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Contribution to the Themed Section: '*A tribute to the life and accomplishments of Sidney J. Holt*'

Sidney Holt, a giant in the history of fisheries science who focused on the future: his legacy and challenges for present-day marine scientists

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Sidney J. Holt (1926–2019) was more than a founding father of quantitative fisheries science, and the man who "helped save the great whales." His accomplishments, over a career spanning seven decades, run deeper: he was a champion of reductionism (i.e. able to identify the factors essential for management) and a systemic thinker who inspired scientists to think critically about marine conservation and management. This article draws on first-hand experiences with Sidney over the last 15 years, when he regularly collaborated with scholars of the ICES Working Group on the History of Fish and Fisheries and the Oceans Past Initiative. Four main themes emerged from our reflections on Sidney's life and legacy, which constitute ongoing scientific challenges: (1) the suitability of maximum sustainable yield as a target reference point for fisheries management; (2) the future of marine mammal conservation; (3) successful implementation of ecosystem-based marine management; and (4) the value of historical perspectives for conservation and management. We consider Sidney's work across these themes, in which he readily collaborated, focused on evidence-based solutions, and, where evidence was lacking, he advocated for the "precautionary principle." We posit there is much that we, and future generations of scientists, can learn from his example.

Keywords: ecosystem-based fisheries management, environmental history, historical ecology, marine mammal conservation, maximum sustainable yield, Sidney J. Holt

Introduction

Sidney J. Holt (28 February 1926 to 22 December 2019) will be familiar to fisheries scientists because of the influential book he wrote with Ray J. H. Beverton during a fruitful period of collaboration between the two young scientists at the Fisheries Laboratory in Lowestoft, UK. *On the Dynamics of Exploited Fish Populations* (Beverton and Holt, 1957) is often referred to as "The Bible of Fisheries Science," because it was the first to outline a broad range of core principles for quantitative analyses of fish population dynamics, multispecies interactions, stock assessments, and the dynamics of fishing fleets. Many stock assessment techniques that underpin fisheries advice today were directly or indirectly derived from the methods Beverton and Holt developed together at Lowestoft in the 1940s and early 1950s (Smith, 1994; Anderson, 2002; Pinnegar *et al.*, 2008).

Later, in 1960, after Holt had commenced working at the Food and Agriculture Organization (FAO) of the United Nations (UN) in Rome, the International Whaling Commission (IWC) invited him to join what became known as the "Committee of Three," a panel of three fisheries scientists who were "independent," i.e. were not specialists in whale stock assessment. They were tasked with providing advice on sustainable yields. By 1961, the panel had completed analyses, which demonstrated that the amount of whaling at the time was unsustainable and that the quotas needed to be drastically reduced if the exploited populations were to recover. Notwithstanding strong opposition by the whaling nations, reduced quotas were established. However, it took more than two decades—during which time Sidney was a strong advocate for whale conservation—before an international moratorium on commercial whaling was agreed in 1982 (Holt, 1985, 2002a, 2002b; Colling *et al.*, 2020; Pauly, 2020).

Sidney Holt was far more than a "founding father of fisheries science" (e.g. Payne *et al.*, 2008) or the man who "helped save the great whales" (Beverton, 2002). Throughout his life, he remained a deeply engaged marine scientist and became increasingly interested in long-term perspectives on marine ecology and ocean management (Engelhard and Pinnegar, 2020). More recently, Sidney regularly collaborated with marine historical ecologists and environmental historians, particularly with scholars of the ICES Working Group on the History of Fish and Fisheries (WGHIST; Figure 1) and the Oceans Past Initiative (OPI). In the last decade of his life, he actively contributed to WGHIST's reports and published papers (e.g. Engelhard *et al.*, 2016) and gave lectures on the historical context of current fisheries management. Even as his health precluded travel, he maintained an active correspondence and remained deeply interested in marine historical ecology and the history of fisheries.

On 4 October 2016, when he was 90 years old, Sidney Holt gave one of his last (if not his last) public talks as keynote speaker at the conference "*Historical Ecology of Semi-enclosed Basins*" organized in Chioggia, Italy (Figure 2). In his seminal lecture on the evolution of the theory of rational fishing in the North Sea, he retraced the many interrelated elements of fisheries science and management across two centuries and demonstrated his strong vocation for addressing ongoing challenges, such as the sustainable harvest of ocean fish (Holt, 2016; Holt and Raicevich, 2018).

