

Summer 2018

Characterizing the Biological Impacts and Human Dimensions of the U.S. East Coast Recreational Atlantic Bluefin Tuna Fishery

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<http://dx.doi.org/10.25773/v5-chn2-zj69>

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Characterizing the Biological Impacts and Human Dimensions of the U.S. East Coast
Recreational Atlantic Bluefin Tuna Fishery

A Dissertation

Presented to

The Faculty of the School of Marine Science

The College of William and Mary in Virginia

In Partial Fulfillment

of the Requirements for the Degree of

Doctor of Philosophy

by

William M. Goldsmith

May 2018

APPROVAL SHEET

This dissertation is submitted in partial fulfillment of

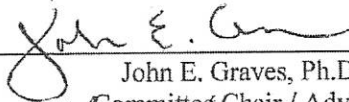
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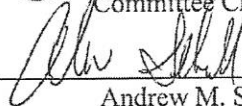


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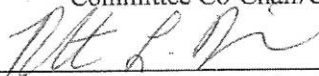
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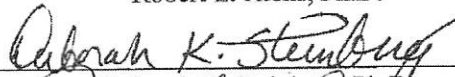
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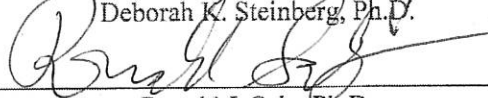
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TABLE OF CONTENTS

ACKNOWLEDGMENTS	v
LIST OF TABLES	vii
LIST OF FIGURES	ix
ABSTRACT	xi
CHAPTER I—Introduction: Ecology, Fisheries, and International and U.S. Management of Atlantic bluefin tuna (<i>Thunnus thynnus</i>)	2
International fisheries history	6
International management and stock status	8
U.S. management	13
The U.S. recreational Atlantic bluefin tuna fishery	15
Human dimensions research in recreational fisheries	25
Post-release mortality research in recreational fisheries	28
Dissertation objectives	29
References	31
Tables	38
Figures	39
CHAPTER II—Characterizing the Preferences and Values of U.S. Recreational Atlantic Bluefin Tuna Anglers	47
Abstract	48
Introduction	49
Methods	53
Results	68
Discussion	73
Acknowledgments	81
References	83
Tables	88
Figures	97
Appendix: Responses to non-DCE (discrete choice experiment) questions	99

CHAPTER III—Decision Making in a Mixed Commercial-Recreational Fishery for Atlantic Bluefin Tuna.....	102
Abstract.....	103
Introduction.....	104
Methods.....	109
Results.....	118
Discussion.....	125
Conclusion	131
Acknowledgments.....	131
References.....	133
Tables.....	138
Figures.....	147
Appendix (Table A1): Demographic and bluefin tuna fishing behavior/attitude characteristics of respondents, broken down by geographic region.....	151
 CHAPTER IV—Performance of a Low-Cost, Solar-Powered Pop-Up Satellite Archival Tag for Assessing Post-Release Mortality of Atlantic Bluefin Tuna (<i>Thunnus thynnus</i>) Caught in the U.S. East Coast Light-Tackle Recreational Fishery	152
Abstract.....	153
Background.....	154
Methods.....	157
Results.....	163
Discussion.....	167
Conclusions.....	172
Declarations	174
References.....	175
Tables.....	179
Figures.....	181
 CONCLUSIONS.....	186
References.....	191
 VITA.....	192

ACKNOWLEDGMENTS

This dissertation is the culmination of a collaborative effort by a diverse, talented, and dedicated group of individuals to whom I am tremendously indebted. I am grateful to my co- advisors, Drs. John Graves and Andrew Scheld, for both their patience and enthusiasm as I endeavored to focus my passion for fisheries into a meaningful and cohesive research project. John, thank you for your support throughout the past four and a half years, whether it meant giving me much needed pep talks whenever my tagging project wasn't going quite as planned, quickly and thoughtfully editing any written work that I sent your way, or simply pulling me into your office to "talk fish." Andrew, I hope you know how much I appreciate the countless hours you put in to helping me navigate what for me was a brave new world of stated choice modeling (and resource economics in general)—thank you for meeting me at the ground level.

The members of my advisory committee, Drs. Rob Hicks, Ron Salz, and Deb Steinberg, provided invaluable insight and guidance. Rob, thank you for your econometric wizardry, and for always asking the tough and thought-provoking questions. Ron, your knowledge of stated choice approaches and human dimensions research, coupled with your expertise on the recreational bluefin fishery, were invaluable assets for completing this work. And Deb, thank you for keeping me honest on the big-picture oceanographic issues, and for your support and advice throughout the arduous writing process.

The input of managers and scientists at the National Marine Fisheries Service (NMFS) was integral to both funding and completing this work. To Brad McHale and Sarah McLaughlin, thank you for sharing your expertise on the Atlantic bluefin tuna fishery and for ensuring that my research questions and approaches were relevant. A special thanks to Sarah for complying with my seemingly endless data requests. In addition, Drs. Cliff Hutt and Kristy Wallmo helped to cultivate this dissertation's economics research from the start—many thanks to both of you for offering essential guidance throughout, from locating funding sources, to refining experimental design, to brainstorming modeling approaches.

This research benefited from a broad array of both private and public support, without which this work would not have been possible. These included: the International Women's Fishing Association; the NMFS Saltonstall-Kennedy Grant Program; the NMFS-Sea Grant Fellowship Program in Marine Resource Economics; the Norcross Wildlife Foundation; the Virginia Institute of Marine Science; and the Virginia Institute of Marine Science Foundation.

I am deeply indebted to the thousands of bluefin tuna fishermen who helped me to complete this dissertation, whether through inviting me on board their vessels to deploy tags, completing a survey, attending a focus group, or simply spreading the word about the work to other fishermen. Special thanks to the numerous charter captains (and their clients) in Massachusetts and North Carolina who repeatedly and generously volunteered to let me join them at sea to conduct my post-release mortality research.

Several other collaborators provided critical logistical and technical support for this multidisciplinary work. In particular, I am grateful to QuanTech, Inc. for distributing surveys and collecting responses, to Marco Flagg and the rest of the Desert Star Systems team for providing me with satellite tags, and to the staff of *On The Water* for letting me use their publication as an outreach platform.

The VIMS “family” was a tremendous asset throughout this process. To Maxine Butler, Cindy Forrester, Heather Longest, and Grace Tisdale, thank you for assisting me with the mountains of travel authorization forms, reimbursement vouchers, and re-budget requests that I brought your way—your diligence and patience, I assure you, did not go unnoticed. To the VIMS student community, thanks for always being there, whether it be assisting with a stubborn R script, paying me a visit at my adopted desk in the library, or just blowing off steam at Juan’s or YROC. I’ll miss you all. Special thanks to Gail Schwieterman and Bethany Williams for the snack supplies and moral support during the final push. Dan Crear, Andy Fallon, and Daniel Wang—congratulations on surviving at least one year with me as your roommate. I’m sure it wasn’t always easy, but living here wouldn’t have been the same without you (in the good sense, I promise). Daniel, it’s been a hell of a four and a half years living under the same roof, and it’s been a privilege to have spent them with you, buddy.

Lastly, to my family, who has been all too aware of my deep and unwavering passion for all things fish for the past 25 years—thank you for providing me with nothing but the utmost support along the way. Mom, I guess all of those too-early mornings, often in the dead of winter, driving me to fishing boats all along the New England coast (and sometimes, in the ultimate self-sacrificing display of devotion, joining me on board!), were not for naught, after all. And Dad, even when the path forward was murky, your confidence in my drive and ability spurred me to keep pushing, to “carry on” and to “do my stuff.” Immense thanks to you both for nurturing my fish-crazed sensibilities from the outset and for enabling me to shape them into a career.

LIST OF TABLES

Table	Page
CHAPTER I	
1. Atlantic HMS Angling category baseline quotas by size class and region	38
CHAPTER II	
1. Attributes and attribute levels included in discrete choice experiments (DCEs) presented to recreational bluefin tuna anglers	88
2. Attribute levels for the “average” 2015 recreational bluefin tuna trip taken along the U.S. east coast.....	89
3. Sample frame and responses by state.....	90
4. Models fitted to angler DCE responses	91
5. Parameter estimates for 2-class latent class logit model fit to DCE data	92
6. Marginal effects of a one-unit change in trip attribute levels on trip probability, given 2015 average bluefin tuna trip levels.....	93
7. Output of multiple linear regression of the log-odds of posterior Class 2 membership as a function of Z parameters	94
8. Class-specific willingness to pay (WTP) for Bluefin Tuna trip attributes.....	95
9. Class-specific compensating surplus (base case: 2015 levels)	96
A1. Responses to non-DCE questions used to inform latent class choice modeling.....	100
A2. Percent of individuals in each class (absolute class assignment) who exhibit specific individual characteristics	101
CHAPTER III	
1. Atlantic bluefin tuna permit structure and quotas.....	138
2. Attribute levels for contingent sequential stated choice (CSSC) survey	139
3. Factors included in the model.....	140
4. Geographic distribution of survey respondents	141

5. Percentage of respondents who completed at least one choice scenario of a given trip type, by stated primary trip type.....	142
6. Comparison of model fit for multinomial logit (MNL) and random parameters logit (RPL) models	143
7. Model estimates for the multinomial logit (MNL) and for the random parameters logit (RPL) with correlated random parameters.....	144
8. Marginal probabilities.....	146
A1. Demographic and bluefin tuna fishing behavior/attitude characteristics of respondents, broken down by geographic region.....	151
 CHAPTER IV	
1. Catch and tag information for 22 Atlantic bluefin tuna tagged with pop-up satellite archival tags	179

LIST OF FIGURES

Figure	Page
CHAPTER I	
1. Estimated positions of Atlantic bluefin tuna electronically tagged with internal archival and pop-up satellite archival tags.....	39
2. Aggregated utilization distribution along the U.S. east coast for 26 juvenile Atlantic bluefin tuna tagged with pop-up satellite archival tags.....	40
3. Atlantic bluefin tuna landings in the eastern Atlantic and Mediterranean from 1950 to 2014 by gear type.....	41
4. Atlantic bluefin tuna landings in the western Atlantic.....	42
5. Estimated fishing mortality and biomass since 1950 for the western stock of Atlantic bluefin tuna.....	43
6. Estimated fishing mortality and spawning stock biomass for eastern Atlantic bluefin tuna	44
7. Total number of school-, large school-, and small medium-size bluefin tuna caught from 2002-2017 along the U.S. east coast.....	45
8. A conceptual model of the recreational fisheries system developed by Fenichel et al. (2013)	46
CHAPTER II	
1. Sample discrete choice experiment (DCE) presented to recreational U.S. east coast Atlantic bluefin tuna anglers	97
2. Willingness to pay (WTP) for the average 2015 bluefin tuna trip by class and overall.....	98
CHAPTER III	
1. Bluefin tuna landings estimates by the Charter/Headboat (CHB) permit holder group as a percentage of the General and Angling category sub-quotas from 2002-2012	147
2. Decision tree for contingent sequential stated choice (CSSC) survey.....	148
3. Example of a fish disposition choice task during a simulated fishing trip scenario.....	149

4. Disposition probabilities for four bluefin tuna fishing scenarios based on 10,000 random draws.....	150
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CHAPTER IV

1. Data recovered from 15 pop-up satellite archival tags deployed on Atlantic bluefin tuna	181
2. Daily summary data transmitted by SeaTag-LOT deployed on Fish #10.....	183
3. Fight times for recreationally caught Atlantic bluefin tuna	185

ABSTRACT

Atlantic bluefin tuna (*Thunnus thynnus*) are targeted by recreational anglers along the east coast of the United States, and the fishery is thought to be of considerable economic value. However, limited knowledge of the preferences and values of fishery participants impedes the ability of managers to maximize fishery benefits and predict harvest patterns, while an incomplete understanding of post-release mortality hinders efforts to estimate total mortality resulting from the fishery. This dissertation used a multidisciplinary approach that relied heavily on cooperative research with the recreational fishing community to examine these questions. A stated choice survey of private anglers permitted to target bluefin tuna (Chapter II) estimated a fishery consumer surplus of over \$14 million in 2015 while revealing striking heterogeneity in angler preferences. Respondents placed a high value on harvesting bluefin tuna, but about half of anglers also valued non-consumptive aspects of bluefin tuna fishing such as catch-and-release. Preference segmentation was largely driven by income and recent bluefin tuna targeting behavior, with high-income anglers who had recently targeted bluefin tuna more likely to belong to the non-consumptive group. These results indicate that liberalization of harvest regulations could result in significant, non-linear increases in effort and harvest should consumptive-oriented anglers decide to re-enter the fishery. A second survey, of Atlantic bluefin tuna fishermen who possess a permit enabling them to fish either commercially or recreationally on a trip-by-trip basis, applied an online contingent sequential stated choice approach to better understand the decision-making of this unique group (Chapter III). Responses indicated that, while some permit holders consistently fish either recreationally or commercially, a substantial proportion of participants change trip type depending on fishery conditions such as prevailing fish size or regulations. The changing behavior of this latter group could potentially result in large shifts in targeting and lead to overages for the commercial handgear sector or recreational sector, and potentially the U.S. bluefin tuna quota as a whole. Lastly, post-release mortality was estimated for juvenile bluefin tuna caught in the increasingly popular light-tackle recreational fishery while also beta testing a newly developed, solar-powered pop-up satellite archival tag designed to enable large-scale, high-precision mortality studies (Chapter IV). Data were only obtained for 15 of 22 deployed tags, with 14 fish demonstrating behavior consistent with survival. One fish was predated upon, likely by a shortfin mako shark, after 17 days, and this was considered a natural rather than a fishing mortality. The low level of estimated post-release mortality, consistent with results from previous studies on different size classes of bluefin tuna caught with various angling gear types, suggests that catch-and-release angling, which Chapter II showed to be highly valued by some anglers, is a viable conservation strategy. Overall, this dissertation provides information regarding both angler preferences and fishery impacts that are of direct relevance to management. Future efforts should be directed to further engaging the recreational bluefin tuna fishing community in order to improve buy-in to management strategies and improve the ability of the United States to maintain fishing mortality within internationally prescribed limits.

Characterizing the Biological Impacts and Human Dimensions of the U.S. East Coast
Recreational Atlantic Bluefin Tuna Fishery

CHAPTER I

Introduction: Ecology, Fisheries, and International and U.S. Management of the Atlantic

Bluefin Tuna (*Thunnus thynnus*)

The Atlantic bluefin tuna (*Thunnus thynnus*) is the largest and most widely distributed of all scombrids (tunas and mackerels), growing to over 900 kg and ranging throughout the North Atlantic and its adjacent seas (Mather et al. 1995, Fromentin and Powers 2005, Rooker et al. 2007). Physical and physiological adaptations (e.g., endothermy) enable bluefin tuna to undertake extensive horizontal and vertical movements and to tolerate water temperatures ranging from 3° to 31° C (Block et al. 2001, Graham and Dickson 2001, Westneat and Wainwright 2001). The species has been recorded in the eastern Atlantic from inside the Arctic Circle south to the Cape of Good Hope, and in the western Atlantic from Newfoundland to 40° S latitude (Mather et al. 1995). Archival tagging studies have demonstrated that bluefin tuna can travel from the continental shelf of North America to the eastern Atlantic in 40 days and can undertake dives to over 1000 m depth, underscoring the extensive habitat utilization of this species (Block et al. 2001). Bluefin tuna are opportunistic feeders and exploit a wide variety of prey types as juveniles and adults (Rooker et al. 2007).

