outliers and incorrect data entries, as well as explore options on how to spatially pool the data for subsequent demographic analysis. Further tabs were added to provide basic summaries of the selected data (Fig.<usb> 4<pick;f4;0>).

<<hd1>>Data modeling

<<texp>>Synthesizing data from multiple sources presents a key challenge to stock assessment. Analyses of different data sources were traditionally carried out independently, and the summaries or parameters from these analyses were used in the assessment model. This approach, however, is less than ideal because information may be lost and uncertainty may be unaccounted for when we "do statistics on the statistics" (<zharv;34>Link 1999<zharvx>; <zharv;37>Maunder and Punt 2013<zharvx>). Such issues have largely been curtailed in contemporary stock assessments, as advances in statistical computing have enabled integrated analyses of data from multiple monitoring programs (<zharv;37>Maunder and Punt 2013<zharvx>). Specifically, statistical modeling tools such as JAGS (<zharv;44>Plummer 2003<zharvx>), AD Model Builder (<zharv;16>Fournier et al. 2012<zharvx>), and Template Model Builder (TMB; <zharv;28>Kristensen et al. 2016<zharvx>) allow the construction of a joint likelihood for an array of observations to, in theory, extract as much information as possible about the biological and fishery processes. From a computational perspective, analyses of a variety of large data sets has never been easier. However, from a human perspective, contemporary stock assessment

biologists are faced with the challenge of understanding and integrating data from multiple sources into a single model and communicating the methods and results to stakeholders and fisheries managers. This challenge was palpable for the data-rich case of Nnorthern cod.

<mc>The Nnorthern cod stock off southern Labrador and eastern Newfoundland is one of the most well-studied stocks in eastern Canada. As such, there are multiple monitoring programs that help inform the status of the stock, and data from most of these programs have been integrated into a state-space stock assessment model, called NCAM (<zharv;7>Cadigan 2016<zharvx>). The model includes information from research vessel autumn trawl surveys (1983–Ppresent), Ssentinel fishery surveys (1995–Ppresent), inshore acoustic surveys (1995–2009), fishery catch-at-age compositions, and reported fishery landings (1983–Ppresent), and tagging (1983–Ppresent). Using a series of observation equations, this TMB-based model simplifies thousands of data points into quantities such as annual recruitment, spawning stock biomass, fishing mortality, and natural mortality. Once the model is fit to the data, the next step is to produce visual representations of the data and model output. The traditional approach would involve producing static presentations and documents with a series of figures and tables. However, with numerous model inputs and outputs, this approach quickly becomes overwhelming for both the analyst and the stakeholders involved for at least two reasons. First, it is no longer feasible for the analyst to include and describe every figure and table produced in a single document. Second, it is difficult for stakeholders to efficiently digest the information that has been compressed into a series of static slides or pages. Interactive documents provide a potential solution to this problem, as they allow much more information to be contained and accessible on a single screen.

<mc>In the pursuit of an easier and more efficient way to communicate results from NCAM, an interactive "dashboard", called NCAM explorer, was developed for the 2018 assessment of Nnorthern cod (<zharv;13>Dwyer et al. 2019<zharvx>). We used R-based packages (Table<usb> 1) to construct a tool for exploring the input and output of NCAM, specifically the flexdashboard package to group interactive plotly-based visuals into a

dynamic document. We also used the crosstalk package to link the data displayed across multiple plots. Via R Markdown, the dashboard is rendered into a self-contained html file that is reproducible, interactive, and easy to update following modifications to the model or the addition of new data. The intent of this tool was not to replace detailed documentation on the model (i.e., <zharv;7>Cadigan 2016<zharvx>; <zharv;13>Dwyer et al. 2019<zharvx>); however, it was built to serve as an interactive alternative to a standard presentation for communicating the latest results to an audience with a working knowledge of the stock and assessment model. Explanatory text and detail were therefore kept to a minimum, allowing the audience to explore the figures and data unencumbered by verbose descriptions.