Objectives of this article

Here, our goal is to shed light on the lesser-known aspects of Sidney Holt's legacy and illuminate his thinking later on in his long and storied career. We do so by reflecting on our recent discussions with Sidney (ca. 2008–2017) alongside some of his most recent, written work either published or unpublished at the time of writing (NB: much of his unpublished work will be included in a forthcoming book edited by Emory D. Anderson and Michael Earle and published by the American Fisheries Society). In particular, we consider how Sidney addressed major scientific and policy challenges. We focus on four themes: (1) the suitability of maximum sustainable yield (MSY) as a target reference point for fisheries management; (2) the future of marine mammal conservation; (3) the challenge of implementing an ecosystem approach to fisheries management in the real world; and (4) the value of historical ecology and environmental history for marine resource and ecosystem management. These themes constitute ongoing challenges in marine science, and Sidney's work supplies specific insights on each. Yet, we also find that the four themes illuminated Sidney's life and work in new ways. While Sidney was human and fallible, here we focus on what our reflections can teach us, while at the same time highlighting his lesser known endeavours. In doing so, we demonstrate that he was not only a champion of reductionism (e.g. being particularly good at differentiating the factors essential to fisheries management and ignoring secondary effects), but he was also a modern, systemic thinker (*sensu* Gallón, 2020) from whom present and future generations of scientists can learn.

Four themes of marine science challenges

Theme 1. Suitability of maximum sustainable yield as a target for fisheries management

Engaged in fisheries science from the beginning, Sidney was not afraid to speak his mind and voice his concerns, but he always started with data, required evidence, and provided alternative solutions—and many of his concerns were later recognized by the wider community.

Although a "founding father" of quantitative fisheries management, throughout his life Sidney Holt increasingly expressed concerns about one elemental concept in marine science established around the time of his own foundational work: maximum sustainable yield (MSY). Defined as the maximum catch (in numbers or biomass) that can be removed from a population over an indefinite period, MSY suggests there is an optimum level of fishing where fisheries yields are maximized while at the same time sustaining the stock over the long-term. Being intuitive as well as simple to understand and calculate without necessarily being data-hungry—at least when applying simplistic surplus production models—MSY achieved widespread appeal. Despite this, Sidney did not consider MSY to be an appropriate fisheries target; he thought it inadequate and worried that it could compromise long-term fisheries productivity. If pursued, he felt it could severely depress fish populations. Later in life, Sidney went so far as to say it was "*the worst idea in fisheries management*" and described it as "*a way to institutionalise greed*" (Holt, 2011a; see also Holt, 2008a).

Sidney came to these conclusions having witnessed the depletion of many fish and marine mammal stocks over his long career—and he did not think that MSY could be verified or falsified with data, experiments, or theoretical principles. He noted, "*The total weight of the population in any specified period may be of interest, and observed changes in it over time may give us hints about what the population is doing—though only hints—but knowledge of*

Figure 1. Sidney Holt (centre) with participants of the 2011 Working Group on the History of Fish and Fisheries, which was held at the Centre for Environment, Fisheries & Aquaculture Science (Cefas) in Lowestoft, UK (26 October 2011).

it is not particularly useful and it certainly does not determine what the useful long-term catch can be." He criticized the "*utopian misconception rooted in the idea that MSY could be achieved from an uncertain knowledge of the total biomass of those populations*" (Holt, 2011b). Instead, he emphasized that, in his view, the productivity of a population is determined by its reproduction, growth, and mortality rates, which are tightly coupled with population age structure, size distribution, and sex ratio for most species. Collectively then, he did not view MSY as a sound, science-based principle for sustainable management, and considered "*... theoretical MSY [an elusive quantity that] may or may not be observable or computable*" (Holt, 2011b; see also Holt, 2012).

During the 1970s, other scientists also began to realize the downsides of MSY as a target, with animal populations harvested for sustained yield taking much longer to recover from disturbance than predicted (e.g. Beddington and May, 1977). Moreover, as levels of harvesting approached MSY, population fluctuations increase, and so too do variations in yields. With time, the wider scientific community became aware of the technical and biological complications inherent in applying MSY in the real world. These included selectivity and maternal effects that could compromise genetic variability and also the resilience of species' wild populations but also complexities from trophic interactions (e.g. predation, competition, and cannibalism) and a multitude of density-dependent factors (e.g. Pilling *et al.*, 2008; Horbowy and Luzeńczyk, 2017). In this context, fisheries scientists proposed that taking into account Ricker's concept of MSY (i.e. the "*largest average catch or yield that can continuously be taken from a stock under existing environmental conditions*"; Ricker, 1975) and the implication of such a definition (i.e. the largest average catch, continuous exploitation, environmental conditions) including risks to the stock would have made MSY a better target (see Mangel *et al.*, 2002).

Even though the use and understanding of MSY have evolved to better align with such concerns, Sidney did not simply dole out criticism. Despite sometimes using strong words, he did recognize that "*... the intentions of the sponsors of MSY are mostly good*" (Holt, 2011c), and, more importantly, he offered solutions to the problems he articulated. In contradiction with many fisheries policies, Sidney thought MSY was more appropriate as a limit than as a target, which is how it is generally used today (ICES, 2019). He also provided alternative fisheries targets, well below fishing limits at MSY (i.e. F_{MSY}), which he felt were not only more sustainable, but also profitable (Holt, 2011b; Holt and Raicevich, 2018), such as maximum economic yield (MEY). MEY refers to the level of output and the corresponding effort that maximize the expected economic profits in a fishery (Dichmont *et al.*, 2010). It specifically accounts for the disproportionally increasing costs of fishing above certain effort levels and maximizes the long-term profit rather than the yield (Grafton *et al.*, 2007; Pilling *et al.*, 2008; Dichmont *et al.*, 2010).