Atlantic bluefin tuna are currently thought to be comprised of two stocks: a western stock that spawns in the Gulf of Mexico, and an eastern stock that spawns in the Mediterranean Sea. Spawning primarily occurs in the Gulf of Mexico from April-June and in the Mediterranean Sea from June-August, and is thought to be stimulated by temperatures above 24° C (National Research Council 1994, Mather et al. 1995, Schaefer 2001, Rooker et al. 2007). The two-stock theory has been supported by electronic tagging, otolith microchemistry, and genetic studies, and fish spawned in each area are

believed to exhibit spawning site fidelity; however, these and other studies also indicate extensive mixing between the two stocks throughout the Atlantic (Figure 1) (e.g., Block et al. 2005, Carlsson et al. 2007, Rooker et al. 2008, Dickhut et al. 2009.). The two stocks are considered to have different maturity schedules, with eastern bluefin tuna assumed to mature at approximately age 4 and western bluefin tuna at approximately age 9 (ICCAT 2015). However, this substantial difference in age at maturity between the stocks, as well as the two-stock model (as opposed, for example, to the existence of metapopulations), continues to be a topic of considerable contention in the scientific community (Lutcavage et al. 1999, Rooker et al. 2007, Galuardi et al. 2010). Most recently, Richardson et al. (2016) reported the collection of 67 bluefin tuna larvae in the Slope Sea, an area north of the Gulf Stream and south of the continental shelf off the northeast United States. In addition to identifying a potential new western spawning ground and challenging the two-stock paradigm, the study also suggested that western Atlantic bluefin tuna mature at age 4-5, with younger fish spawning in the Slope Sea and older individuals (age 9+) spawning in the Gulf of Mexico, which would alter (increase) estimates of the potential productivity of the western stock (Richardson et al. 2016).

Horizontal movements of bluefin tuna not related to spawning (i.e., for foraging) remain poorly understood, and are thought to vary among individual fish, years, and regions (Fromentin and Powers 2005). Much of what is currently understood about bluefin tuna habitat utilization has been learned from electronic tagging studies, including the use of internal archival tags, pop-up satellite archival tags, and ultrasonic transmitters (e.g., Lutcavage et al. 1999, Brill et al. 2002, Block et al. 2005). Studies along the U.S. east coast show that both juvenile and adult bluefin tuna make extensive use of

continental shelf waters extending from the Mid-Atlantic to southern New England, presumably for foraging (Figure 2) (Wilson et al. 2005, Galuardi and Lutcavage 2012). Generally, movements are thought to be influenced by favorable environmental conditions and prey availability. Bluefin tuna closely associate with oceanographic features such as sea surface temperature fronts and with key forage species such as Atlantic herring (*Clupea harengus*) (Fromentin and Powers 2005, Schick and Lutcavage 2009, Golet et al. 2013). Nevertheless, short-term movements and longer-term changes in migrations and distribution—for example, the sudden appearance and disappearance of large numbers of bluefin tuna off the Brazilian coast in the 1960s—cannot be fully explained by environmental and forage factors, underscoring the difficulty in predicting the presence of bluefin tuna in a given area at a given time (Fromentin and Powers 2005).

Certain aspects of Atlantic bluefin tuna life history make the species more vulnerable to overexploitation than other tunas. Tropical tunas tend to grow quickly and reach maturity at a young age, have a relatively small maximum size and short lifespan, and spawn year-round; bluefin tuna, meanwhile, are comparatively slow-growing and late-maturing, have a large maximum size, are long-lived (maximum lifespan is ~40 years), and only spawn for one to three months out of the year (Fromentin and Fonteneau 2001, ICCAT 2017). Higher bluefin tuna recruitment variability resulting from the shorter spawning window (and thus a reduced probability of spawning in environmental conditions favorable for larval survival), coupled with a longer lifespan, leads to lower population turnover, lower yields, and greater relative declines in spawning stock biomass for a given level of fishing mortality compared to tropical tuna species (Fromentin and Fonteneau 2001). Fishing pressure is believed to have reduced the

productivity of the western Atlantic bluefin stock through selective harvest of older individuals (> 8 years old) since the 1970s, which has truncated the age structure of the stock. As a result, each individual fish has fewer opportunities to reproduce over the course of its lifetime, so the chances of spawning when environmental conditions are favorable for larval survival are reduced, diminishing the ability of the stock to buffer against poor recruitment years (i.e., the storage effect) (Secor et al. 2015).

International fisheries history

Atlantic bluefin tuna have been fished in the Mediterranean Sea since the 7th millennium B.C. (Desse and Desse-Berset 1994, as cited in Fromentin and Powers 2005). Until the 16th century, handlines and seines were the primary gears used to harvest them, but between the 16th and 19th centuries seines were largely replaced by traps, which require fewer fishermen to operate (Doumenge 1998 [as cited in Fromentin and Powers 2005], Ravier and Fromentin 2001). An historical analysis estimated that Mediterranean trap catches since the 16th century have averaged approximately 15,000 metric tons (mt) annually (Ravier and Fromentin 2002). During the 19th century, bluefin tuna fisheries expanded out of the Mediterranean Sea—for example, with the development of a handline fishery for juvenile bluefin tuna and albacore (*Thunnus alalunga*) in the Bay of Biscay (Bard 1981, as cited in Fromentin and Powers 2005).

According to Mather (1995), bluefin tuna fisheries on both sides of the Atlantic expanded dramatically following World War II due to the development and/or refinement of three fishing techniques: 1) live-bait fishing; 2) pelagic longlining; and 3) purse seining. The Bay of Biscay juvenile bluefin tuna fishery experienced dramatic catch increases when the live-bait method was adopted during the late 1940s, with French

landings, for example, increasing from 600 mt in 1948 to between 1,900 and 3,500 mt per year during the 1950s (Mather 1995). The first large-scale purse seine fishery for Atlantic bluefin tuna arose off the coast of Norway during the late 1940s and landings increased to as much as 16,000 mt per year during the 1950s before dramatically declining in the early 1960s, possibly due to a shift in migratory patterns (Mather et al. 1995, Fromentin and Powers 2005). In the 1950s and 1960s, purse seine fisheries for juvenile bluefin tuna developed in the Mediterranean Sea and in the western Atlantic off the east coast of North America from North Carolina to Massachusetts, with effort and catches for the latter peaking in 1964 at 21 vessels and 5,600 mt, respectively (Squire 1959, Wilson 1965, Mather et al. 1995). Small-scale fisheries for large, mature bluefin tuna also existed in the western Atlantic during this time using gears such as harpoons, handlines, and rod-and-reel; however, due to lack of market demand, landings remained relatively low (Fromentin and Powers 2005). Japanese pelagic longline vessels first began targeting tunas in the Atlantic during the late 1950s, and rapidly increased effort such that most Atlantic waters from 40° N to 40° S (including spawning grounds in the Gulf of Mexico and Mediterranean Sea) were being fished by the end of the 1960s (Mather 1995, Fromentin and Powers 2005). From 1962-1967 the Japanese longline fleet encountered large numbers of bluefin tuna as bycatch while targeting tropical tunas off the coast of Brazil and harvested 5,000 to 12,000 mt annually before the fishery suddenly collapsed (Fromentin and Powers 2005, Porch 2005). Combined bluefin tuna landings in the western Atlantic peaked in 1964 at 18,608 mt, largely driven by the Japanese fishery off Brazil and the U.S. purse-seine fishery for juveniles (ICCAT 2017). Other nations, such

as China, Venezuela, and the Soviet Union, followed the Japanese in conducting pelagic longline fishing throughout the Atlantic during the 1960s and 1970s (Mather 1995).

Market demand for large bluefin tuna increased dramatically during the 1970s and 1980s with the rise of the Japanese sushi-sashimi market, increasing the profitability of the fishery and leading to further increases in fishing capacity (Fromentin and Powers 2005, Porch 2005). The development of new technology for locating schools of bluefin tuna, storing landed fish at sea, and “farming”/fattening bluefin tuna in pens greatly increased the efficiency of the fishery (Fromentin and Powers 2005, ICCAT 2015). Landings, primarily driven by purse-seine effort, increased markedly in the Mediterranean Sea, where reported catches exceeded 50,000 mt in 1996, and were likely 50,000-61,000 mt annually during the following decade, due to widespread under-reporting of landings (Figure 3) (Fromentin and Powers 2005, ICCAT 2015). In contrast, landings in the western Atlantic have remained relatively stable since 1982, when a TAC with nation-specific quotas was imposed (Figure 4) (ICCAT 2015).

International management and stock status

Declining catches of Atlantic bluefin tuna in the 1960s demonstrated the need for international management of highly migratory fish species and led to the signing of the International Convention for the Conservation of Atlantic Tunas in 1966 (Porch 2005). The Convention was followed by the 1968 establishment of the International Commission for the Conservation of Atlantic Tunas (ICCAT), a regional fishery management organization responsible for the management and conservation of tunas and tuna-like species in the Atlantic Ocean (Porch 2005). However, no bluefin tuna regulations were adopted by ICCAT until a 6.4 kg minimum size was implemented in

1975 (ICCAT Rec. 74-01). Bluefin tuna stock assessments, using cohort analysis and virtual population analysis (VPA), began to be conducted by ICCAT's Standing Committee on Research and Statistics (SCRS) in the late 1970s (Fromentin and Powers 2005). In the early 1970s, bluefin tuna were assumed to constitute a single, Atlantic-wide stock; however, beginning in 1976 the SCRS began considering separate eastern and western stocks based on different spawning times and seasons, and tagging data that showed limited east-west exchange (ICCAT 2002, Fromentin and Powers 2005). In 1980, the SCRS presented separate stock assessments for eastern and western stocks, with the two management units divided at the 45° W meridian for statistical convenience (ICCAT 2002, Fromentin and Powers 2005). Atlantic bluefin tuna have continued to be managed by ICCAT as separate eastern and western stocks, although this strategy has come under increased scrutiny due to evidence of 1) extensive mixing between the putative stocks (for foraging), 2) additional spawning grounds in the Atlantic, and 3) more similar life-history characteristics (i.e., age at maturity) between eastern and western fish than previously believed (Lutcavage et al. 1999, Block et al. 2005, Rooker et al. 2008, Dickhut et al. 2009, Richardson et al. 2016, ICCAT 2017). As a result, the SCRS has explored alternative modes of assessing and managing bluefin tuna that, for example, explicitly incorporate east-west mixing (e.g., Powers and Porch 2004, ICCAT 2017).

Western stock

In recognition of a general decline in the western stock, ICCAT initiated a total allowable catch (TAC) for the stock beginning in 1982, followed by a 30 kg minimum size for harvest in 1992 (ICCAT Rec. 81-01, ICCAT Rec. 92-04, Porch 2005). The western stock continues to be managed using a TAC, which is divided among nations that

participate in the western fishery. The annual TAC has ranged from 800 mt (1982) to 2,700 mt (2003-2006), with landings peaking at 3,319 mt in 2002 (ICCAT Rec 81-01, ICCAT Rec 02-07, ICCAT 2015). Initially, nations that harvested less than their annual quota for a given year were able to carry forward up to 100% of that nation's allocated quota to the following year; however, the percentage of a nation's quota that could be carried forward in the event of underharvest was subsequently reduced to 50% and then to 10% in 2007 and 2011, respectively (ICCAT Rec. 98-07, ICCAT Rec. 06-06, ICCAT Rec. 10-03).

According to the 2017 stock assessment for western bluefin tuna, spawning stock biomass (SSB) declined from the mid-1970s to the early 1980s (when a TAC was imposed), and then fluctuated at about 50% of the 1974 level until the early 2000s (ICCAT 2015). In 1999, ICCAT began a 20-year rebuilding plan for western bluefin tuna which aimed to increase stock biomass to the size associated with maximum sustainable yield (B_{MSY}) with a 50% or greater probability by 2018 (ICCAT Rec. 98-07). According to both the VPA and Stock Synthesis (SS) models used for the 2017 stock assessment, total fishing mortality (F) has decreased and stock biomass has increased since the rebuilding plan was implemented (Figure 5) (ICCAT 2017). Recruitment for the western stock has generally varied without any pattern since the mid-1970s, with very strong recruitment occurring for the 2003 year class (ICCAT 2015).

As a result of uncertainties regarding future recruitment potential for both eastern and western Atlantic bluefin tuna stocks, in 2017 ICCAT's SCRS decided against evaluating the species using biomass-based reference points such as MSY (ICCAT 2017). Instead, F-based reference points, which do not require an understanding of a stock's

recruitment potential, were used, with $F_{0.1}$ serving as a proxy for F_{MSY} . $F_{0.1}$ was estimated using recent recruitment information, with the assumption that recruitment will be similar in the near future (ICCAT 2017). The 2017 assessment estimated that overfishing was not occurring ($F/F_{0.1} = 0.59$) for the western stock (ICCAT 2017). At the 2017 ICCAT meeting, the western bluefin TAC for 2018-2020 was set at 2,350 mt (ICCAT Rec. 17-06).

While the minimum size for western Atlantic bluefin tuna has been 30 kg since 1992, ICCAT, in recognition of the United States' historical recreational fishery for juvenile bluefin tuna, granted a tolerance of 8% for undersized fish to each nation fishing on the western stock—that is, nations could land up to 8% of their quota as sub-30 kg fish. However, the recommendation specified that sub-30 kg bluefin tuna could not provide any “economic gain”—that is, they could not be sold and thus could only be caught as part of a recreational fishery (ICCAT Rec. 92-04). In 2007, when the TAC was decreased, the tolerance for sub-30 kg fish was increased to 10%, again with the specification that those fish could not provide any economic gain (ICCAT Rec. 06-06). Currently, the 10% tolerance is balanced over a two-year period—that is, a nation's harvest of sub-30 kg bluefin tuna for two consecutive years cannot exceed 10% of the combined bluefin tuna quota over those two years (ICCAT Rec. 14-05).

Eastern stock

The eastern stock, thought to be approximately an order of magnitude larger than the western stock, was not managed using a TAC until 1999, when a 32,000 mt TAC was implemented; however, the TAC was undermined by serious under-reporting through 2007 and SSB remained at low levels through the mid-2000s (ICCAT Rec. 98-05,

ICCAT 2015). In 2007, ICCAT initiated a 15-year rebuilding plan intended to rebuild the stock to B_{MSY} with at least 50% probability by 2022 (ICCAT Rec. 06-05). The TAC gradually decreased to 22,000 mt in 2009, and then sharply decreased to 13,500 mt in 2010 due to a revision of the rebuilding plan to rebuild the stock to B_{MSY} with at least 60% probability by 2022 (ICCAT Rec. 09-06, ICCAT 2015). The TAC fluctuated between 12,900 and 13,400 mt from 2011-2014 before increasing to 16,142 mt in 2015, 19,296 mt in 2016, and 23,655 mt in 2017 (ICCAT 2017). The minimum size limit for eastern bluefin tuna was increased to from 6.4 kg to 10 kg in 2005, and subsequently to 30 kg—the same as for western bluefin tuna—in 2007, when the rebuilding plan was initiated (ICCAT Rec. 04-07, ICCAT Rec. 06-05).

Fishing mortality for juvenile eastern bluefin tuna (ages 2-5) increased through the late 1990s and then sharply declined in the late 2000s due to the increase in the minimum size limit (Figure 6a). For older fish (ages 10+), fishing mortality increased from the mid-1990s through the late 2000s—consistent with the targeting of large fish for Mediterranean “farming”/fattening operations—but subsequently declined in response to stricter TACs (Figure 6b). As a result, spawning stock biomass has increased since the late 2000s (Figure 6c). Recruitment, meanwhile, declined during the 2000s but increased in 2011 (ICCAT 2017).

As with the western stock, estimates of stock status for eastern Atlantic bluefin tuna (also described in ICCAT 2017) are based on F-based reference points rather than biomass-based reference points. The VPA model used in the 2017 assessment estimated that the eastern stock is not currently experiencing overfishing ($F/F_{0.1} = 0.34$). Stricter TACs and improved compliance with ICCAT regulations are credited with having helped

to improve the status of the eastern bluefin tuna stock. In its 2017 assessment, the SCRS projected that annual landings of up to 36,000 mt could be maintained through 2022 with a greater than 60% probability of overfishing not occurring (ICCAT 2017). As a result, at the 2017 ICCAT meeting the TACs for 2018, 2019, and 2020 were set at 28,200 mt, 32,240 mt, and 36,000 mt, respectively (ICCAT Rec. 17-07). However, overcapacity and non-compliance, which undermine rebuilding efforts, still remain of concern.