<mc>The NCAM dashboard (Supplement 2[1]) contains a series of pages, the first of which provides terse point-form background on the model (page named "Background"). Subsequent pages provide a series of diagnostic plots for assessing model fits to catch ("Landings"; accessed from the "Fishery" drop-down menu), survey ("RV<usb> survey", "SN survey", and "SS survey"; accessed from the "Surveys" drop-down menu), and tagging ("Tagging") data. For instance, the "RV<usb> survey" page includes plots of observed and predicted values of mean numbers per tow captured in the research vessel survey (Fig.<usb> 5<pick;f5;0>). The dashboard also includes pages focused on model estimates such as selectivity ("Selectivity"; accessed from the "Fishery" drop-down menu) and catchability ("Catchability"; accessed from the "Surveys" drop-down menu). Pages for viewing trends in various population parameters are included under the "Trends" drop-down menu, where the "Retrospective analysis" page displays results from a retrospective analysis, the "Model comparison" page displays population trends from different model runs, the "Status and rates" page displays trends in stock size and vital rates (Fig.<usb> 6<pick;f6;0>), and the "Productivity" page focuses on trends in Sspawning Sstock Bbiomass (SSB) and recruitment. Finally, details on the projections are accessed from the "Projections" drop-down menu ("Assumptions", "Past projections", "Retro projections", and "Results" pages), and key inputs and outputs are accessed from "Tables" drop-down menu ("Inputs", "Settings", "Outputs" pages). The plots and tables included in the dashboard are similar to those typically presented at

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assessment meetings and in research documents. However, there are two key benefits of this approach over the modus operandi of producing static documents and slides. First, interactive plots nested in a dashboard permit relatively easy and efficient access to the details, as it replaces scrolling through tens, if not hundreds, of pages or slides with mouse-clicks across a smaller number of dynamic pages holding data-rich illustrations (i.e., both broader patterns and finer details in the data are accessible via zooming and tooltips). Second, the automated nature of the dashboard circumvents the monotonous, time-consuming, and error-prone task of copying and pasting figures, tables, and values into documents and slides, although, we note that this issue can be addressed through other approaches (e.g., slide shows can easily be made using R markdown). Both benefits expedite the process of exploring a range of model configurations, as the automated output facilitates quick views of standard diagnostics and the interactive plots facilitate detailed explorations and comparisons of models with different configurations. For instance, explorations of the residual plots in the dashboard allowed the authors to quickly identify conflicts between two surveys used in the model. Potential solutions to this problem were then explored by modifying the configuration of the model, and these changes were quickly evaluated using a dashboard that is produced in seconds.

<mc>The dashboard also makes it easy to share the results with colleagues and stakeholders, as it is rendered into a self-contained html file. This allows others to independently scrutinize details of both data and the model that are typically only accessible to the analyst. Such access improves the transparency of the stock assessment model, which, in turn, leads to richer discussion and scrutiny of the biological and statistical rigor of the model. For instance, visualizations depicting the model assumptions, process errors, and confidence intervals around the projections raised important questions on the impact of the assumptions on the projections from the model. These questions were raised during the first assessment meeting in which this tool was used, and the ensuing discussions left us with the impression that this tool helped the assessment biologists, academics, resource managers, and fisheries representatives in the room gain a deeper understanding of the uncertainties and the patterns in the risk tables. Feedback and personal testimony from multiple stakeholders who have used the

dashboard reaffirmed our impression that the tool is helpful, as there was general agreement that access to the details eases communication and relieves any potential concerns that something is hidden.

<<hd1>>From bespoke to general tools

<<texp>>The interactive tools highlighted here were custom built to solve data visualization challenges that are common to many fisheries management organizations, but the solutions presented are specific to the Northwest Atlantic Fisheries Centre. The concept is therefore broadly applicable; however, the underlying code will require modifications to accommodate region- and stock--specific data management and modelling approaches. Even within our own region, different approaches and needs meant that the code behind NCAM explorer (Supplement 2[1]) required modifications when applied to a model developed for another cod stock. Nevertheless, considerable chunks of code were recycled, and, in the process, new features were added to allow the visualization of multiple model configurations within the one dashboard. Additionally, a French colleague is currently modifying the tool to visualize output from SAM, a state-space stock assessment model widely used to assess ICES stocks (<zharv;42>Nielsen and Berg 2014<zharvx>). Likewise, the concept behind RStrap Explorer and the tagging tool could be applied to other regions, and the most efficient approach may be to build upon existing general frameworks (e.g., StoX software; <zharv;25>Johnsen et al. 2019<zharvx>). These are, of course, early days in the development and application of interactive tools to stock assessment. Because the tools we highlight are themselves general, flexible, and accessible, we suspect that bespoke applications will continue to be developed in parallel with more general stock assessment dashboards depending on user needs and preferences. Regardless of the approach, a common goal is to make the workflow more efficient, reproducible, and transparent.