Theme 2. Advocating for marine mammal conservation

A fierce defender of whales, Sidney argued for caution due to scientific uncertainty, and for shifting the burden of proof, promoting the "precautionary principle" and demonstrating his broad perspective on natural systems as well as the people who depend upon them.

Sidney leveraged his understanding of (fish) population dynamics and stock assessment to develop approaches for assessing marine mammal populations, which differ from many fish species in having limited reproductive capacity and low recruitment, and to advocate for stringent measures to preserve severely depleted whale populations (Holt, 1974, 1985, 1992). For populations

Figure 2. Sidney Holt (left, front) and other participants at the conference "*Historical Ecology of Semi-enclosed Basins: past, present and future of seas at risk*" organized at Palazzo Grassi, Department of Biology, University of Padua, in Chioggia, Italy, where he gave a keynote lecture on 4 October 2016 (photo: Tim Holt).

reduced to extremely low levels, the likelihood of recovery once direct fishing mortality is controlled depends on the survival of a viable nucleus of individuals. In this context, he acknowledged the importance of addressing all sources of incidental mortality and other anthropogenic disturbances including bycatch, harmful fishing gear, ship-strikes and noise, and of introducing tailored measures to protect species during critical periods in their life history (Holt, 1992, 2002c; see also Van Waerebeek and Leaper, 2008).

Although Sidney's endeavours in whale protection primarily focused on the larger species most severely depleted by commercial whaling, his efforts to invoke a science-based approach to conservation also benefited the smaller cetaceans (IUCN, 1979). He repeatedly questioned the evidence used by some IWC Member Nations to justify unlimited whaling through special permits for whaling for "scientific purposes." Sidney argued for caution because of scientific uncertainty and his belief that the burden of proof in fisheries or marine mammal management should shift to those willing to exploit marine resources (Dayton, 1998).

Sidney Holt also cast a wide net for solutions to whale conservation—that is, he considered all sectors as potential sources for solutions and attempted to bring broad societal perspectives to bear on debates. He never underestimated the importance of multilateral approaches, especially for conserving marine mammals that are highly mobile and not constrained within the jurisdictions of one state. Transboundary conservation measures were required for these species, leading to the "global commons" perspective (UN and the High Seas; and UN Convention of the Law of the Sea [UNCLOS 1982]), and Sidney helped draft the resulting policies. His sustained efforts within (and outside) the IWC managed to substantially reduce, but not completely halt, the harvest of whales. Patiently explaining the scientific basis for reduced harvests through diplomatic pathways, but frustrated by the potential threat that whaling might re-emerge, Sidney ultimately took an activist approach. As a Greenpeace representative and adviser to the International Fund for Animal Welfare, he later became a member of the Sea Shepherd marine conservation organization, a group of activists who directly confronted Japanese whaling in the Antarctic sanctuary.

Throughout his life, Sidney remained an ambassador for the plight of the whales (e.g. Holt, 1999, 2002a, 2002b, 2003), continuing to write papers on the subject until he was well into his 80s. In 2007, his paper titled "*Whaling: Will the Phoenix rise again?*" expressed his concerns on the possible re-emergence of whaling, post-moratorium (Holt, 2007).

Holt (2006a) heavily criticized the calls made by the Institute for Cetacean Research (ICR, Japan) in the early 2000s for the continued culling of whales, which the ICR postulated was necessary to prevent whales from "consuming, worldwide, many times more marine living resources than are landed by fisheries" (Tamura and Ohsumi, 1999). He argued that the ICR call aimed instead to terminate the standing moratorium on commercial whaling and other conservation measures established by the IWC and would reopen unsustainable whaling, under the guise of maintaining global food security. Sidney took his arguments a step further, calling for the need to take a broader, more critical look at the "extremely wasteful and destructive ways" most countries (whaling and non-whaling) use to exploit living marine resources for nutritional benefit today (Holt, 2006a).

As a defender of the whales, he also promoted application of the "precautionary principle," i.e. to err on the side of caution where the necessary scientific basis was lacking. This was before the term became common language in marine policy (e.g. ICES, 1997; Holt, 2002a). Sidney was a fierce advocate of this principle even in tense high-level negotiations on, for example, the introduction of whaling regulations and the revised management procedures (Holt, 1999).

Theme 3. Barriers to successfully implementing ecosystem-based marine management

Despite articulating the founding principles for ecosystem-based management well before such terms were adopted into the

mainstream, Sidney offered critical and timely concerns for its implementation.