U.S. management

In the United States, Atlantic bluefin tuna are managed under the Atlantic Tunas Convention Act (ATCA) and the Magnuson-Stevens Fishery Conservation and Management Act (MSA) (NOAA 2006). The 1975 passage of the ATCA granted the National Marine Fisheries Service (NMFS) legislative authority to implement ICCAT recommendations (Nickler 1999). The MSA, passed in 1976, established a 200-mile exclusive economic zone (EEZ) and authorized the development of eight regional fishery management councils, and along with its subsequent amendments established 10 national standards for domestic fisheries management. Among these national standards was the requirement that all fishery management plans (FMPs) prevent overfishing while achieving optimum yield, the latter defined as the maximum sustainable yield “as reduced by any relevant economic, social, or ecological factor.” Other national standards include basing management upon the best available science, fairly allocating fishing privileges among users, and minimizing bycatch and bycatch mortality (NOAA 2007).

Despite the passage of the MSA, the U.S. fishery for bluefin tuna and other Atlantic tunas was not managed by regulations other than the implementation of ICCAT recommendations (under the ATCA) until the early 1990s. The 1990 amendment of the

MSA authorized the Secretary of Commerce to manage Atlantic tunas, along with other highly migratory species (HMS; tunas, billfish, swordfish, and sharks), in the EEZ. The Secretary delegated this management authority to NMFS, which created the Atlantic HMS Management Division in 1992 (NOAA 1999). The HMS Management Division is responsible for permitting, monitoring, and implementing regulations for all commercial and recreational HMS fisheries. In 1999, the HMS Management Division finalized the first FMP for Atlantic tunas, including bluefin tuna, and combined it with existing FMPs for swordfish (1985) and sharks (1993) to create a single FMP for Atlantic Tunas, Swordfish, and Sharks (i.e., the 1999 FMP). An existing FMP for billfish (1988) was added to the 1999 FMP in 2006 to create the Final Consolidated Atlantic HMS FMP (NOAA 2006).

The HMS Management Division domestically apportions ICCAT-allocated bluefin tuna quota among different user groups as specified in the 1999 FMP. These sub-quotas were initially set in 1992 when the HMS Management Division was established and were based on the historical share of the catch for each group from 1983-1991, though they were later adjusted due to the reduction of the purse-seine fishery (NOAA 1999). There are six separate user groups—five commercial and one recreational—among which the bluefin tuna sub-quota is divided: General (commercial handgear) (47.1% of U.S. quota); Angling (recreational) (19.7%); Purse Seine (18.6%); Longline (8.1%); Harpoon (3.9%); and Trap (0.1%). 2.5% of the U.S. quota is placed in the Reserve category to be allocated as needed over the course of the fishing year (FR 71 58058, 10/2/2006). The HMS Management Division has the authority to conduct in-season management actions to maximize use of the domestic bluefin tuna quota while

preventing overages, such as sub-quota transfers among categories/subcategories, changes to daily retention limits, and interim fishery closures (FR 71 58058, 10/2/2006).

Possession of an Atlantic HMS permit for a given category is necessary to target (and retain) bluefin tuna (or other Atlantic HMS) when using that gear type. Annual HMS permits can be purchased for each of these categories as well as for a seventh group, the Charter/Headboat (CHB) category, which can fish either under the Angling (recreational) or General (commercial) category (and thus contribute to both sub-quotas) on a trip-by-trip basis (64 FR 29090, 5/28/1999). The domestic bluefin tuna quota is also subdivided by size class, with size measured in curved fork length (CFL): young school (< 69 cm CFL); school (69 cm - < 119 cm CFL); large school (119 cm - < 150 cm CFL); small medium (150 cm - < 185 cm CFL); large medium (185 cm - < 206 cm CFL); and giant (206 cm CFL or greater) (60 FR 14381, 3/17/1995). Sixty-nine cm is equivalent to the 6.4 kg ICCAT minimum size implemented in 1975 (ICCAT Rec. 74-01), whereas 119 cm CFL, the size dividing the school and large school sizes, is equivalent to the current 30 kg ICCAT minimum size (60 FR 14381, 3/17/1995). Recreational anglers primarily target and harvest bluefin tuna measuring less than 185 cm CFL, whereas commercial fishermen have been restricted to harvesting fish measuring greater than 185 cm CFL since 1992 (Murray-Brown et al. 2007).

The U.S. recreational Atlantic bluefin tuna fishery

History

Recreational fishing for Atlantic bluefin tuna became popular in the waters off the U.S. east coast and Atlantic Canada in the early 20th century, although anglers were catching bluefin tuna in this region with hook and line as early as the 1870s (Anderson

1990). During the 1920s, 1930s, and 1940s, wealthy anglers, inspired by adventure writers such as Ernest Hemingway and Zane Grey, caught bluefin tuna using a variety of methods, including trolling and drifting with dead bait, from North Carolina to Nova Scotia. The increasing popularity of the fishery eventually gave rise to tuna fishing clubs and charter boats in popular fishing locations such as Sea Bright, NJ and Montauk, NY (Farrington 1937, Heilner 1937, Farrington 1949, Schmidt 1985, Bochenek 1989). Elite pioneering anglers from North and South America and even from Europe traveled to Nova Scotia, Maine, and Massachusetts each summer and fall to target giant bluefin tuna with rod and reel, landing fish to over 400 kg (Farrington 1937, Farrington 1949, Grey [date unknown]). South of Cape Cod, anglers targeted juvenile bluefin tuna, called “junior torpedoes” by sportfisherman and writer S. Kip Farrington, Jr., during the late spring and summer months (Farrington 1949). Following World War II, recreational fisheries for bluefin tuna and other HMS became more popular along the U.S. east coast due to the greater availability and affordability of sportfishing boats as well as improved technology for locating and catching fish (Bochenek 1989, Anderson 1990, Marcek 2013).

Recreational fishery: current characteristics

Presently, recreational anglers target bluefin tuna aboard both charter and private vessels from Maine to North Carolina (Marcek 2013), and utilize a variety of methods, including trolling, live-bait fishing, chumming/chunking with dead bait, and light-tackle casting or jigging with artificial lures. The geographic distribution and availability of bluefin tuna along the U.S. east coast varies from year to year (Marcek 2013). Generally,

however, a winter fishery for small medium and large medium/giant-size bluefin tuna occurs from January-March off North Carolina's Outer Banks and southern Virginia. Historically, a fishery for school-size bluefin tuna has occurred off the coasts of Virginia and Maryland during the late spring and early summer months, although in recent years catches in the southern management region have been low compared to those from more northern ports (Figure 7) (personal communication, J. Graves, VIMS, 2016; personal communication, NMFS, Fisheries Statistics Division, 2017). Anglers off the coast of southern New England target bluefin tuna ranging in size from school-size fish to giants during the summer and through the fall, while the fishery in the Gulf of Maine during that time period has primarily landed fish greater than 185 cm CFL over the past several years.

The recreational fishery for bluefin tuna and other HMS is of considerable economic importance to many coastal communities and individuals on the U.S. east coast. Economic impacts resulting from recreational HMS fisheries arise from several sources, including private angler expenditures, tournaments, recreational charters, and businesses that support HMS fishing activities (e.g., tackle shops, marinas, hotels) (NOAA 2017). A survey of HMS Angling category permit holders (private anglers) from Maine to North Carolina estimated that in 2011, this group spent \$23.2 million in direct trip expenditures (e.g., fuel, bait), \$151 million on durable goods (e.g., boats, fishing tackle), and generated \$266 million in total economic output (Hutt et al. 2014). These estimates do not represent the total economic impacts associated with HMS fishing, as the study only surveyed private HMS anglers who own vessels, not others who fish on those private vessels, or operators or participants in the for-hire HMS fishery. Given the

high costs associated with targeting HMS (e.g., tackle, boats), the for-hire charter industry plays an important role in providing HMS fishing opportunities to anglers who otherwise would not have access to such species (Hutt and Silva 2015). A 2013 logbook study on the for-hire (charter) sector by Hutt and Silva (2015) found that HMS charters from Maine to Virginia generated \$12.1 million in gross revenue, \$4.8 million in net returns, and \$31.9 million in economic output. Bluefin tuna were the third-most commonly targeted HMS by charters in this region, at 35% of all trips (Hutt and Silva 2015). Only one study has specifically examined the economic activity associated with the recreational Atlantic bluefin tuna fishery: Bohnsack et al. (2002) surveyed recreational anglers (private-boat anglers and charter clients) who participated in the 1997 winter (January-March) bluefin tuna fishery off Hatteras, NC and found that they spent nearly \$3.6 million locally, resulting in an economic impact of \$4.6 million on the Hatteras-area economy (Bohnsack et al., 2002).

Management

As is described in the 1999 FMP and the subsequent 2006 Consolidated Atlantic HMS FMP, the recreational Angling category is domestically apportioned 19.7% of the U.S. bluefin tuna quota allocated by ICCAT. For 2017, as for 2015 and 2016, the recreational sector's sub-quota amounted to 195.2 mt (82 FR 19615, 4/28/2017). This sub-quota is further divided among the different bluefin tuna size classes and between the northern and southern regions of the U.S. east coast, divided at 39°18' N latitude (Great Egg Inlet, NJ), in order to maintain equity in bluefin tuna access/landings along the coast (Table 1) (66 FR 42801, 8/15/2001). Recreational anglers primarily target bluefin tuna in the school, large school, and small medium size classes, with only a very small annual

quota (maximum 2.3% of Angling sub-quota) for “trophy” (185 cm CFL or greater; i.e., large medium and giant-size) bluefin tuna, which was provided for the recreational fishery beginning in 1995 and is equally divided among the north region, south region, and Gulf of Mexico (large bluefin tuna are incidentally encountered by anglers targeting other tunas and billfish in the Gulf of Mexico) (60 FR 38505, 7/27/1995; FR 71 58058, 10/2/2006; 79 FR 71510, 12/2/2014). Harvest of school-size bluefin tuna is limited to 10% of the U.S. quota (108.4 mt for 2017) balanced over a two-year period (ICCAT Rec. 14-05); of that total, 18.5% (20.1 mt) is kept as a reserve for in-season or annual adjustments and fishery-independent research (FR 71 58058, 10/2/2006; 80 FR 52198, 8/28/2015). Of the remaining 88.3 mt, 52.8% (46.6 mt) is allocated to the southern region and 47.2% (41.7 mt) is allocated to the northern region (FR 71 58058, 10/2/2006; 80 FR 52198, 8/28/2015). For 2017, a total of 4.5 mt of “trophy” bluefin tuna was allocated to the Angling category, with 1.5 mt allocated to the northern region, southern region, and the Gulf of Mexico, respectively (80 FR 52198, 8/28/2015). Once the school and trophy landings limits have been accounted for, the remaining Angling category quota is designated for the large school and small medium size classes, which are largely managed together for quota and regulation purposes (personal communication, S. McLaughlin, NMFS). For 2017, the annual sub-quota for large school/small medium bluefin tuna was 82.3 mt; as with the school category, 52.8% (43.5 mt) was allocated to the southern region, and 47.2% (38.9 mt) was allocated to the northern region (FR 71 58058, 10/2/2006; 80 FR 52198, 8/28/2015). The HMS Management Division has the authority to transfer bluefin tuna quota among these size class- and region-based subcategories over the course of a fishing season, as long as doing so does not result in

more than 10% of domestic harvest consisting of school-size bluefin tuna (FR 71 58058, 10/2/2006).

In addition to the previously mentioned in-season quota transfers, the HMS Management Division uses a combination of permitting, size and bag limits, and monitoring to facilitate bluefin tuna harvest while maintaining landings within the Angling category sub-quota. In order to target and harvest bluefin tuna and other HMS recreationally, vessel owners must obtain annually for each vessel either an HMS Angling or HMS CHB permit (67 FR 77434, 12/18/2002). CHB permit holders are required to possess a valid Merchant Marine License or Uninspected Passenger Vessel License (64 FR 29090, 5/28/1999). As of October 2016, from Maine to North Carolina, where almost all directed bluefin tuna effort occurs on the U.S. east coast, there were 12,716 Angling-permitted vessels and 2,463 CHB-permitted vessels (NOAA 2017). The HMS Management Division regulates harvest based on daily and annual size and bag limits for each permit holder group, reserving the right to adjust such limits (including closing harvest) over the course of a season in order to maximize utilization of the Angling sub-quota and prevent overages (FR 71 58058, 10/2/2006). Retention limits for CHB permit holders tend to be more liberal than those for Angling permit holders in order to attract charter clients (FR 80 27863, 5/15/2015). The default recreational retention limit for both permit holder groups is one school, large school, or small medium-size bluefin tuna per vessel per day, along with one large medium or giant-size bluefin tuna per vessel per year (i.e., annual trophy) (64 FR 29090, 5/28/1999). Since 1999, daily harvest limits for school, large school, and small medium-size bluefin tuna have varied widely, ranging from as many as one combined school, large school, and

small medium-size bluefin tuna per *person* per day for both Angling and CHB permitted vessels (up to 6 bluefin tuna per private vessel, and up to 35 bluefin tuna per charter vessel [headboat]) to a complete prohibition on harvest for all size classes for both permit holder groups to account for the previous year's overharvest (FR 68 35822, 6/17/2003; 68 FR 64990, 11/18/2003). Generally, however, daily harvest limits for these three size classes combined has ranged between one and three bluefin tuna per vessel per day for both permit holder groups.

To monitor the harvest of Atlantic bluefin tuna and other HMS, the HMS Management Division relies on a combination of survey data and self-reporting by HMS permit holders. Since 1992, NMFS has administered the Large Pelagics Survey (LPS) from Maine to Virginia from June through October. The LPS utilizes a dockside intercept survey (Large Pelagics Intercept Survey; LPIS) to estimate average recreational catch per trip (harvested, released alive, and released dead) by species for private and charter vessels. In addition, the LPS uses a telephone survey (Large Pelagics Telephone Survey; LPTS) of HMS Angling and CHB permit holders to assess average effort (Foster et al. 2008). Furthermore, the HMS Management Division requires Angling and CHB permit holders to report any recreational bluefin tuna landings or dead discards within 24 hours of the end of the trip via the Automated Landings Reporting System (ALRS), accessed either via phone, internet, or smartphone app (79 FR 71510, 12/2/2014; FR 82 19615, 4/28/2017). Reporting via the ALRS is not required in Maryland and North Carolina, where catch-card programs exist (NOAA 2013).

Management challenges and rationale for research

Managing the recreational bluefin tuna fishery remains a significant challenge for the HMS Management Division, despite the strategies outlined above. Lack of effective real-time monitoring of recreational bluefin tuna harvest inhibits the Management Division's ability to track recreational harvest over the course of a fishing season and can lead to Angling category sub-quota overages (Nickler 1999, NOAA 2013). The two means by which recreational bluefin tuna harvest is measured over most of the fishery's range—LPS and ALRS—have each been shown to have significant shortcomings.

The LPS catch and effort estimates typically operate on a lag of about one month—for example, landings estimates for the month of July would not be available until the end of August (NOAA 2013; personal communication, S. McLaughlin, NMFS). During periods of high landings, this lack of real-time catch data could compromise the ability of the HMS Management Division to prevent landings overages for the bluefin tuna Angling sub-quota. In addition, the limited sample frame (Maine through Virginia, June-October) may result in underestimates of catch or effort (e.g., if bluefin tuna were to appear off the Virginia coast in May). Another major concern with the LPS pertains to assumptions regarding coverage gaps in the survey—that is, the catch and landings of HMS anglers who are not sampled by the LPIS or LPTS, respectively (Foster et al. 2008). For example, the LPIS does not sample trips that return to port at night, or which return to private docks; catch rates for these groups are not assumed to differ from those of anglers who are surveyed during the day at public locations, but that assumption has not been tested. Similarly, the effort of anglers not surveyed by the LPTS—vessels fishing illegally (e.g., without an HMS permit), vessels fishing in a state different from their

permitted state, and vessels permitted after creation of the LPTS sample frame for that year—may differ from that of anglers who are sampled by LPTS (Foster et al. 2008).