<<hd1>>Towards open stock assessment

<<texp>>The amount of data available to scientists has grown by orders of magnitude in recent decades as has the complexities of data management, exploratory data analysis, formal analyses, and associated diagnostics (<zharv;33>Lewis et al. 2018<zharvx>). The majority of this sequence of events, sometimes called "the data pipeline" (<zharv;29>Leek and Peng 2015*a*<zharvx>), hasve not traditionally been part of the peer- review process, which sees only the end products of an analysis. However, decisions made along the data pipeline increasingly influence the outcome of the study. <zharv;17>Gelman and Loken (2014)<zharvx> coined the term "garden of forking paths" to illustrate that different conclusions can be arrived at depending on what decisions are made during different stages of the analysis. OwingDue to a number of limitations, such as available pages in journals, much of the data pipeline is not transparent nor is it reproducible. A number of authors have recently advocated for a culture of open science and reproducible research, (i.e., a change in the transparency and reproducibility of science; (<zharv;20>Hampton et al. 2013<zharvx>, <zharv;21>2015<zharvx>; <zharv;29>Leek and Peng 2015*a*<zharvx>, <zharv;30>2015*b*<zharvx>). Proponents of open science and reproducible research highlight a number of benefits, including a more productive and responsible scientific culture, an ability to address larger and more complex questions, as well as a more efficient workflow and ability to reproduce one's own work (<zharv;15>Fomel and Claerbout 2009<zharvx>; <zharv;35>Lowndes et al. 2017<zharvx>).

<mc>A culture of openness is actively evolving in the field of stock assessment, and, at this point, it is not hard to picture a future where it is commonplace for the full data pipeline to be open and accessible. Open resources are actively being developed and used to improve accessibility to all the data, methods, and results that feed into stock assessments (e.g., the Transparent Assessment Framework; <zurl>https://taf.ices.dk/app/about<zurlx>; <zharv;36>Magnusson and Millar 2020<zharvx>). Likewise, tools are being developed to facilitate the creation of reproducible advisory documents (e.g., <zharv;24>ICES 2018<zharvx>; <zharv;3>Anderson et al. 2020<zharvx>; <zharv;46>Regular et al. 2020<zharvx>), and these documents can be interactive, as is the case for the VISA tool (<zharv;24>ICES 2018<zharvx>), or they can be supplemented by interactive tools. There is plenty of opportunity for synergies between these initiatives, as

most are being developed using R, and all details and decisions can be traceable and accessible using an online repository, such as GitHub. We therefore foresee a future where stock assessments become increasingly open and reproducible.

<mc>Providing open access to code and data, however, does not necessarily make a stock assessment more accessible. We believe that interactive tools, such as those presented here and in Appendix A, represent an important step forward in terms of open science, as they make the peer review process more efficient. Although these tools do not reveal the entire data pipeline, a wide range of stakeholders and scientists can easily access and review details of an analysis without running a line of code. For most participants of a stock assessment, even if the entire pipeline was completely open, the details would remain inaccessible simply because most participants are already overcommitted (<zharv;4>Banks 2011<zharvx>) and do not have the time to fully review and recreate a particular analysis in its entirety. Further, in the case of NCAM, considerable statistical experience and expertise is required simply to run the model. However, the dashboard approach removes many of these obstacles. The html file contains all model inputs, outputs, and diagnostics in an open, and easy to use, interactive document that can be distributed prior to meetings. As such, participants can assess the results and diagnostics at their leisure. Specific experience with the tools used to generate the results are not required to constructively and critically review the results presented in the dashboard.