Ecosystem-based management (EBM) is a relatively recent (mid-1990s) term in marine science, relying on the principle that ecosystems, being dynamic and complex with many feedbacks, should be managed holistically rather than using more traditional approaches that focus on individual species or stocks (UNEP, 1992; Pikitch *et al.*, 2004). It instructs management to explicitly consider the impacts on the structure and function of ecosystems as well as species interactions. While EBM has increased rapidly in popularity and acceptance, Sidney Holt felt it was still a long way from implementation. In 2011, he observed that

> *[i]t is now fashionable for some of an ecological frame of mind, looking at the catastrophic state of global sea fisheries, to lament that management of fishing based on assessments of the dynamics of fish populations on a stock by stock basis has failed and that the only way forward is by what is variously called—but rarely vigorously defined – 'ecosystem management', 'ecosystem approach to management' or 'ecosystem approach to fisheries management' (EAFM). It is not my intention here to enter into a polemic on this matter—though I will admit that I find most of such arguments entirely unsatisfactory with respect to the urgency of a viable praxis for management.* (Holt, 2011c; see also Holt, 2013).

However, Sidney also helped provide the scientific foundation for EBM. Early in his career, he demonstrated that a deeper understanding and appreciation of natural systems than applied in his early work on individual fish stocks, i.e. considering the many interactions between species and populations, their environment, and human communities, is fundamental to effectively managing them. In fact, in a review of EBM, Long *et al.* (2015) identified a paper by Sidney and Lee M. Talbot entitled "*New principles for the conservation of wild living resources*" (1978) as the origin of many EBM principles we use today. For example, these principles include that "*The ecosystem should be maintained in a desirable state such that (a) consumptive and non-consumptive values could be maximized on a continuing basis, (b) present and future options are ensured, and (c) risk of irreversible change or long-term adverse effects as a result of use is minimized*" and that their management should "*include a safety factor to allow for the facts that knowledge is limited and institutions are imperfect*" (Holt and Talbot, 1978). Principles put forward by Sidney and his co-author (1978) for the conservation of wild living resources subsequently became incorporated into the United Nations Convention on the Law of the Sea (UNCLOS 1982). Innovative at the time, these principles were wide-ranging, directly and indirectly encompassing ideas around the importance of ecosystem dynamics and function, temporal and spatial scales, uncertainty, adaptive management, scientific knowledge, and ongoing monitoring. The principles were later re-examined and updated by Mangel *et al.* (1996), with Sidney as a co-author (see also Mangel, 2020, for a very recent appraisal of their work on these principles).

Despite this, Sidney had ongoing trepidations regarding EBM throughout his career. His first concern was a lack of clarity about what it meant in practice, stating "*. . . this much talked about approach, notwithstanding an enormous grey literature referring to it, has about as many quasi-definitions as there are buns in a baker's dozen*" (Holt, 2008b). His concern is corroborated by the large number of definitions that exist for the concept and by the efforts invested in exploring them (e.g. Browman and Stergiou, 2005). Further, because no universal framework exists for its implementation, the principles emphasized vary depending on the overarching objectives of the stakeholder aiming to achieve EBM (Bianchi, 2008). Sidney's second concern was how EBM could be practically implemented within existing management frameworks (Holt, 2011a). Indeed, while almost all national and international policies at least denote the necessity and value of holistic approaches, their implementation and success remains challenging for many reasons; particularly, because of the scale and complexity of ecosystems as well as management frameworks, the numerous and diverse stakeholders with competing interests, and synergies between stakeholder interests and the cumulative impacts of human activities. Finally, similar to his concerns regarding MSY and the potential to prematurely reopen whaling, Sidney remained sceptical that we had the knowledge required to underpin pragmatic ecosystem-based management advice. Even the Holt and Talbot (1978) paper acknowledges that "*We have as yet no sure means of predicting such consequences*" of changes in the composition of the ecosystem and that "*[a]lthough a number of methods have been devised and used to estimate the parameters of the models described, they all depend on assumptions that are both overly simplistic and unproven.*"

Sidney's concerns regarding EBM are echoed in other themes from his career. As with MSY and whales, he feared the ambiguity of EBM could be exploited, e.g. used to legitimize the overharvesting or culling of marine mammals for the ostensible benefit of fisheries (Holt, 2006b), and called for precaution. As he noted at the 33rd Conference of the International Association of Aquatic and Marine Science Libraries and Information Centre in September 2007: "*What is clear is that apart from the basic problem of definition there is remarkably little depth to the science about it. I propose to leave it alone until the fog clears*" (Holt, 2008b). That said, Sidney recognized the need for EBM and the potential for careful management to achieve some of its desired outcomes—i.e. holistic management is crucial, but its implementation remains elusive. As suggested early on in Holt and Talbot (1978), Sidney felt precaution and perhaps simpler approaches should initially be employed, stating that, in lieu of aiming for all of EBM's objectives "*. . . a basic management system for fishing that keeps the fishing intensity relatively low, and hence the fish stocks relatively abundant, will contribute to an ecosystem approach. . .especially if it is relatively unselective—not alter the 'natural' structure of the fish populations*" (Holt, 2011b).