The ALRS was intended to serve as a real-time census-based tool for monitoring recreational bluefin tuna harvest. However permit holders' extremely low compliance (10-20%) with this reporting requirement has impeded the ALRS's effectiveness as a management tool (NOAA 2006, NOAA 2013). Such poor compliance makes it difficult for the HMS Management Division to quickly adapt management measures in response to periods of intensive effort and high landings, which can result in bluefin tuna sub-quota overages for the Angling category sector.

The most prominent example of such an overage occurred during 2009, when the Angling category dramatically exceeded its allocated sub-quota. The large 2003 western Atlantic bluefin tuna year class (ICCAT 2017) led to a high availability of small medium-size (six-year-old) fish off the southern New England coast in 2009, resulting in an estimated 566 mt of Angling category landings—nearly three times the 199 mt base quota (NOAA 2013). These high catch rates occurred despite the fact that, for the entirety of 2009, the daily bag limit for the large school/small medium size class never exceeded one fish per vessel per day for both Angling and CHB permit holders (74 FR 26110, 6/1/2009). While the overall U.S. base quota was not exceeded that year due to low commercial landings, commercial landings since 2009 have increased, and future Angling category overages could result in U.S. quota overages. Due to concerns about again exceeding the Angling sub-quota, harvest of small medium-size bluefin tuna was prohibited for the majority of the 2010 and 2011 fishing seasons, a management action that drew the criticism of charter captains who expressed the need for more stable

regulations for marketing purposes (75 FR 33531, 6/14/2010; 76 FR 18416, 4/4/2011; NOAA 2013). In addition, these regulations, adjusted during the spring following catch estimates for the North Carolina winter fishery, enabled harvest of small medium-size bluefin tuna for the southern management region while prohibiting harvest of fish of that size class in the northern region, a management action not in accordance with the MSA's fourth National Standard of "fair and equitable" allocation" (C.F. R. §600.325).

In recent years, there have been efforts to improve monitoring capabilities for recreational bluefin tuna harvest. For example, a 2012 pilot study in Massachusetts demonstrated the potential of more broadly implementing census-based landings tag programs like those in Maryland and North Carolina to improve real-time monitoring capabilities and more nimbly respond to periods of high catch (NOAA 2013). In addition, upcoming methodological changes to the LPS and more user-friendly angler reporting strategies (e.g., smartphone apps for the ALRS) may serve to reduce uncertainty regarding landings estimates (personal communication, D. Van Voorhees, NMFS, 2015; NOAA 2016; FR 82 19615, 4/28/2017).

Despite these potential improvements to monitoring recreational bluefin tuna harvest, significant challenges to effectively managing the fishery remain. First, while knowledge of bluefin tuna recruitment and movements continues to improve, very little is known about the motivations, preferences and values of recreational bluefin tuna anglers. Without understanding what drives angler behavior, it is difficult to predict how angler effort and harvest may vary as a function of changing fish availability (e.g., abundance, size distribution, and proximity to the coast) or changes in regulations. For CHB permit holders, such factors may also influence decision-making regarding whether to

target/harvest juvenile (sub-185 cm) bluefin tuna (thereby contributing to the Angling sub-quota), or whether to target adult bluefin tuna for commercial sale (thereby contributing to the General sub-quota). This lack of forecasting ability may jeopardize the capacity of the HMS Management Division to keep harvest within the Angling sub-quota (and the overall U.S. bluefin tuna quota). Even if in-season monitoring capabilities were to improve, constantly changing regulations over the course of a season in response to changing harvest could prove economically disruptive (e.g., charter captains may not be able to advertise a given catch limit). In addition, while the economic impacts of bluefin tuna and other HMS fisheries have been examined (e.g, Hutt et al. 2014), the lack of understanding of angler preferences and values limits the ability of the HMS Management Division to maximize the fishery's socioeconomic benefits, thereby preventing it from achieving optimum yield as required by the first National Standard of the MSA (C.F.R. §600.310).

A second major challenge for managing the recreational bluefin tuna fishery is estimating the discard mortality of bluefin tuna that are released, either voluntarily or due to regulations, by recreational anglers. Previous studies on some of the bluefin tuna size classes have suggested low post-release mortality, but in order to fully understand the recreational fishery's impact (i.e., fishing mortality) on the bluefin tuna stock, inform management strategies, and provide anglers with guidelines to reduce post-release mortality, further studies across different size classes and gear types are necessary.

Human dimensions research in recreational fisheries

Over the past several decades, resource management scholars have increasingly called for better integration of the social sciences into fisheries management. As early as

the 1970s, some individuals recognized the need to consider fisheries management within a broader conceptual framework of the “human ecosystem” (reviewed in Voiland and Duttweiler 1984). According to Orbach (1980), understanding the human component of fisheries is important for predicting how management actions will affect the well-being of people involved in a fishery, as well as for informing the allocation of fishery resources among competing groups (e.g., commercial and recreational) depending on the importance of the fishery to each group. In addition, without properly understanding the preferences and motivations of fishermen, management strategies may have unintended consequences on the behavior of fishermen (e.g., effort and harvest), and thus on the fishery resource itself, undermining management’s effectiveness and threatening a fishery’s sustainability (Fulton et al. 2011, Fenichel et al. 2013, Hunt et al. 2013). Fishing behavior may, for example, change as stock status or management strategies change, and simply extrapolating past behavior under different conditions could lead to inaccurate predictions (Fulton et al. 2011). And yet even into the 2000s, despite the large amount of social science literature on the human dimensions of fisheries, fisheries scientists and managers rarely incorporate such considerations into assessment and management processes, and a considerable disconnect persists between social scientists and natural scientists working on fisheries issues (Fulton et al. 2011, Fenichel et al. 2013, Hunt et al. 2013).

Understanding the preferences, motivations, and behavior of recreational fishermen can be especially challenging because unlike commercial fishermen, their incentive to go fishing is something other than maximizing profit. Motivations for recreational fishing can generally be grouped into catch-related (e.g., catching trophy

fish, obtaining fish for eating) and non-catch-related (e.g., experiencing nature, spending time with friends) factors, and can vary widely across different angler groups (e.g., fishing mode, target species) (Calvert 2002, Fedler and Ditton 1994). But understanding angler motivations and preferences for a given recreational fishery is critical to ensure that the benefits of the fishery to those using it are being maximized (Fedler and Ditton 1994). Some researchers have created conceptual frameworks that bring together the biological and human aspects of recreational fisheries and demonstrate how human dimensions research can be explicitly incorporated into management (e.g., Hunt et al. 2013, Fenichel et al. 2013) (Figure 8). The intent of such frameworks is to guide management actions that can maximize welfare of anglers in a given fishery while maintaining an acceptable level of fishing mortality. Yet such a system requires appropriate, fishery-specific inputs—for example, definitions of angler welfare, and predictions of how angler effort, fish harvest/mortality and angler welfare may change as management and stock status changes. Furthermore, the definition and maximization of welfare can be difficult, because while objectives for the biological system and the economic component of the human system are frequently well-defined, social objectives for a fishery are usually less clear (Fulton et al. 2011). Not defining these objectives impedes the achievement of optimum yield and fair and equitable allocation among user groups, as required by the first and fourth National Standards of the MSA (C.F.R. §600.310, C.F.R. §600.325).

In recognition of the socioeconomic value of recreational angling as well as the sector's potentially high harvest/fishing mortality rates for certain species, NMFS recently strengthened efforts to better understand and enhance recreational fisheries. As

part of its effort to improve its relationship with the recreational community, NMFS announced the Recreational Fisheries Engagement Initiative in 2009 and appointed a National Policy Advisor for Marine Recreational Fisheries (NOAA 2011). In 2010, NMFS held the first National Saltwater Recreational Fishing Summit, which led to the development of national and regional Recreational Saltwater Fisheries Action Agendas (including one for HMS) in 2014 and the publication of the National Saltwater Recreational Fisheries Policy in 2015 (NOAA 2014a, NOAA 2015). The National Saltwater Recreational Fisheries Policy specified six guiding principles, including: promote public access to quality recreational fishing opportunities; provide social, cultural, economic, and ecological information on recreational fisheries; and communicate and engage with the recreational fishing public (NOAA 2015). The 2016-2017 HMS Regional Implementation Plan for this new policy supports the promotion of fair and equitable access to recreational HMS fisheries, management that improves recreational opportunities for HMS, and socioeconomic analyses of HMS anglers to assess the effects of current or proposed regulations (NOAA 2016). Improved understanding of the human dimensions of HMS recreational fishermen—who are highly specialized and may have different preferences and values than anglers who target other species (Bohnsack et al. 2002, Ditton and Stoll 2003)—would enhance effective management of Atlantic bluefin tuna and other HMS while addressing the Guiding Principles of the National Saltwater Recreational Fisheries Policy.

Post-release mortality research in recreational fisheries

Quantifying post-release mortality—the percentage of fish that die following release—is critical for estimating the overall contribution of recreational fisheries to

fishing mortality for a given species or stock. Such information is important both for stock assessment purposes and for inter-sector (e.g., commercial/recreational) allocation decisions, where the relevant good to allocate is fishing mortality rather than landings (Abbott 2015). Post-release mortality has the potential to influence a stock's size and age structure and can vary widely across species, environmental conditions, fishing gear, and method of capture (Muoneke and Childress 1994, Cooke and Suski 2005, Arlinghaus et al. 2007, Pollock and Pine 2007). While some general factors may influence post-release mortality across species (e.g., mechanical damage, air exposure, angling duration), species-specific research—and environment-, gear-, and method-specific research for those species—is necessary (Cooke and Suski 2004; Cooke and Suski 2005).

Post-release mortality research on HMS is valuable not only for sharpening estimates of fishing mortality resulting from recreational fishing (e.g., for inputs into stock assessments), but also for promoting regulations and best practices for reducing post-release mortality (Horodysky and Graves 2005, Graves and Horodysky 2008, Heberer et al. 2010, Graves et al. 2016). Given the importance of such research, in 2014 the HMS Management Division included estimating post-release mortality of HMS across gear types as a high-priority research item (NOAA 2014b). Furthermore, the 2016-2017 Atlantic HMS Regional Implementation Plan for the National Saltwater Recreational Fisheries Policy included “promoting best practices for safely handling and releasing fish” as a key objective (NOAA 2016).

Dissertation objectives

The purpose of this dissertation is to better understand the decision-making, preferences, and values of Atlantic bluefin tuna fishermen while also improving estimates

of the overall impact (i.e., fishing mortality) of the recreational fishery on the bluefin tuna resource. Chapter II uses a stated choice modeling approach to examine the motivations, values, and preference heterogeneity of private recreational anglers who target bluefin tuna. Chapter III uses a novel sequential stated choice technique to investigate the factors that affect the trip type decisions (commercial or recreational) of CHB permit holders. Together, these results will help to inform optimal management of the U.S. Atlantic bluefin tuna fishery that maximizes welfare derived from the fishery while also providing valuable effort and harvest forecasting information that can be used to predict the effect of regulations on fishing mortality. Chapter IV describes the use of a novel solar-powered pop-up satellite tag to estimate post-release mortality in the increasingly popular light-tackle recreational fishery for juvenile bluefin tuna, which will improve estimates of overall fishing mortality resulting from the fishery while also informing best practices to ensure safe release.

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Table 1. 2017 Atlantic HMS Angling category baseline quotas by size class and region.
Sources: FR 71 58058, 10/2/2006; 80 FR 52198, 8/28/2015.

Size Class	2017 quota (mt)	% of size class quota	% of Angling quota
School^a			
Reserve	20.1	18.5	--
North of 38°18'N	41.7	47.2	--
South of 38°18'N	46.6	52.8	--
Total	108.4	--	55.5
Large school/small medium			
North of 38°18'N	38.9	47.2	--
South of 38°18'N	43.5	52.8	--
Total	82.3	--	42.2
Large medium/giant			
North of 38°18'N	1.5	33.3	--
South of 38°18'N	1.5	33.3	--
Gulf of Mexico	1.5	33.3	--
Total	4.5	--	2.3
Overall	195.2	--	--

^a The percentages allocated to the northern and southern regions reflect the allocation after accounting for the reserve; a total of 88.3 mt was allocated between the regions in 2017.

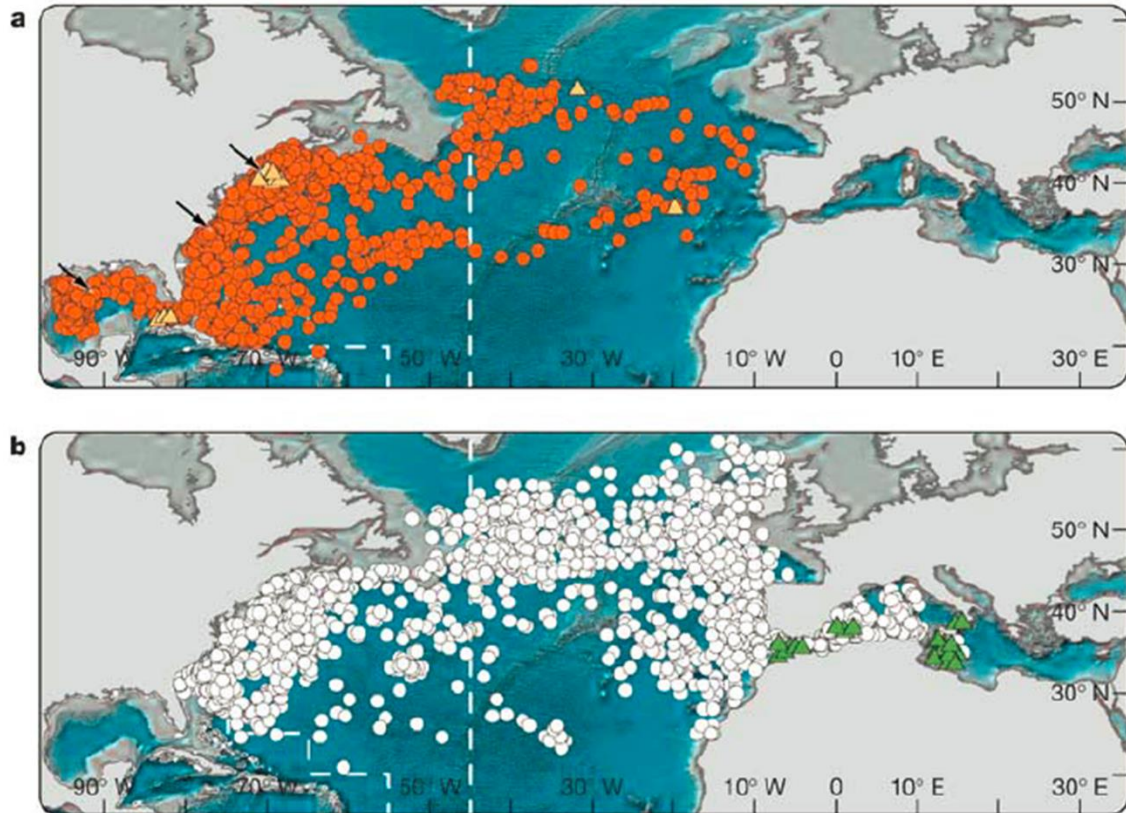


Figure 1. Estimated positions (circles) of Atlantic bluefin tuna electronically tagged with internal archival and pop-up satellite archival tags off the east coast of the United States (black arrows) during 1996-2004 by Block et al. (2005). **a.** Positions of Atlantic bluefin tuna characterized as western breeders ($n = 36$). **b.** Positions of Atlantic bluefin tuna characterized as eastern breeders ($n = 26$). Triangles in each panel represent recapture locations of electronically tagged fish. The vertical dashed line in both panels represents the 45° W meridian used by ICCAT to separate the eastern and western stocks. Figure courtesy of Block et al. 2005.