<<hd1>>Conclusions

<<texp>>Visualizations play an important role in communicating fisheries science to a wide range of stakeholders (<zharv;32>Levontin et al. 2017<zharvx>), and here we posit that interactive tools extend the utility of data visualizations by providing a richer approach to communicating scientific information. However, we must acknowledge there are costs to adopting the use of interactive tools. The first and obvious one being that staff are required to have both the time and training to effectively develop these tools. Ideally, professional programmers and graphic designers would be hired to construct dashboards and other interactive infographics (<zharv;40>McInerny et al. 2014<zharvx>),

but fisheries management organizations rarely have the resources to fund such initiatives. Consequently, the process of communicating fisheries science tends to be the responsibility of fisheries scientists, who lack formal training in these fields. In our three examples, the developers (first, second, and third authors) were relatively proficient with R and have natural aptitudes for programming and graphic design, but all had their formal training in field-based population ecology. While some learning time was needed, the learning curve was relatively minor because there was no need to learn a new programming language (e.g., JavaScript, CSS, etc.). We can confirm that an R user can construct a basic dashboard within a day, using Supplement 1<<usb>> as a guide, and a more custom dashboard in a matter of weeks. Moreover, a growing user base means that most programming issues can be readily addressed through simple Internet searches. There are also a growing number of exemplars (Appendix A), beyond what we show here, to inspire the development of new interactive tools. Once over the initial learning curve, the time investment may not be much greater than one would invest into a standard presentation. We expect the accessibility and quality of these tools to continue to improve as more people in the fisheries community develop and use interactive documents. It is our experience that the upfront time investment has been worthwhile considering the improved efficiency of delivering products for subsequent stock assessments and in the quality of the data exploration and understanding.

<<hdack>>Acknowledgements

<<hd1>>References

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<<app>>
<<hd1>>Appendix A

<<texp>> ~~P~~The following is a partial list of applications developed to explore and communicate marine and fisheries science:

<<bl>>Marine Aggregates Application (<zurl>https://openscience.cefas.co.uk/ma_tool/<zurlx>): a benthic-focused tool to assist with marine license application and compliance monitoring.
<mc>Species Dashboard (<zurl>https://shiny.marine.ie/speciesdash/<zurlx>): a tool for exploring biological fisheries data collected in Irish waters.
<mc>The Stock Book (<zurl>https://shiny.marine.ie/stockbook/<zurlx>): a tool for accessing up-to-date information on the status of fish stocks in Irish waters.
<mc>Data-Limited Fisheries Toolkit demo (<zurl>https://www.datalimitedtoolkit.org/demo<zurlx>): an application for demonstrating the key features of the management strategy evaluation toolkit.
<mc>Toy Tuna MSE application (<zurl>https://puntapps.shinyapps.io/tunamse/<zurlx>): a toy MSE example built to allow users to enter various management procedures and assess their performance.
<mc>Exploring Groundfish in an Ecosystem Context (<zurl>https://incorporatingecosystemapproach.shinyapps.io/indiapp/<zurlx>): a tool accessing results from an analysis exploring links between stock indices and ecosystem trends.
<mc>EcoCast Explorer (<zurl>https://coastwatch.pfeg.noaa.gov/ecocast/explorer.html<zurlx>): an application for displaying results from a dynamic ocean management tool focused on bycatch avoidance (see <zharv;22>Hazen et al. 2018<zharvx> for more detail).

<mc>B-VBGM! Bayesian Von Bertalanffy Growth Model tool
(<zurl>https://fishecology.shinyapps.io/B-VBGM/<zurlx>): a supplement to
<zharv;8>Catalán et al. (2018)<zharvx> that facilitates the exploration of the model
described in the paper.

<mc>Beyond Temperature tool
(<zurl>https://heatherwelch.shinyapps.io/beyond_temperature/<zurlx>): a supplement to
<zharv;39>McHenry et al. (2019)<zharvx> that allows the exploration of habitat suitability
hindcasts and projections by species and model type.

<mc>BRSApp (<zurl>https://catalinagomez.shinyapps.io/BRSApp/<zurlx>): a supplement
to <zharv;19>Gomez et al. (2016)<zharvx> that allows the exploration of behavioural
response severity scores of marine mammals to noise.