Theme 4. Value of historical ecology and environmental history for marine resource and ecosystem management

Sidney recognized the importance of a long-term vision for conservation and management, and his latest research was dedicated to reconstructing the origin and evolution of ideas, concepts, and principles in fisheries management.

Sidney Holt was known to marine historical ecologists through his membership and involvement in the ICES WGHIST and OPI groups. He was actively engaged and tremendously supportive of these groups' collaboration with managers and their production of new knowledge (Engelhard and Pinnegar, 2020). Indeed, when reading his work from across the years, it becomes clear that Sidney knew the importance of long-term observations and the integration of historical perspectives into contemporary management. For example, in 1969, he published an article in *Scientific*

American entitled "*The food resources of the ocean*," noting in the first paragraph the need to "*retain our perspective*." He was referring to the long-term role of the oceans in providing societies' fish protein and transport needs and how this value would likely continue as new uses of ocean resources emerged (Holt, 1969). He also showed a deep appreciation for how marine management—and mismanagement—was ultimately rooted within the limits of our own perceptions and our history.

Sidney was not only interested in understanding past events and their relevance to marine ecosystems today, but also in the basis of past and present ideas, how they evolved and became dogma, and the importance of openly challenging our assumptions (Holt, 2008b). He was extremely knowledgeable about the history of science and scientific thought, and this was not limited to marine resource management (Holt, 2006b, 2008b). His breadth and depth of knowledge and clarity of thinking were striking. In later years, he combined that knowledge with his lived experiences with and criticisms of fisheries science and management in the 20th century (Holt, 1998, 2009; Holt and Raicevich, 2018), with the aim of demonstrating mistakes made and how we might mitigate them. Importantly, this critique included reflections on his own work (Holt, 2008b). Sidney chose to leverage his understanding to clarify the history and context of his own research and those of his contemporaries. He did this not to demonstrate his own place in history nor the significance of his work, but to show how our actions have deep roots that need to be understood. It suggests the importance of examining our past and present with a more critical eye so that we may improve in the future. In doing so, he always acknowledged and provided insights on the role of other scientists (and their research) that guided and inspired his scientific achievements, an attitude already evident in his early-career work: see, for example, referencing to the book by Kostitzin (1939) in relation to the derivation of the spawner–recruit relationship, in Beverton and Holt (1957).

Sidney also recognized the considerable value contained within sources of information that are not traditionally used in fisheries management, including historical sources, that "*. . .can only be pursued through access to the grey literature of all kinds*" and that "*much of the crucial scientific work on which conservation actions are based remains in the grey documents of committees, not all being published eventually, and some never. These are immensely important because they usually contain detail that gets omitted from later publications*" (Holt, 2008b). He also noted how this can uncover answers to "solved" problems that have been lost and then reinvented, such as the mathematical models proposed by Baranov (1925) that described the relationship between sustainable yield and fishing effort. These were forgotten and then rediscovered by western scientists after World War II—and were, in fact, originally proposed 23 years earlier, as outlined in an exchange of letters between Professors Chrystal and Patton in 1901 (Holt, 2008b). Sidney's perspective shows the importance of resources—for data and for previously identified solutions—that exist outside of conventional peer-reviewed journals, the need to make these available within the public domain, and to protect them from destruction or loss.

Finally, for many young marine historical ecologists and environmental historians, Sidney embodied a link between past and present fisheries science and was able to provide a human perspective on past decision-making (Holt and Raicevich, 2018). In this way, he provided context that included demonstrating the shortcomings of scientific knowledge, management priorities, and politics across the eras (Holt, 1998, 2008b; Holt and Raicevich, 2018). His involvement in the scientific process and decision-making spanned more than 70 years, during which he witnessed ideas being reinvented and debates being repeated time and again—and his willingness to revisit past discussions, and engage in new ones, encouraged continual reanalysis and thoughtful criticism of current practice. He was also aware of his own limitations and of the value of learning from sources outside of our own expertise (Holt, 2008b), and it was his systems-level thinking and desire for evidence and solutions that most critically connected the past with the present.

Reflections on Sidney's legacy

By exploring Sidney Holt's published and unpublished works and reflecting on our own experiences with him, we identified four main themes through which to reflect on both the well- and lesser-known aspects of Sidney's life and work. These themes were (1) the suitability of MSY as a target for management; (2) advocating for marine mammal conservation; (3) implementing ecosystem-based management; and (4) the value of historical perspectives and approaches. Yet, we aimed to do more than simply remember Sidney's work in these four areas. We also considered what lessons might be distilled for present and future marine scientists, and determined both a specific and a more general lesson from his role in each (Table 1).