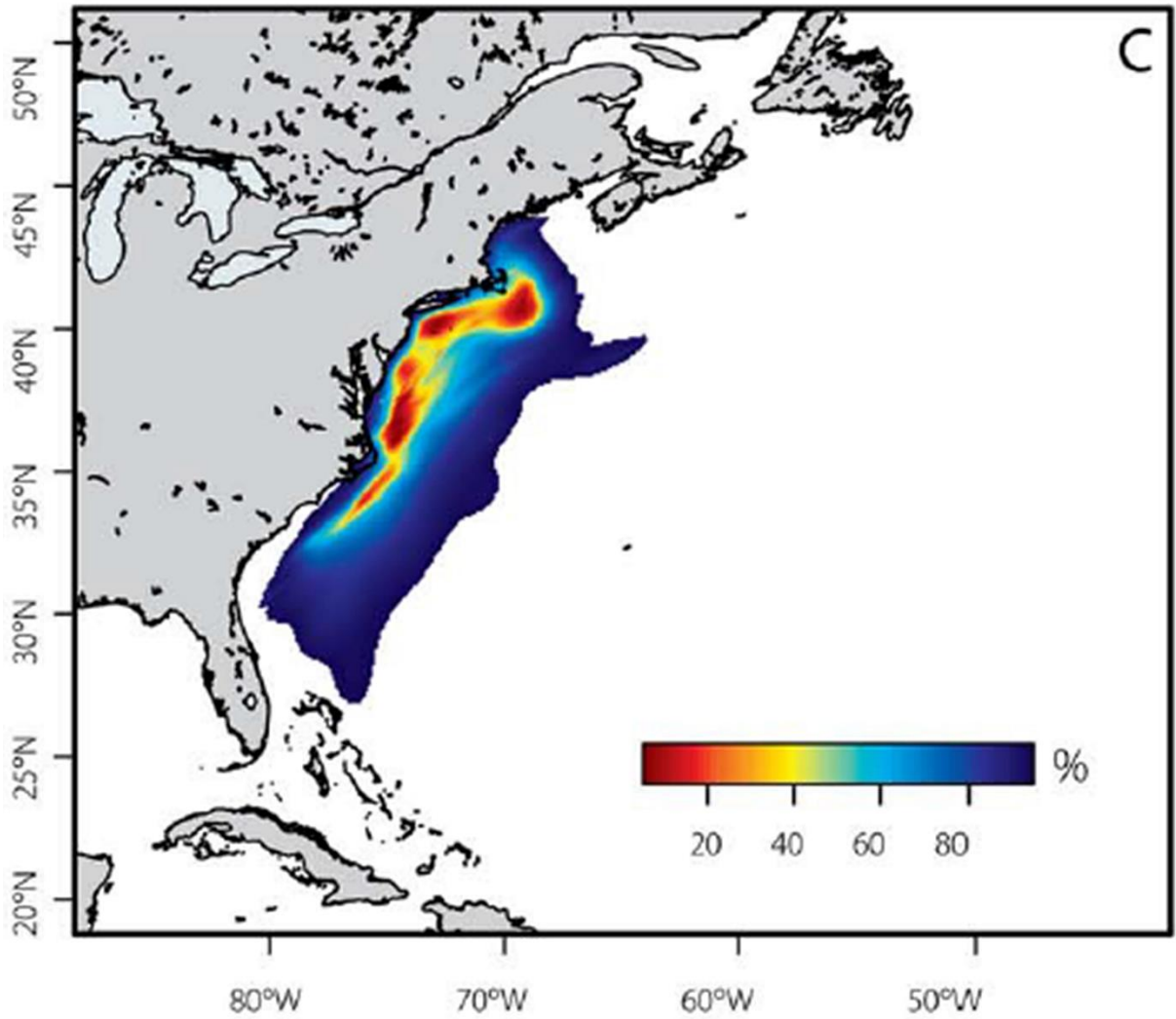


Figure 2. Aggregated utilization distribution along the U.S. east coast for 26 juvenile Atlantic bluefin tuna tagged with pop-up satellite archival tags during 2007-2009 by Galuardi and Lutcavage (2012). Tagged fish made extensive use of coastal waters extending from Cape Cod south to Cape Hatteras. Figure courtesy of Galuardi and Lutcavage 2012.

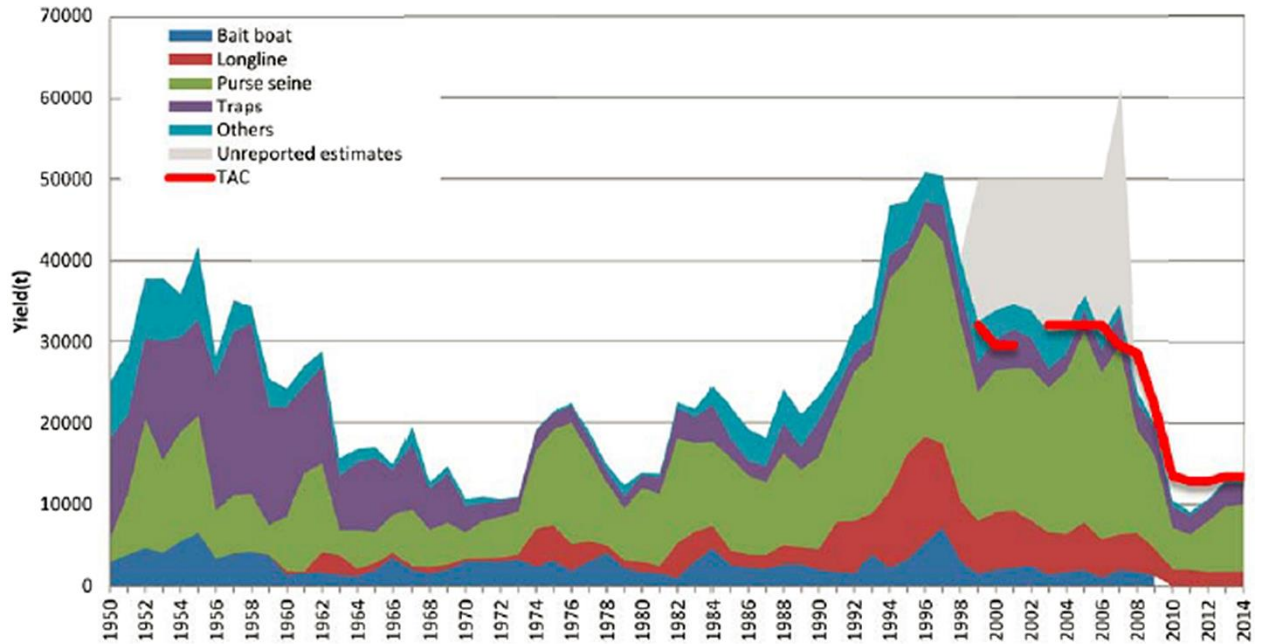


Figure 3. Atlantic bluefin tuna landings in the eastern Atlantic and Mediterranean from 1950 to 2014 by gear type. The gray area for the years 1998 to 2007 represents the estimated unreported landings during that time period. “TAC” refers to the annual total allowable catch. Figure courtesy of the ICCAT Standing Committee on Research and Statistics (2017).

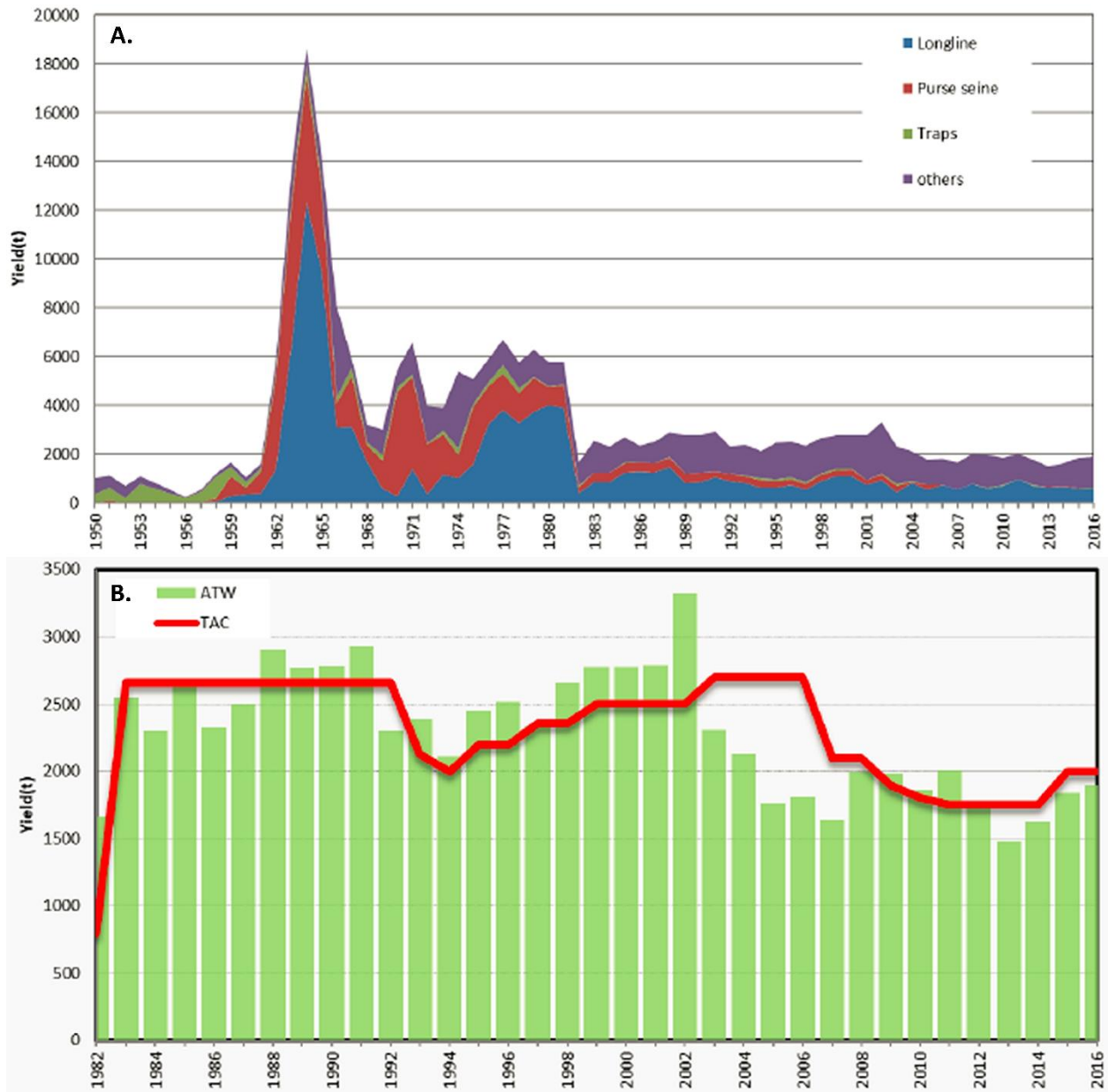


Figure 4. Atlantic bluefin tuna landings in the western Atlantic from 1950-2016 by gear type (a) and since the imposition of an annual total allowable catch (TAC) beginning in 1982 (b). Figure courtesy of the ICCAT Standing Committee on Research and Statistics (2017).

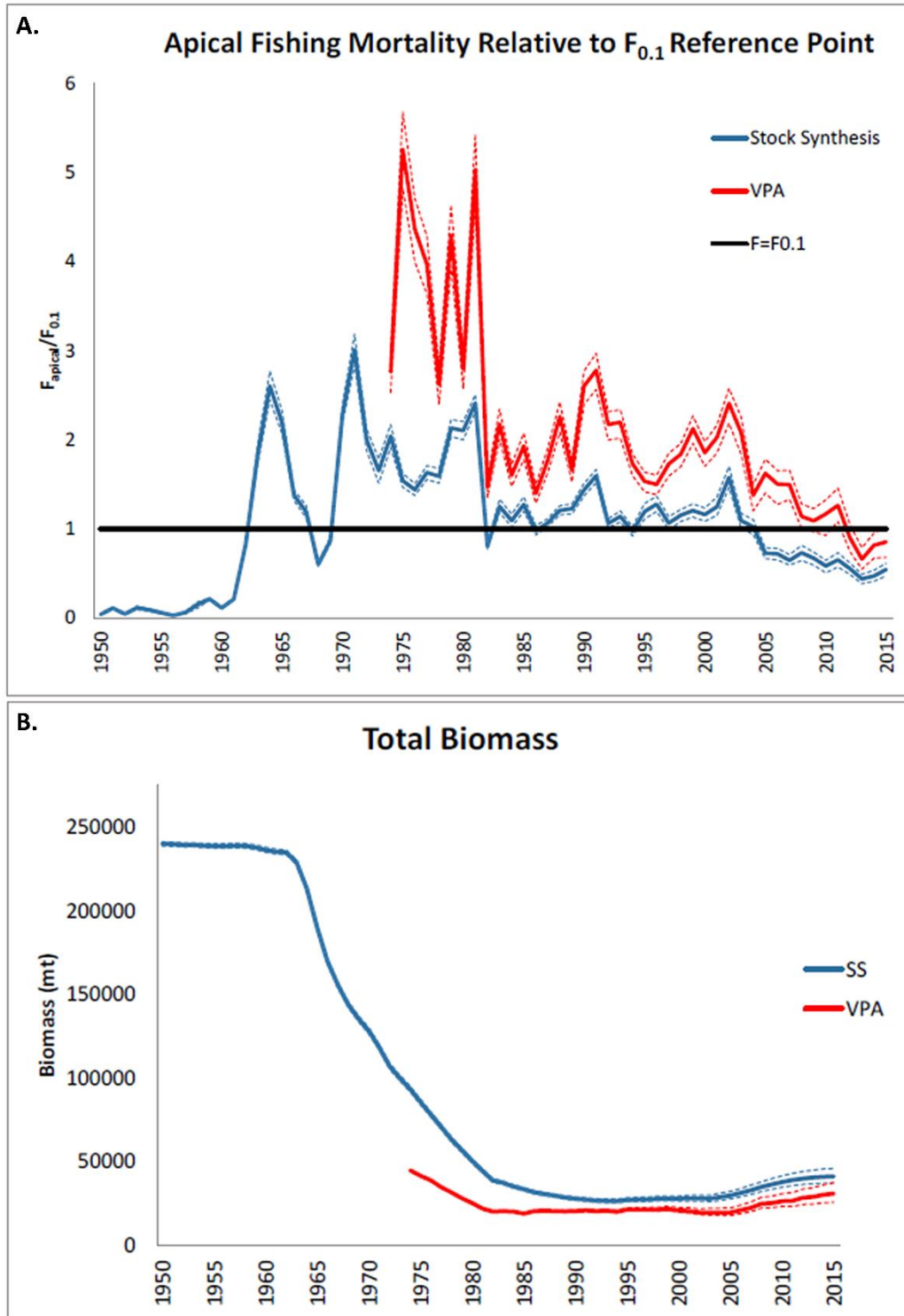


Figure 5. Estimated fishing mortality (a) and biomass (b) since 1950 for the western stock of Atlantic bluefin tuna, based on Stock Synthesis (SS; blue) and virtual population analysis (VPA; red) models. Dashed lines indicate 80% confidence intervals. Figures courtesy of the ICCAT Standing Committee on Research and Statistics (2017).