<mc>VISA tool (e.g., <zurl>https://ices-tools-dev.github.io/VISA_tool/hke.27.3a46–
8abd.html#ices_advice_2018<zurlx>): an alternative to pdf files for displaying and
exploring up-to-date ICES advice (developed to meet an "EU request on dissemination of
ICES advice beyond pdf files"; <zharv;24>ICES 2018<zharvx>).

<<appx>>

<</PICK;f1;0;0;block>>**Fig.** <usb> **1.**<med><ems>Screen shot of the "Survey Indices" page of
the RStrap Explorer application. The "Basic Inputs" sidebar is fixed across all pages and
allows the user to specify the species, NAFO Ddivisions, season, and survey years of
interest. The "Biomass Index" sub-tab is illustrated here. This sub-tab shows a time-
series of biomass data with 95% confidence intervals, with a break in the lines when the
survey gear changed from an Engle to Campelen trawl, for both cod (*Gadus morhua*;
species code 438) and American Pplaice (*Hippoglossoides platessoides*; species code
889). All trend lines can be toggled off using plotly's dynamic user interface.
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<</PICK;f2;0;0;block>>**Fig.** <usb> **2.**<med><ems>"Age and & Length
FrequenciesDistributions" tab of the RStrap Explorer tool. This tab illustrates the length
frequency distributions of both cod (*Gadus morhua*; species code 438) and American
plaice (*Hippoglossoides platessoides*; species code 889) binned into 2<usb> cm length

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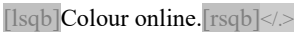
bins. The binning is easily modified using the "Length Grouping" field in the "Advanced Options" drop down menu (shown on left side). [lsqb]Colour online.[rsqb]</.>
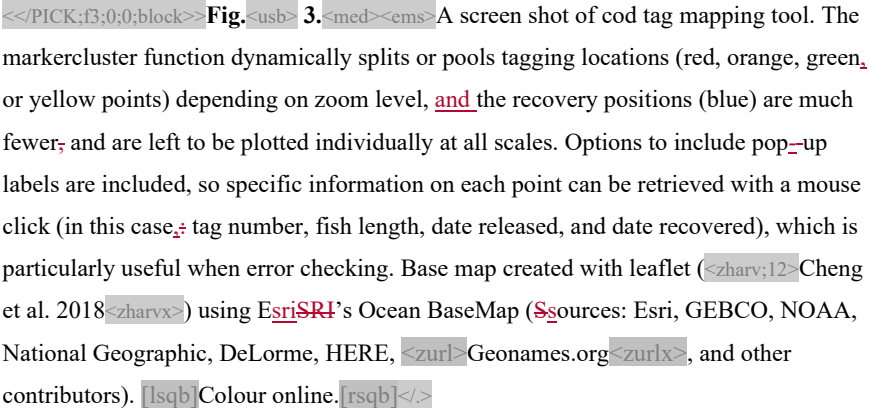
</PICK;f3;0;0;block>>**Fig.**<usb> **3.**<med><ems>A screen shot of cod tag mapping tool. The markercluster function dynamically splits or pools tagging locations (red, orange, green, or yellow points) depending on zoom level, and the recovery positions (blue) are much fewer, and are left to be plotted individually at all scales. Options to include pop-up labels are included, so specific information on each point can be retrieved with a mouse click (in this case, tag number, fish length, date released, and date recovered), which is particularly useful when error checking. Base map created with leaflet (<zharv;12>Cheng et al. 2018<zharvx>) using EsriSRI's Ocean BaseMap (Ssources: Esri, GEBCO, NOAA, National Geographic, DeLorme, HERE, <zurl>Geonames.org<zurlx>, and other contributors). [lsqb]Colour online.[rsqb]</.>
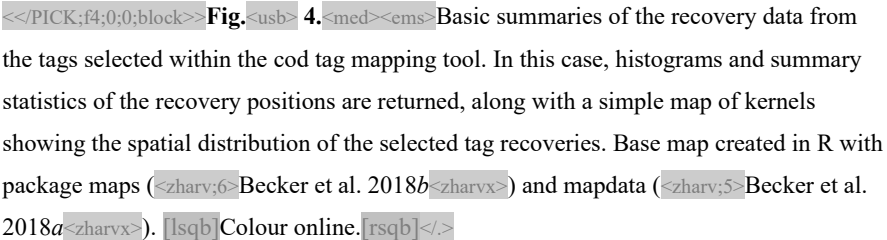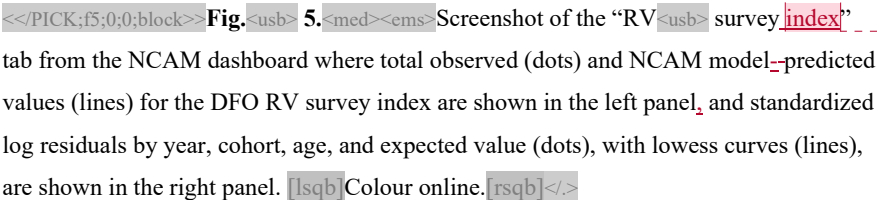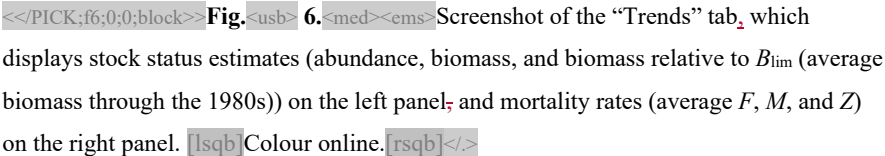
</PICK;f4;0;0;block>>**Fig.**<usb> **4.**<med><ems>Basic summaries of the recovery data from the tags selected within the cod tag mapping tool. In this case, histograms and summary statistics of the recovery positions are returned, along with a simple map of kernels showing the spatial distribution of the selected tag recoveries. Base map created in R with package maps (<zharv;6>Becker et al. 2018*b*<zharvx>) and mapdata (<zharv;5>Becker et al. 2018*a*<zharvx>). [lsqb]Colour online.[rsqb]</.>