In addition to these lessons, for us the four themes also illustrate Sidney Holt's legacy and who he was as a scientist in several ways. First, collectively they demonstrated that Sidney was a *systemic thinker*. Gallón (2020) defines a systemic thinker as being one who has "*the theoretical and practical ability to observe, think, model, simulate, analyze, design, and synthetize components, functions, connections, structures, interrelationships, and dynamics across disciplines, functions, organizations, people, trends, and cultures in ways that lead to insightful problem interventions for attaining solutions aligned with sustainable development.*"

Of course, Sidney's most well-known achievement in fisheries science demonstrates his ability to simplify complex questions and employ reductionism to focus on essential components for scientific understanding. Indeed, Sidney's foundational contribution to fisheries science, as well as his work on whales, was reductionist as it focused specifically on population numbers and dynamics—ignoring vast realms of wider knowledge—to provide insight for the management of complex systems. Here, we consider Sidney's work *beyond* these accomplishments—and we do not find Sidney's ability as a systemic thinker to be at odds with his capacity to leverage reductionist science for foundational insights. Indeed, we find that work from across his career shows that it was his understanding of the larger system—including people—that allowed him to employ reductionist science so skilfully.

Indeed, ever curious, Sidney not only aimed to answer specific questions of immediate importance but also contemplated their broader context. This included the larger ecosystem, for instance in his concerns about MSY, whaling, and in his foundational thoughts about EBM, as well as the longer temporal context, as shown in his historical framing of contemporary research and management and engagement with WGHIST and OPI. We believe he also saw his science—and his advocacy—as embedded within broader economic, social, and political human systems. Evident in our discussion of his commitments to whale conservation and his collaborative work on the past, he sought wide

Table 1. Key messages distilled from our review of the published and unpublished works of Sidney Holt from the four main themes.

Theme	Specific key lesson	Broader lesson
1. Suitability of maximum sustainable yield (MSY) as a target	Sidney believed that the use of MSY as a fisheries management target was at the expense of more comprehensive approaches, and that more efficient targets (i.e. MEY) could be used. He felt other approaches and targets were more suited to fisheries management, and could better protect the stock from collapse while achieving socio-economic benefits.	We can and should critique the foundations of our approaches to science and management, even those broadly accepted or applied—yet always do so with evidence and work to offer solutions to the problems we bring to light.
2. Advocating marine mammal conservation	Scientists must keep alert to broader (societal and political) signals regarding the resumption of whaling, and the exploitation of any other depleted stocks. We should also try to go a step further and critically reflect on wasteful and destructive practices for exploiting marine (living) resources.	Knowledge in one area may help illuminate other perspectives and the larger picture, but solutions need to be supported by evidence. When evidence is lacking, precaution is critical—lack of evidence or complacency can mean we ignore threats and past mistakes.
3. Barriers to successfully implementing EBM	Ecosystems are complex, and while our understanding of them continues to grow, we may not yet understand them well enough to introduce effective EBM. Moreover, ambiguity around its definition and implementation could be exploited by some to deter action. For these reasons, among others, a precautionary approach offers a useful alternative when EBM implementation remains a challenge.	A systems view is critical for contextualizing our thinking, but simply acknowledging its value or outlining theory is insufficient. We also need to develop pragmatic approaches for management that reflect the broader context and ensure these are based upon sound science, and invoke the precautionary principle when evidence is lacking.
4. Value of historical ecology and environmental history	History is crucial for contextualizing current conditions and contemporary fisheries management, and can provide a deeper evidence base on the evolution and history of current ideas (and management approaches). Management as we know it today developed over time and will evolve in the future as well.	There is rarely one single solution, and the process of problem-solving should be dynamic. We must continually develop solutions and question assumptions as new knowledge and experience is gained, with a clear eye on history to remind us how the current state came to be. That clarity should also encourage us to revisit past ideas and approaches, including self-critique when new information arises.

partnerships for solutions, engaging with scientists, including practitioners in other disciplines, as well as managers, politicians, and conservationists. It was through those partnerships that many of us got to know Sidney beyond our textbooks, and had the opportunity to work with him.

Second, and hand-in-hand with being a systemic thinker, Sidney was also *solutions-oriented*. We believe this, in part, motivated his broader ecological thinking and his reaching out to those beyond fisheries and the scientific community. He cared deeply about addressing our most pressing concerns—and knew he was not the only one able to provide solutions. He recognized that finding answers for the challenges facing fisheries and whales requires an understanding of context, just as it may require working with others from outside his discipline and even outside science. His commitment to resolving problems is also clear in his fervent dedication to evidence. Sidney was committed to and prioritized evidence for demonstrating effective solutions; he critiqued the lack of rigour and data quality used in surplus production models to estimate MSY, within management decisions regarding whaling, and in the implementation of EBM. Sidney consistently asked his colleagues and peers to provide evidence to support the answers they proposed, and he consistently employed it to support his own critiques and alternative suggestions. As a result, he was not afraid to challenge popular principles, including MSY and EBM, where he felt these did not offer a solution based in sound science, nor did he avoid self-criticism when new information arose.