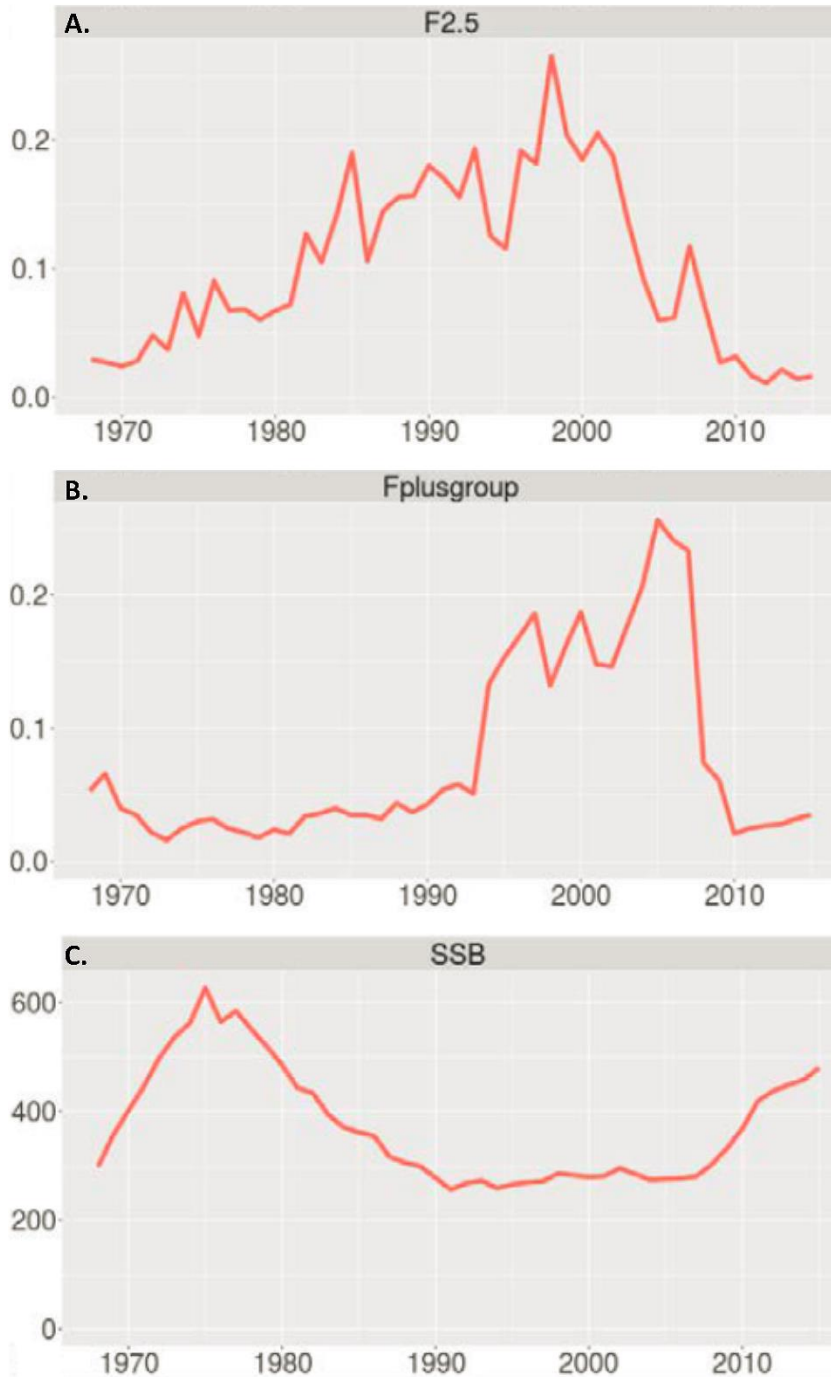


Figure 6. Estimated fishing mortality and spawning stock biomass for eastern Atlantic bluefin tuna, based on the VPA model used for the 2017 stock assessment. **a.** Estimated fishing mortality for fish ages 2-5. **b.** Estimated fishing mortality for fish ages 10+. **c.** estimated spawning stock biomass (in thousands of metric tons). Figures courtesy of the ICCAT Standing Committee on Research and Statistics (2017).

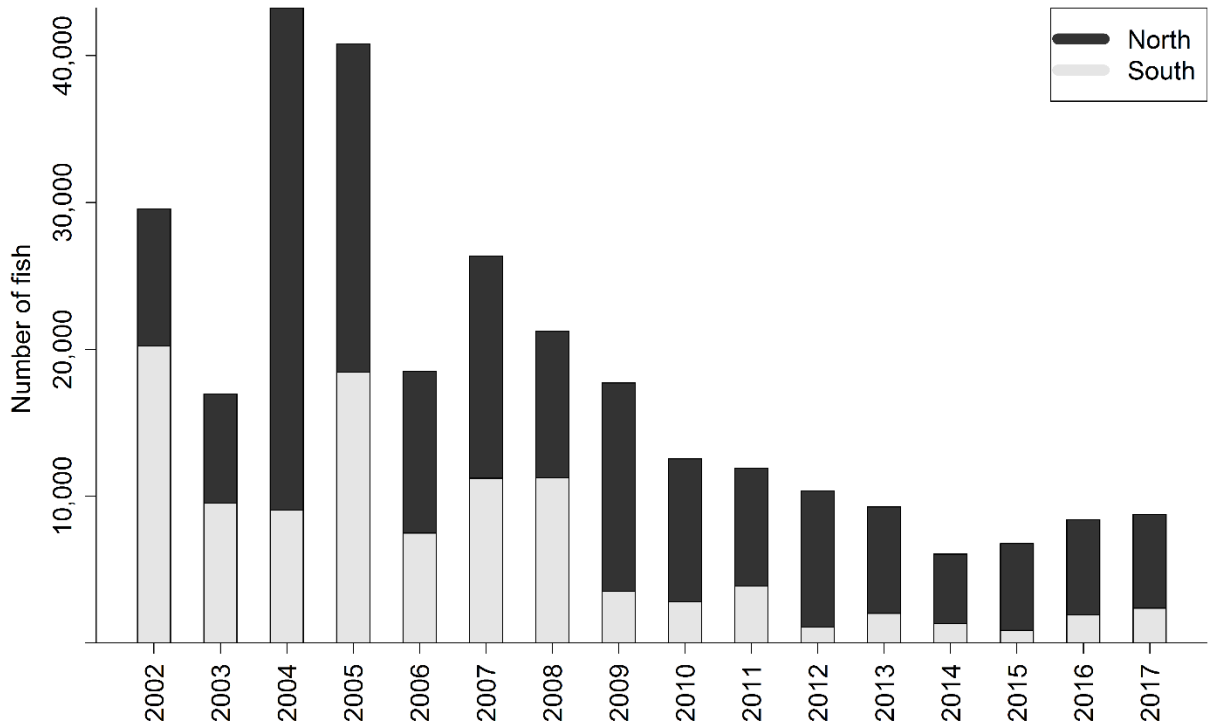


Figure 7. Total number of school-, large school-, and small medium-size bluefin tuna (< 185 cm CFL) caught (both harvested and released) from 2002-2017 in the northern and southern bluefin tuna management regions (north and south of 38°18'N, respectively) along the U.S. east coast, based on LPS estimates (personal communication, NMFS, Fisheries Statistics Division, 2017). Percent standard errors for annual catch estimates range from 9.1-22.5% for the northern management region and from 6.5-18.8% for the southern management region. 2017 estimates are preliminary (data were accessed 12/03/2017).

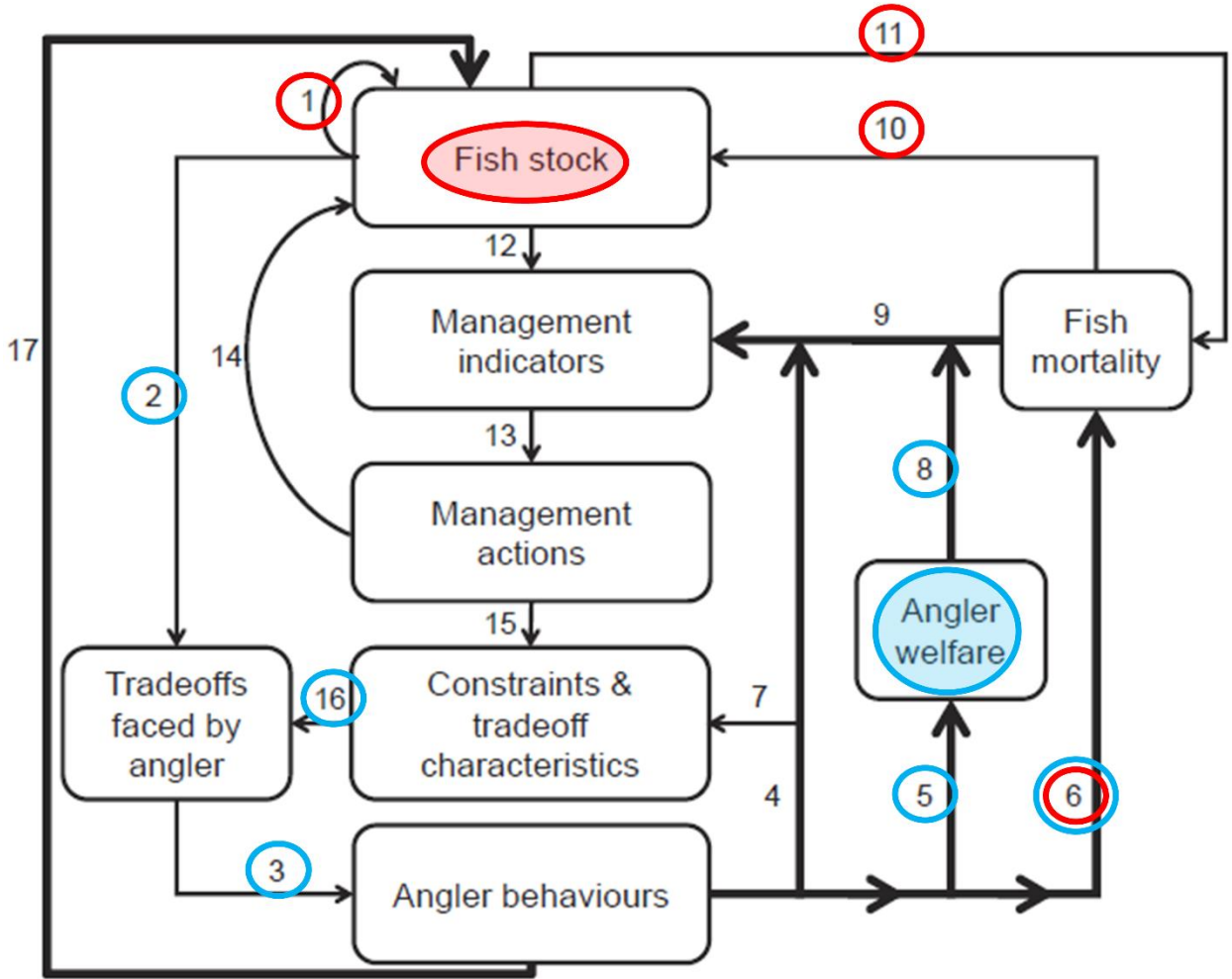


Figure 8. A conceptual model of the recreational fisheries system developed by Fenichel et al. (2013), with linkages indicated by arrows. Fisheries science typically focuses on the state of the fish stock itself (red), including growth, reproduction, and movements (1) as well as mortality (10) resulting from both fishing (6) and natural (10) causes. Often neglected, however, is the human component of the recreational fisheries system (blue), including how stock status (2) and management impacts (16) affect angler behavior (3), welfare (5), and fishing mortality (6), as well as how angler welfare considerations should be incorporated into management efforts (8). Figure courtesy of Fenichel et al. (2013).

CHAPTER II

Characterizing the Preferences and Values of U.S. Recreational Atlantic Bluefin Tuna

Anglers

ABSTRACT

The Atlantic Bluefin Tuna (*Thunnus thynnus*) is the target of a recreational fishery along the U.S. east coast that is thought to be of considerable economic value. In some years, recreational landings have exceeded the sector's annual sub-quota due to changes in fish availability, limited predictability of angler effort, and difficulties in real-time monitoring of catch. Understanding the drivers of angler behavior is critical for predicting how effort and harvest may vary as a function of changing fish availability, regulations, or costs. To investigate angler decision-making, preferences, and values, we surveyed private recreational anglers from Maine to North Carolina and employed discrete choice experiments to determine how regulatory and non-regulatory trip-specific variables influence trip-taking behavior. A latent class ranked logit model identified two distinct classes of anglers who exhibited differing preferences in regard to the importance of non-consumptive aspects of Bluefin Tuna fishing (e.g., catch-and-release). Income and recent Bluefin Tuna targeting were the primary determinants of class membership, with higher-income anglers who have targeted Bluefin Tuna in the past five years significantly more likely to be in the class that derives substantive benefits from non-consumptive angling activities. An annual consumer surplus exceeding \$14 million was estimated for the 2015 fishery, and potential welfare impacts of possible management changes (compensating surplus) are discussed. In addition, we identified a large amount of latent effort currently present in the fishery in the form of consumptive-oriented anglers. As a result, liberalization of harvest regulations could potentially lead to a large influx of effort into the fishery, which could impede the ability of managers to maintain harvest levels within prescribed limits.

INTRODUCTION

Over the past several decades, resource management scholars have advocated for better integrating the social sciences into fisheries management (Voiland and Duttweiler 1984, Fenichel et al. 2013). Understanding the human component of fisheries is important for predicting how management actions will affect the well-being of fishery participants, as well as for informing the allocation of fishery resources among competing user groups (Orbach 1980). In addition, without properly understanding the preferences and motivations of anglers, predicting behavioral responses (e.g., effort and harvest) is difficult, potentially undermining management's effectiveness and threatening a fishery's sustainability (Fenichel et al. 2013, Fulton et al. 2011, Hunt et al. 2013). Fishing behavior may, for example, change as stock status or management strategies change, and simply extrapolating past behavior under different conditions could lead to inaccurate predictions (Fulton et al. 2011). Furthermore, while determining the preferences and motivations of recreational anglers is challenging (compared to commercial fishermen, who are often thought to be largely motivated by profit), understanding drivers of angler behavior for a given fishery is critical for ensuring that the fishery's benefits are being maximized (Fedler and Ditton 1994).

The Atlantic Bluefin Tuna *Thunnus thynnus* supports a popular private and for-hire recreational fishery along the east coast of the United States from Maine to North Carolina (Marcek and Graves 2014). Of the Bluefin Tuna quota allocated to the United States by the International Commission for the Conservation of Atlantic Tunas (ICCAT), 19.7% (195.2 mt for 2017) is domestically apportioned to the recreational Angling category by the National Marine Fisheries Service's (NMFS) Highly Migratory Species

(HMS) Management Division (NMFS 2006; 82 FR 19615, 4/28/2017). This sub-quota is further divided among Bluefin Tuna size classes and between the northern and southern regions of the U.S. east coast, divided at 39°18' N latitude (Great Egg Inlet, NJ), in order to maintain equity in Bluefin Tuna access and landings along the coast (66 FR 42801, 8/15/2001).

The HMS Management Division uses a combination of permitting, size and bag limits, and monitoring to keep recreational Bluefin Tuna landings within the Angling category sub-quota. In order to recreationally target and harvest Bluefin Tuna and other HMS (billfishes, sharks, swordfish, and tunas), private vessel owners must obtain an annual HMS Angling permit (67 FR 77434, 12/18/2002); as of October 2016, there were 12,716 such permits issued for vessels with principal ports from Maine to North Carolina (NMFS 2017). Bluefin Tuna harvest is regulated on a trip level using size and bag limits, which the HMS Management Division reserves the right to adjust over the course of a season in order to maximize utilization of the Angling sub-quota and prevent overages (FR 71 58058, 10/2/2006). For example, in 2017 Angling permit holders were permitted to retain two school-size Bluefin Tuna (69 - < 119 cm curved fork length [CFL]) per vessel per day, one large school (119 - < 150 cm CFL) or small medium-size (150 - < 185 cm CFL) Bluefin Tuna per vessel per day, and one large medium (185 - < 206 cm CFL) or giant (206+ cm CFL) Bluefin Tuna per vessel per year (i.e., an annual trophy) (FR 82 19615, 4/28/2017). To monitor recreational Bluefin Tuna catch and effort, NMFS administers the Large Pelagics Survey (LPS) from Maine to Virginia from June through October (Foster et al. 2008). In addition, the HMS Management Division requires Angling permit holders to report any recreational Bluefin Tuna landings or dead discards

within 24 hours of the end of the trip through the Automated Landings Reporting System (ALRS), accessed via telephone, internet or smartphone app (79 FR 71510, 12/2/2014; FR 82 19615, 4/28/2017).¹

Despite these strategies, managing recreational Bluefin Tuna harvest has proven challenging due to inter-annual variability in fish availability, limited predictability of angler effort, and difficulties in accurate monitoring of recreational landings. LPS estimates become available in waves, typically a month (or longer) after the end of each wave. This lag in data availability limits the ability of the HMS Management Division to monitor the Angling category fishery in real-time to inform in-season management adjustments, which could compromise the ability to prevent landings overages for the Angling sub-quota (NMFS 2013; personal communication, S. McLaughlin, NMFS). In addition, permit holders' extremely low compliance with the ALRS reporting requirement (10-20%) has impeded its effectiveness as a real-time monitoring tool (NMFS 2013).² As a result, significant sub-quota overages can occur. In 2009, for example, recreational anglers landed an estimated 566 mt of Bluefin Tuna—nearly three times the sub-quota—due to the increased availability of small medium-size Bluefin Tuna resulting from particularly strong recruitment in 2003 (NMFS 2013, ICCAT 2017). This overage occurred despite the fact that the daily retention limit for this size class in 2009 never exceeded one fish per vessel per day (74 FR 26110, 6/1/2009). Harvest of small medium-size Bluefin Tuna was subsequently prohibited for the majority of the

¹ Reporting via the ALRS is not required in Maryland and North Carolina, where catch-card programs exist (NMFS 2013).