</PICK;f5;0;0;block>>**Fig.**<usb> **5.**<med><ems>Screenshot of the "RV<usb> survey index" tab from the NCAM dashboard where total observed (dots) and NCAM model-predicted values (lines) for the DFO RV survey index are shown in the left panel, and standardized log residuals by year, cohort, age, and expected value (dots), with lowess curves (lines), are shown in the right panel. [lsqb]Colour online.[rsqb]</.>

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</PICK;f6;0;0;block>>**Fig.**<usb> **6.**<med><ems>Screenshot of the "Trends" tab, which displays stock status estimates (abundance, biomass, and biomass relative to B_{lim} (average biomass through the 1980s)) on the left panel, and mortality rates (average F, M, and Z) on the right panel. [lsqb]Colour online.[rsqb]</.>

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<<tt>>**Table 1.** Names and descriptions of the key packages used to build the interactive applications presented in this paper.

Package	Description
shiny	Makes it incredibly easy to build interactive web applications with R. Automatic "reactive" binding between inputs and outputs and extensive prebuilt widgets make it possible to build beautiful, responsive, and powerful applications with minimal effort (<zharv;10>Chang et al. 2018<zharvx>).
shinydashboard	Create dashboards with "Shiny". This package provides a theme on top of "Shiny", making it easy to create attractive dashboards (<zharv;9>Chang and Borges Ribeiro 2018<zharvx>).
rmarkdown	Convert R Markdown documents into a variety of formats (<zharv;2>Allaire et al. 2018<zharvx>).
flexdashboard	Format for converting an R Markdown document to a grid-oriented dashboard. The dashboard flexibly adapts the size of its components to the containing web page (<zharv;1>Allaire 2017<zharvx>).
plotly	Easily translate "ggplot2" graphs to an interactive web-based version and (or) create custom web-based visualizations directly from R (<zharv;49>Sievert 2018<zharvx>).
leaflet	Create and customize interactive maps using the "Leaflet" JavaScript library and the "htmlwidgets" package. These maps can be used directly from the R console, from "RStudio", in Shiny applications, and R (<zharv;12>Cheng et al. 2018<zharvx>).
crosstalk	Provides building blocks for allowing html widgets to communicate with each other, with Shiny or without (i.e., static .html files) (<zharv;11>Cheng 2016<zharvx>).

<<tabft>>**Note:** Descriptions are directly from the DESCRIPTION file of each package.</.>

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