Yet, we do not always have all the data we would like. The third point from our reflection is that Sidney proposed a path forward even when the necessary evidence was lacking, as he believed was the case with MSY, whaling, and EBM—and his proposal was *never* inaction. Instead, he argued for caution in our use of ocean resources until sufficient evidence was available to support alternative actions. This perspective was ahead of its time. It is now echoed in the "precautionary principle," an idea now accepted as a best practice within fisheries management (e.g. ICES, 1997), protection of the environment (UNEP, 1992), protecting human health from pollution (e.g. World Health Organization, 2004), and emerging technologies (European Commission, 2009). Sidney was also progressive in showing that being cautious was more than just waiting for sound scientific evidence. As with MSY, whales, and EBM, he asserted that when evidence is deficient, ambiguous, or entirely lacking, the deeper concern is that threats will be ignored and ambivalence will be exploited.

Finally, we note that Sidney's focus on evidence and his nature as a systemic thinker who was solutions-oriented are intertwined with our final theme: his deep appreciation for history and historical sources. That is, the elements of his life and legacy we have so far outlined converge with an appreciation for understanding our past. Sidney's regard for data extended to the large quantities of unpublished grey and historical literature, such as the whaling logbooks and documents produced by government organizations and committees, believing it to be "*... among the best sources of hard information*" and vulnerable to loss or destruction (Holt, 2008b). His systemic view also encompassed greater temporal contexts, as he recognized that human and environmental history hold great insights for understanding our present situation and the journey that led us here. Information from the past also provides valuable context for critiquing the present and supporting the development of new solutions by expanding the depth of the evidence. Moreover, and as Sidney was aware, history can help us avoid repeating past mistakes, a particular fear of his with regard to whaling (Holt, 2007). It is also this point that most often brought Sidney into our lives, and it was because of these motivations—for holistic understanding, for evidence-based solutions, and being unafraid to critique, including self-criticism—that our experiences with Sidney were so rich and fulfilling, and much more than, for example, learning fisheries science from one of its founding fathers.

Sidney reminded us that management today developed iteratively over time—and will continue to evolve in the future. He demonstrated that even foundational principles should be revisited as the science develops, whether this be our application of early theories, such as MSY, or of more recently defined approaches, such as EBM. Deeper knowledge of the underlying assumptions and context can impart new solutions or help rediscover solutions for "old" problems. Moreover, many of the "new" ideas and initiatives today have a long history, e.g. as many key principles of EBM were suggested by Holt and Talbot in 1978 (see also Mangel *et al.* 1996; Holt, 2006b; 2014). Sidney appreciated that the process of problem-solving should be dynamic, and we must continually revisit our solutions and underlying assumptions as time passes and new knowledge and experience is gained. Simply because an approach is popular (EBM) or foundational (MSY) does not mean we should continue to apply it without criticism nor fail to try and improve upon it; we can and should strive for better solutions.

Collectively, our reflections on Sidney Holt's scientific career demonstrate that he was a systemic thinker, solutions-oriented, and committed to evidence, precaution, and learning from history—and his systemic thinking bridged elements, disciplines, and perspectives, even while some of his foundational solutions stemmed from reducing a problem to its essential parts. Together, we find that these elements reveal Sidney as a *modern thinker*, often ahead of his contemporaries. This is evident in each of our themes—from his fears around MSY and whaling, to concerns alongside founding thoughts about EBM and his recognition of the value of precaution. Research is also increasingly demonstrating the importance of history for understanding ecosystems (e.g. foundational papers such as Pauly, 1995; Jackson *et al.*, 2001) and informing emerging management approaches (e.g. Engelhard *et al.*, 2016; Caswell *et al.*, 2020). In our reflection across the themes, we note how many of us are increasingly focused on the larger ecosystem and human contexts—broader impacts, if you will—of our work and see echoes of these impulses in Sidney's work too. Sidney's focus on finding practical solutions for management by reaching beyond his field and beyond the academy is also in keeping with present-day orientations of scientific investigation. More and more, research is directed towards broader applications, both across disciplines and with other practitioners and stakeholders, to address the problems facing society. Many of us are also motivated to be more vocal in advocating for society to address environmental problems, such as climate change. Sidney's lifelong approach to science and advocacy, as evidenced by his many collaborations with policymakers during his work at the IWC and during the EU's Common Fisheries Policy negotiations, demonstrates that he was consistently ahead of his time in this regard as well. Collectively, this modern approach meant that, even in the later years of his life, Sidney continued to contribute across many facets of ocean science, and his active engagement with us, and with WGHIST and OPI, remained thought-provoking and enjoyable.