² This compliance estimate pre-dates the introduction of the smartphone app in 2017, which may improve compliance, but estimates following its introduction are not available.

2010 and 2011 fishing seasons (75 FR 33531, 6/14/2010; 76 FR 18416, 4/4/2011; NMFS 2013).

Little attention has been given to how Bluefin Tuna availability, regulations, and other factors (e.g., costs) affect angler effort and fishing behavior. A better understanding of these human dimensions would decrease the likelihood of overages as the behavioral response to shifting resource conditions could be anticipated and incorporated by managers. In addition, while the economic impacts of Bluefin Tuna and other HMS fisheries have been examined (e.g., Bohnsack et al. 2002, Hutt et al. 2014), the lack of understanding of individual angler preferences and values limits the ability of the HMS Management Division to maximize the fishery's socioeconomic benefits and thus achieve optimum yield, as is required by the first National Standard of the Magnuson-Stevens Fishery Conservation and Management Act (C.F.R. §600.310).

Few studies have examined the factors influencing behavior and decision-making of recreational Bluefin Tuna anglers. This lack of information limits the ability of managers to anticipate shifts in fishing pressure or appropriately balance conservation measures with socioeconomic objectives. Stoll and Ditton (2006) used a contingent valuation approach to evaluate annual willingness to pay (WTP) for different management scenarios among recreational Bluefin Tuna anglers in the largely catch-and-release Hatteras, NC fishery. The authors found, not surprisingly, that WTP was lowest in the least-flexible, catch-and-release only regulatory scenario. The scope of this study was fairly limited however, considering the effect of only one attribute, harvest limit, on angler WTP in a single fishing location. Acknowledging a degree of complexity, Sutton and Ditton (2001) found that Bluefin Tuna catch-and-release behavior in the Hatteras

fishery varied according to angler preferences and lifestyle, and additionally suggested that situational variables, such as fish size, may be important in Bluefin Tuna recreational angler decision-making.

The purposes of this study were twofold. First, we aimed to improve predictions of private recreational Bluefin Tuna fishing effort and harvest by evaluating the decision-making and preferences of anglers. Second, we endeavored to identify the magnitude and sources of economic welfare derived from the fishery by anglers in order to inform management strategies that maximize angler benefits while maintaining landings within biologically acceptable limits. In addition, we examined potential sources of heterogeneity acting on decision-making and derived value of the fishery by Bluefin Tuna anglers.

METHODS

We surveyed private recreational anglers permitted to target Atlantic Bluefin Tuna along the U.S. east coast from Maine to North Carolina during the spring and early summer of 2016. The survey consisted of two main parts: 1) A sequence of stated choice questions regarding hypothetical fishing trips to investigate decision-making, preferences, and tradeoffs, and to identify individual angler benefits; and 2) a series of direct questions regarding angling behavior, attitudes, and demographics.

Survey design and delivery

In stated choice surveys, individuals are presented with hypothetical, multi-attribute alternatives (i.e, fishing trips) and asked to rank or choose their most preferred. Responses can be used to analyze decision-making, identify tradeoffs, and evaluate preferences – tasks otherwise difficult or impossible for non-market goods (Hanley et al.

1998; Louviere et al. 2000; Freeman 2003). As the angling experience is, in many instances, a non-market good, these methods have found frequent use in analyses which seek to identify value and understand behavior in recreational fisheries. Typically, these studies evaluate preferences and policy options by offering respondents choice alternatives consisting of regulatory variables (e.g., size and bag limits, seasons), catch characteristics/fishery outcomes (e.g., size/number of fish caught), and, in many cases, cost (Aas et al. 2000, Oh et al. 2005, Carter and Liese 2012, Lew and Larson 2012). Respondent decisions can be used to quantify, for example, angler WTP for kept versus released fish (Carter and Liese, 2012), distinct values which may be confounded using other, simpler methods.

Discrete choice experiments (DCEs), a type of stated choice survey in which respondents are asked to select their most preferred of several multi-attribute alternatives, were used in this study. Regulatory and non-regulatory attributes and attribute levels for the DCEs that covered a realistic range of harvest regulations, fishery outcomes, and costs were determined in consultation with NMFS HMS Management Division staff and recreational Bluefin Tuna anglers. Given the complex regulatory nature of the fishery (multiple size classes, each with its own harvest limits) and our interest in non-consumptive aspects of Bluefin Tuna fishing (such as hooking and losing fish), a total of eight attributes was identified for this study: three regulatory attributes, four catch related attributes, and a trip cost attribute (Table 1). Prior to survey implementation, focus groups with HMS Angling category permit holders were held in Hyannis, MA and Toms River,

NJ in January and February 2016, respectively, to review draft survey materials and provide feedback regarding attributes/levels and the overall clarity of the questionnaire.³

DCEs frequently consist of two multi-attribute alternatives as well as a third “opt-out,” or in this case, “no trip” alternative (Hanley et al. 1998, Carter and Liese 2012). Respondents were asked to imagine that they could take one of two hypothetical Bluefin Tuna fishing trips described or not go Bluefin Tuna fishing at all, and to select the options that they preferred most and least, allowing for a full ranking of the three alternatives (Lew and Larson 2012). Following Carter and Liese (2012), DCEs also included a “derived” attribute, “Legal Harvest,” which clarified to respondents the quantity of Bluefin Tuna of each size class that they were legally allowed to keep based on the quantity and size of fish caught and stated bag limits. Additional definitions boxes on the survey pages containing DCEs further clarified the meaning of each component of the choice task (Figure 1).

While a full factorial experimental design—generating choice sets that include all possible combinations of attribute levels—allows for main effects and interactions among attributes to be estimable and independent, such a design is not practical for complex choice experiments (Kuhfeld 2010). In the study described here, a full factorial design would result in 7,776 separate choice alternatives; if each alternative were combined with every other alternative, that would result in $7,776^2 = \sim 60$ million unique DCEs. We therefore utilized a fractional factorial design, where a subset of the full factorial design is selected such that effects of interest may be efficiently estimated (Louviere et al. 2000). Macros in SAS software (SAS 9.3; SAS Institute, Inc., Cary, NC USA) as described by

³ We attempted to host a focus group with Angling permit holders in North Carolina, but were unable to identify a large enough group of permit holders located within a reasonable distance of a central meeting location.

Kuhfeld (2010), were used to develop an experimental design that maximized balance and orthogonality. After specifying certain interactions (e.g., bag limit and catch, which interact in determining harvest) and applying restrictions (e.g., eliminating dominated choice sets in which one alternative had more favorable bag limits, catch, and cost than the other alternative), an experimental design of 32 choice sets drawing on 144 choice alternatives was developed. Because 32 choice sets would be too many decisions for a single respondent to make, the choice sets were blocked into eight blocks of four choice sets each, a number assumed not cognitively burdensome and used in previous stated choice studies of recreational anglers (Carson et al. 1994, Hanley et al. 1998, Aas et al. 2000, Hicks 2002).

In addition to the four DCEs, each survey included general questions to understand how angler preferences and motivations correspond to behavior and values as well as to address HMS Management Division interests. Questions were asked regarding demographics, primary target species, Bluefin Tuna fishing behavior and experience level, and Bluefin Tuna fishing and management preferences and attitudes. Attitudinal questions included, for example, Likert scale questions asking respondents to indicate the impact of the number of Bluefin Tuna harvested on trip satisfaction, which could be used to assess an angler's degree of consumptive orientation (defined here as the degree of preference for harvesting fish). In addition, anglers were asked if they would prefer a short Bluefin Tuna season (two months) with high daily harvest (three fish from 69 - < 185 cm CFL per vessel per day) or a long Bluefin tuna season (six months) with low daily harvest (one fish from 69 - < 185 cm CFL per vessel per day).

The survey research firm QuanTech, Inc. (Rockville, MD USA), which holds a continuing agreement with NMFS to handle confidential HMS Angling permit holder information, was responsible for survey implementation and data collection. Names and contact information for Angling permit holders were obtained from the HMS Management Division and provided to QuanTech. A stratified random sample was drawn from individuals who possessed an Angling category permit as of December 31, 2015 with a listed primary port from Maine to North Carolina (from north to south: Maine, New Hampshire, Massachusetts, Rhode Island, Connecticut, New York, New Jersey, Delaware, Maryland, Virginia, and North Carolina). Approximately 20% of Angling permit holders were selected from each state, for a total sample size of 2,600. Within each state, selected permit holders were randomly assigned one of the eight survey versions (blocks), with roughly an equal number of each survey version distributed in each state. In order to increase response rates, extensive outreach to the recreational fishing community was conducted both prior to and during survey delivery.⁴

Response rates for mail surveys generally tend to be higher than or equal to those for internet surveys (Shih and Fan 2008, Manfreda et al. 2008, Olsen 2009). In addition, a mixed-mode economic impact survey of a subset of HMS Angling permit holders from Maine to North Carolina by Hutt et al. (2014), which obtained a 57% response rate, received nearly twice as many responses via mail compared to the internet. Given these findings, we elected to use a mail survey for this project. The survey protocol and all materials were approved by the College of William and Mary's Protection of Human Subjects Committee (Protocol # PHSC-2015-11-19-10758-amscheld).

⁴ These efforts included a column describing the survey in the U.S. east coast recreational fishing magazine *On The Water* (East Falmouth, MA USA) and the posting of information on several online recreational fishing forums.

Survey distribution occurred during April-June 2016, and the survey delivery protocol followed a modified Dillman approach (Dillman et al. 2009) consisting of up to four mailings, including a pre-notification letter, initial survey package, reminder postcard, and second questionnaire. Several steps were taken in order to maximize response rates following recommendations from both the literature and focus group participants. Permit holders who completed the survey were automatically entered into a random drawing to win one of two \$500 cash prizes, as previous studies have indicated that low-odds, large-prize lotteries are the most cost-effective means to increase response rates (Gajic et al. 2012). Since non-monetary incentives help to increase response rates (Edwards et al. 2009), we enclosed in the pre-notification mailing a sticker in the shape of a Bluefin Tuna that included the Virginia Institute of Marine Science (VIMS) logo. Lastly, as aligning research with an academic (rather than government) organization was suggested by focus group participants for improving response rates, all correspondence materials noted that the project was being led by VIMS and included the VIMS logo or letterhead. Respondents were also informed that they would receive a summary of survey findings.

Model estimation

Stated choice modeling is based on random utility theory, which assumes that an individual makes decisions in a way that integrates information across choice alternatives in order to maximize an underlying utility function (Louviere and Timmermans 1990). The utility U derived by individual n for each alternative attribute bundle i can be described with a utility function that contains both an observable component described by a model (V_{ni}) and an unobservable random error component (ε_i). For individual n , the

utility of alternative i can thus be written as: $U_{ni} = V_{ni} + \varepsilon_i$. Individual n will choose alternative i if U_{ni} is greater than the utility associated with all other alternatives j in the choice set. The portion of utility described by the model V_{ni} , also called the deterministic component of utility, can be rewritten as βx_{ni} , where x_{ni} is a vector of the attributes in alternative i for individual n , and β is a vector of parameters that reflect the utility of those attributes (Train 2009).

The most straightforward random utility model, the conditional logit, assumes that the random, unobserved component of utility ε_i is independently and identically Gumbel-distributed, and thus the probability that individual n selects alternative i can be written as:

$$(1) \quad P_{ni} = \frac{e^{\beta x_{ni}}}{\sum_j e^{\beta x_{nj}}}$$

where the denominator sums over all alternatives in the choice set, indexed here by j . The probability of selecting a given choice alternative can then be calculated as a function of the attributes in that alternative, as a function of the attributes in the other alternatives in the choice set, and as a function of the attributes of the individual in combination with alternative specific attributes (Train 2009).

Many stated choice studies of recreational anglers use an extension of the conditional logit model known as the random parameters (or mixed) logit (e.g., Lew and Larsen 2012), which allows for random taste variation, correlation in errors across choices, and unrestricted substitution patterns (Train 2009). By allowing coefficients for

parameters of interest to vary across individuals, researchers are able to investigate heterogeneity in preferences.

While the random parameters logit is a powerful tool for identifying heterogeneity, it is less effective in explaining the *source* of heterogeneity among respondents (Boxall and Adamowicz 2002). Because a primary goal of this study was to parse out differences among Bluefin Tuna anglers that might be applicable for management purposes (i.e., to identify discrete subpopulations of anglers) (Provencher et al. 2002), we elected to use a specialized form of the random parameters logit known as the latent class (or finite mixture) logit model. The underlying theory of the latent class model is that an individual's choice behavior is affected not only by observable attributes present in the choice sets but also by unobserved (or latent) preference heterogeneity (Greene and Hensher 2003). In the latent class model, each of the β parameters takes M possible values corresponding to M segments in the population, with each segment having its own distinct preferences. The probability of individual n choosing alternative i thus becomes:

$$(2) \quad P_{ni} = \sum_{m=1}^M S_m \left(\frac{e^{\beta_m x_{ni}}}{\sum_j e^{\beta_m x_{nj}}} \right),$$

where β_m refers to the utility parameters for each segment M , and S_m refers to the proportion of the population that belongs in segment M (Train 2009). Such an approach requires the researcher to hypothesize the number of discrete segments, or classes, into which the population separates (Boxall and Adamowicz 2002). Given this hypothesis and the assumption of independently and identically Gumbel-distributed random error terms,

the probability of individual n 's membership in segment m , also known as the classification function, becomes:

$$(3) \quad P_{nm} = \frac{e^{\lambda_m Z_n}}{\sum_{m=1}^M e^{\lambda_m Z_n}},$$

with Z_n representing a vector of individual-specific characteristics hypothesized to affect segment membership, and λ_m the vector of parameters corresponding to those individual traits, with parameters for one class set to 0 as the base case (modified from Boxall and Adamowicz 2002). One notable benefit of this approach is that the researcher is not forced to assume an individual's (unknown) class membership—instead, a class probability is assigned for each individual (Morey et al. 2006). The latent class model jointly estimates segment membership (based on individual characteristics) and segment-specific choice probabilities (based on segment-specific utility parameters) (modified from Boxall and Adamowicz 2002):

$$(4) \quad P_{ni} = \sum_{m=1}^M \left(\frac{e^{\lambda_m Z_n}}{\sum_{m=1}^M e^{\lambda_m Z_n}} \right) \left(\frac{e^{\beta_m X_i}}{\sum_{j=1}^J e^{\beta_m X_j}} \right).$$

The latent class model has been successfully used with stated preference data to identify discrete population segments in several environmental applications, including wilderness park choice (Boxall and Adamowicz 2002), marine protected area preferences (Wallmo and Edwards 2008), and freshwater recreational angler preferences (Provencher et al. 2002, Morey et al. 2006).