We also find Sidney Holt was a trans- or interdisciplinary scientist (Sember, 1990) because he integrated knowledge, synthesized approaches, and erected unified frameworks from across disciplines. He had the capacity to collaborate with scientists and practitioners from many different scientific fields, sectors, and institutions and so exemplifies what some describe as a "T-shaped person" whose skills have both depth and breadth (Hansen, 2010; Brown *et al.*, 2015); that is, across multiple disciplines and thoroughly within specific disciplines. Sidney played a fundamental role in developing much of the science underpinning our understanding of marine ecosystems and how we may measure our impacts upon them, but he also translated complex science into practice, engaging managers, policymakers and decision makers, advocates, and the general public. Thus, in addition to his modern approach, we may also learn from Sidney as a collaborator. Indeed, personal attributes such as adopting multiple perspectives and applying knowledge across the traditional disciplinary boundaries are identified training needs for future marine scientists, for example, as necessary furthering innovation in the European Union's strategy for a blue economy (European Commission, 2014), the European Marine Board Expert working group on Marine Graduate Training (Vincx *et al.*, 2018), and the Rome Declaration (European Marine Board, 2014).

A final way we can learn from Sidney Holt is in his ability to reflect over time and on his own work. Despite his monumental contributions to fisheries science and conservation, he never ceased in his scientific endeavours and his drive to revisit and advance past work. Through our engagement with Sidney, the history of fisheries science came alive—but he also yearned to discover how it could connect us to what comes next. Sidney's interests in historical marine ecology and maritime history provoked him to reframe his earlier eminent fisheries science works and to motivate us to do better. He leveraged history to show us how these contributions are part of a continuum—one that is far from over. We are reminded that the challenges of our past do, in fact, remain—as evident in our four themes, core challenges of our present and our future. Now, it is our responsibility to continue Sidney's legacy by demonstrating to scientists, managers, and the wider public why we need to carefully examine marine ecosystems and our relationships with them through time. Thus, it is our hope that we may also become future-focused by expanding our temporal window, and broadening our perspectives beyond discrete disciplines or sub-disciplines. In this way,

Table 2. Overarching advice to science from Sidney Holt across the four themes: (1) suitability of MSY as a target; (2) advocating marine mammal conservation; (3) barriers to successfully implementing EBM; and (4) value of historical ecology and environmental history.

Overarching messages to the scientists of today	*Themes*
Be curious—*much may be learnt by looking to other fields, disciplines, and people.*	**2, 4**
Be honest—*always aim to achieve analyses and solutions that are based on evidence.*	**1, 3**
Be pragmatic—*use best available science or the precautionary approach where needed.*	**1, 2, 3**
Be rigorous—*strive to create a sound theoretical background.*	**1, 2, 3**
Be brave—*even popular and widely applied concepts require constructive criticism.*	**1, 2, 3**
Be aware—*of the larger system as well as its historical roots.*	**3, 4**
Be responsible—*take responsibility for sharing your thoughts and vision and be self-critical; strive to offer solutions not just criticism.*	**1, 2, 3**
Be collaborative—*many and diverse voices are critical for developing novel solutions.*	**2, 3, 4**

we may bring our expertise to bear on the four challenges outlined in this contribution.

Collectively, from our reflections on the four themes, we distilled a set of overarching messages that may provide useful advice for the scientists who would follow in Sidney's footsteps (Table 2). While each of the messages may not be novel *per se*, we found that Sidney often embodied these practices in his work, and these traits have demonstrable value for those responsible for forwarding science and management, both today and tomorrow.

Conclusions

If Sidney were with us today, we believe he would dare us to ask: what assumptions are we making that remain unchallenged? What systems, and what research and policy, do we take for granted, as either unchanging or unchangeable? Which missing factors must be considered, and what new perspectives might add value? Such questions exemplify what scientists today may learn from his legacy. By considering the broader perspective and by collaborating outside our core disciplines and scientific circles, we can gain greater breadth of knowledge and become better equipped to develop solutions. Further, if we are to address today's most pressing problems, we need to remain focused on practical solutions that are not only grounded in sound science, but can also find real-world implementation and enforcement. When we feel the proposed solutions are unfeasible or unsubstantiated, we should be empowered to speak out, while making sure that criticism is constructive and followed up with alternative solutions. Any conclusions and solutions must be based on strong evidence and a high level of rigor. No matter how monumental a piece of work, Sidney challenged us to continue to appraise it so that it could be improved and to reflect on it within broader contexts as well as in light of new information. Finally, we must find ways to document our past and integrate historical data and perspectives to inform modern and future management, and so we may learn from our mistakes and the decisions we have already made.

For our final words, we turn to Sidney himself: "*Let me conclude by asserting that understanding of the birth and evolution of key ideas, notions, concepts, unproven theories, untested hypotheses and glorious principles can help us invent better ones and thus serve conservation if that is our purpose. But, possibly more important: that history can help us distinguish between, and remember, what is a hypothesis, what is an observed set of facts, what is truly a principle, what is a mere assumption, and so on. In particular to be aware of the process by which what is convenient assumption. . . becomes believed by nearly everyone, after a generation or so, to be reliable and incontrovertible fact on which can be based the management of marine ecosystems.*" (Holt, 2008b).

Data availability statement

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