Following Lew and Larsen (2012), we extended the latent class model to account for 1) the full ranking of choice alternatives obtained by asking respondents to select their most and least preferred alternatives and 2) the panel nature of the data (each respondent answered up to four DCEs). Using the full rank ordering of alternatives, as opposed to simply the most preferred alternative, increases the number of choice observations obtained for each respondent, thereby reducing the variances of parameter estimates (Chapman and Staelin 1982). Given that our choice sets had three options, the probability that an individual in class m chooses alternative i as most and alternative k as least preferred ($\Pr [i > j > k]$) corresponds to the probability of choosing alternative i as best among the three alternatives ($\Pr [i | i, j, k]$) multiplied by the probability of choosing alternative j as best among the remaining two alternatives ($\Pr [j | j, k]$), summed across classes:

$$(5) \quad P_{ni} = \sum_{m=1}^M \left(\frac{e^{\lambda_m Z_n}}{\sum_{m=1}^M e^{\lambda_m Z_n}} \right) \left[\left(\frac{e^{\beta_m X_i}}{e^{\beta_m X_i} + e^{\beta_m X_j} + e^{\beta_m X_k}} \right) \left(\frac{e^{\beta_m X_j}}{e^{\beta_m X_j} + e^{\beta_m X_k}} \right) \right].$$

Assuming independence of choices (and error terms) across the choice sets, the probability that a person makes a given sequence of choices across the multiple choice sets becomes the product of individual choice probabilities for that sequence, resulting in the following log-likelihood:

$$(6) \quad \ln L = \sum_{n=1}^N \ln \left(\sum_{m=1}^M \left(\frac{e^{\lambda_m Z_n}}{\sum_{m=1}^M e^{\lambda_m Z_n}} \right) \left\{ \prod_{t=1}^T \left[\left(\frac{e^{\beta_m X_i}}{e^{\beta_m X_i} + e^{\beta_m X_j} + e^{\beta_m X_k}} \right) \left(\frac{e^{\beta_m X_j}}{e^{\beta_m X_j} + e^{\beta_m X_k}} \right) \right] \right\} \right),$$

where t represents each of up to four choice sets answered by each respondent.

The utility of a given trip alternative (and thus the probability of selecting that trip) for members of a given class was assumed to be a linear function of the 11 attributes that characterized each trip, while an alternative-specific constant (ASC) was used to represent the utility of not going Bluefin Tuna fishing (Option C), as has been done in previous choice experiments for recreational fisheries (e.g., Carter and Liese 2012, Duffield et al. 2012, Lew and Larsen 2012). The probability of class membership, meanwhile, was assumed to be a function of individual-specific variables, including those relating to fishing behavior (e.g, avidity, target species), attitudes (e.g, consumptive orientation), and demographics (e.g., region, income).

Model fit for varying levels of classes (1 [conditional logit], 2, 3, 4, and 5) and differing vectors of individual parameters was assessed using Akaike's Information Criterion (AIC) and the Bayesian Information Criterion (BIC), following previous studies (e.g., Boxall and Adamowicz 2002, Wallmo and Edwards 2008). Hypotheses regarding which individual parameters to include were informed by focus group discussions and by answers to non-DCE questions in the surveys (see Appendix). One hundred model runs were conducted for each model with differing class structures using the high performance computing cluster at VIMS to ensure model convergence, which was assessed by the stability of the model's negative log-likelihood over model runs. AIC and BIC were also used to compare latent class model fit with the standard conditional logit model. All model estimation was performed using the non-linear minimization function ("nlm") in the statistical programming software R (R Core Team 2016).

Model analysis

Following the selection of the final model and the identification of discrete classes, the probability of an individual's membership in each class was calculated based on the classification function. This prior probability was then adjusted to account for the sequence of choices actually made by that individual, resulting in a posterior probability of class membership (see Greene 2008). To estimate the marginal effect of individual characteristics on the posterior probability of class membership for each individual n , the log-odds of membership in class m were regressed against the vector of individual characteristics Z included in the model as dummy variables (Bucklin and Gupta 1992, Boxall and Adamowicz 1999):

$$(7) \quad \ln\left(\frac{P_{nm}}{1-P_{nm}}\right) = b_m Z_n + \varepsilon_{mn}, m = 1, \dots, M.$$

The marginal effect of each variable on class membership was then calculated by estimating class membership probability for dummy variable values of 0 and 1 while holding other variables constant at the overall respondent average. Additionally, we assigned individuals to a class based on their highest posterior class probability (Bucklin and Gupta 1992, Boxall and Adamowicz 1999), and then used a combination of Student's t tests (for continuous, normally distributed data), permutation tests (for heavily skewed data), and Fisher exact tests (for categorical data) to test for significant differences in individual-specific variables among classes.

WTP refers to the monetary compensation needed by an individual so that utility remains unchanged when a choice attribute level is changed. To calculate WTP for each

class m for various aspects of a Bluefin Tuna fishing trip, the parameter corresponding to the attribute of interest a was divided by the negative of the cost parameter c :

$$(8) \quad WTP_{ma} = -\frac{\beta_{ma}}{\beta_{mc}}, m = 1, \dots, M.$$

To calculate several measures of angler welfare and preferences, including marginal effects of attribute changes on trip probability, compensating surplus of regulatory changes, and consumer surplus, it was necessary to estimate attribute levels for an “average” recreational Bluefin Tuna fishing trip on the U.S. east coast during 2015 (the most recent complete fishing year prior to survey delivery) (Table 2). Estimates of the numbers of school, large school, and small medium-size Bluefin Tuna harvested and released, as well as the number of large medium and giant-size Bluefin Tuna released, from Maine to Virginia during June-October 2015 were obtained through an online LPS query (personal communication, NMFS, Fisheries Statistics Division, 2017). An estimate of the number of large medium and giant-size Bluefin Tuna retained by Angling category permit holders from Maine to Virginia during 2015 was obtained through a data request to the NMFS HMS Management Division (personal communication, S. McLaughlin, NMFS, 2017).⁵ Total Bluefin Tuna fishing effort (number of trips) by private anglers from Maine to Virginia during June-October 2015 was obtained through an LPS data request (personal communication, R. Kitts-Jensen, NMFS, 2017); harvest and release estimates for the different Bluefin Tuna size classes were divided by the effort estimate to

⁵ Because private anglers surveyed in the LPS include General category permit holders, LPS estimates for landed large medium and giant-size Bluefin Tuna are far larger than the number of fish harvested by Angling category permit holders. As a result, a separate data request was made for all reported trophy category Bluefin Tuna harvested in 2015.

calculate per-trip values. Focus group attendees suggested that roughly 1/3 of Bluefin Tuna hooked were lost prior to landing, an estimate used to derive the average number of fish hooked and lost per trip. Lastly, we used Hutt et al.'s (2014) estimate of per-angler-trip expenditures for HMS Angling category permit holders targeting Atlantic tunas in 2011 from Maine to North Carolina (\$534) as an average Bluefin Tuna trip expenditure value.

With average trip data in hand, class-specific WTP for the average trip could be calculated by taking the sum of the products of 2015 average attribute levels X (excluding cost) and their corresponding parameters β , subtracting the value of the ASC, and dividing by the negative of the cost parameter:

$$(9) \quad WTP_{m2015} = \frac{(\sum_{a=1}^A \beta_{ma} X_{2015}) - \beta_{mNoTrip}}{\beta_{mc}}, m = 1, \dots, M.$$

A weighted average WTP for the entire sample was estimated by summing the product of class-specific WTP and probability of class membership across all classes (Domanski and von Haefen 2010). In addition, class-specific marginal probabilities of taking a Bluefin Tuna fishing trip were calculated for each attribute.⁶

⁶ The marginal effect of trip attributes on the class-specific probability of taking a Bluefin Tuna fishing trip was determined by calculating each class's logit probability while holding attributes at the 2015 average levels but varying the attribute level of interest from 0 to 1 (with the exception of cost, which was changed by \$100); the difference in probabilities then represented the marginal effect of a one-unit increase in attribute a .

To determine the effect of possible management changes on the welfare of recreational Bluefin Tuna anglers, we estimated class-specific compensating surplus under relevant plausible regulatory scenarios (Hanemann 1984, Hoyos 2010):

$$(10) \quad \textit{Compensating Surplus}_m = -\frac{1}{\beta_{mc}} [\ln(\sum e^{\beta_{ma}X_1}) - \ln(\sum e^{\beta_{ma}X_0})],$$

where X_0 and X_1 represent the vector of trip attributes at the status quo (2015 average trip) and after management changes, respectively. Welfare impacts were examined for the following management changes: No harvest of large medium or giant-size Bluefin Tuna; no harvest of any Bluefin Tuna; and complete closure of the fishery (i.e., no permitted targeting of Bluefin Tuna).

Consumer surplus for each class for 2015 was estimated by multiplying class-specific per-trip consumer surplus by the estimated number of Bluefin Tuna trips taken by that class in 2015. The estimated number of trips for members of each class was calculated by multiplying the total number of Bluefin Tuna trips taken in 2015 by the proportion of all active Bluefin Tuna fishermen who belonged to that class (i.e., respondents who indicated having targeted Bluefin Tuna in the previous five years). Summing these class-specific estimates provided a consumer surplus estimate for the fishery as a whole:

$$11) \textit{Consumer Surplus} = \sum_{m=1}^M [(P_{mActive} * TotalTrips_{2015})(WTP_{m2015} - TripCost_{2015})].$$

Ninety-five percent confidence intervals for welfare measures (WTP, compensating surplus, and consumer surplus) and marginal effects were generated using the bootstrapping method suggested by Krinsky and Robb (1986), based on 10,000 random draws from a multivariate normal distribution with a mean and covariance matrix set to model estimates. Each draw was used to calculate one estimate for the measure of interest (welfare or marginal effect); following all calculations, the distribution for that measure was evaluated. This approach to calculating the distribution of welfare impacts has been used previously with logit models in an environmental valuation context (see Park et al. 1991, Domanski and von Haefen 2010, Hoyos 2010, Haab et al. 2012).

RESULTS

Response rates and non-DCE findings

Of the 2,485 eligible respondents in the sample frame, 1,154 (46.4%) returned the survey having answered at least one question, while 980 (39.4%) completed at least one DCE. The proportion of respondents from each state who completed at least one DCE did not differ significantly from the proportion of the total sample from each state ($p > 0.05$), suggesting a lack of geographic response bias (Table 3). Preliminary analysis of non-DCE survey questions suggested regional segmentation and led to the inclusion of regional dummy variables in modeling efforts, along with other demographic, attitudinal, and behavioral variables (see Appendix for a summary of responses to non-DCE questions).

The latent class model

Final model specification

While latent class models with two, three, four, and five classes were attempted, convergence was only achieved for the two-class, 31-parameter model (Table 4): 20 of 100 model runs had a negative log-likelihood of between 4857 and 4858, while all models with larger class structures failed to converge to a stable negative log-likelihood. The three-class model, while not fully converging, appeared to separate one of the two classes in the two-class model into two separate classes rather than identifying three novel classes, lending support to the two-class model. Model selection criteria indicated that the two-class model provided a markedly better fit to the data than did the conditional logit model (Δ AIC = -1728.9).

Parameter estimates for the final two-class model can be found in Table 5. Of the two-class models tested (each with differing individual-specific variables to inform class membership), the best-fitting model included the 12 alternative-specific attributes and six individual-specific variables. These included dummy variables for 1) consumptive and non-consumptive orientations,⁷ 2) annual income over \$150,000⁸, 3) primary ports in New England and New York/New Jersey (NY/NJ), and 4) having targeted Bluefin Tuna in the last five years. Latent class probabilities were 0.53 and 0.47 for Class 1 and Class 2, respectively. Of anglers posteriorly assigned to Class 1 (posterior probability > 0.5), 96.4% were assigned with > 80% probability (91.8% with > 90% probability), and 97.1%

⁷ Consumptive and non-consumptive orientation dummy variables were assigned based on respondents' answers to two five-point Likert scale questions included in the non-DCE portion of the survey. Respondents who selected "Agree" or "Strongly Agree" for each of the following two statements were considered consumptively oriented: "I would never target Bluefin Tuna if I were not allowed to retain fish"; and, "Generally speaking, I would be more satisfied with a Bluefin Tuna fishing trip if I were able to bring more fish back to the dock (e.g., I am more satisfied with a trip on which I retain three Bluefin Tuna than a trip on which I retain two Bluefin Tuna)." Respondents who selected "Disagree" or "Strongly Disagree" with each of these statements were considered non-consumptively oriented. Only respondents who indicated that they had targeted Bluefin Tuna in the past five years were asked to answer these questions.

⁸ The median annual income for respondents was between \$100,000 and \$150,000, with nearly 40% of respondents indicating annual income greater than \$150,000 (See Table A1).

of anglers posteriorly assigned to Class 2 were assigned with > 80% probability (94.3% with > 90% probability).

As expected, coefficients for harvest were positive and significant for both classes, and coefficients for cost were negative. The classes differed notably, however, in the effect of the catch on utility. Because the model included both a catch variable and a harvest variable for each Bluefin Tuna size class, catch parameters might be considered to represent the utility of catching and releasing a Bluefin Tuna (i.e., the model parameter identified the effect of an increase in catch independent of changes in harvest). Catch-and-release of Bluefin Tuna generally increased utility (and thus probability of trip choice) for Class 1, but had the opposite effect on Class 2 for large school/small medium and large medium/giant-size Bluefin Tuna. In addition, the no-trip ASC for Class 1 was negative and significant, indicating a preference for Bluefin Tuna fishing regardless of trip characteristics. This result reflects the fact that all 523 respondents assigned to Class 1 selected the no-trip option as their least-preferred option for at least one DCE, compared to only 24.3% of Class 2 respondents.⁹ These differences resulted in a significantly higher probability of taking a Bluefin Tuna trip at average 2015 levels for Class 1 (0.96) than for Class 2 (0.27), and in varying (often opposite) marginal effects of attribute changes on trip probability—that is, how a marginal change in a trip attribute (e.g., increasing school-size Bluefin Tuna harvest from 0 to 1) would change the

⁹ Collection of information regarding least-preferred alternatives would not have been possible in a standard DCE format that only asked for a respondent's most-preferred alternative, thus illustrating the benefit of using a ranked logit approach. When a two-class model was run only using information on most-preferred alternatives, Class 1 parameter estimates were similar to those of Class 1 in the ranked model, whereas for Class 2, only the cost parameter was significant. Moreover, the latent class probability for Class 2 in the unranked model was 0.95, suggesting that the model without a full ranking of choice alternatives was unable to effectively resolve class structure and identify preference heterogeneity.

probability of an individual's taking a Bluefin Tuna trip given their class membership (Table 6).

Latent class characterization

Income and Bluefin Tuna targeting were the only two individual-specific variables to significantly influence class membership (Table 7). The multiple linear regression on the log-odds of class membership as a function of the individual-specific parameters revealed that individuals who had an annual income of over \$150,000 and who had targeted Bluefin Tuna in the past five years were significantly more likely to be in Class 1; an individual possessing both of these characteristics was 71.4% more likely to be in Class 1.¹⁰ Fisher exact tests indicated that a significantly higher percentage of individuals posteriorly assigned to Class 1 had targeted Bluefin Tuna in the past five years and had annual income over \$150,000 compared to those in Class 2, while New England or NY/NJ residency and consumptive orientation were not significantly different between classes (Table A.2.). Interestingly, a significantly higher percentage of permit holders posteriorly assigned to Class 2 were from Mid-Atlantic states, possibly due to the reduced proportion of Mid-Atlantic permit holders who had recently targeted Bluefin Tuna compared to anglers from other regions (see Table A1).

Angler welfare

WTP values show striking differences in preferences among the two classes (Table 8). Class 1 members exhibited positive WTP for catching and releasing Bluefin Tuna of all size classes, while Class 2 members were indifferent to catching and releasing school size-fish and actually indicated a negative WTP for catching and releasing larger

¹⁰ The increase in Class 1 probability due to both having high income and having recently targeted Bluefin Tuna is not simply the sum of the increases in Class 1 probability for each characteristic (shown in Table 7) because the two are weakly correlated (Spearman's ρ is 0.07).

size classes, meaning that these individuals lose utility by practicing catch-and-release (and would have to be paid in order to do so). Class 1 members exhibited a WTP of - \$1438 for the no-trip ASC—in other words, these individuals would have to be paid over \$1400 to not go on a Bluefin Tuna fishing trip—indicating the high value placed on simply going Bluefin Tuna fishing, regardless of trip outcomes. For Class 2 members, however, WTP for the no-trip ASC was not different from 0, indicating their indifference to a Bluefin Tuna trip independent of trip attributes (namely, harvest). Despite these contrasts in non-consumptive preferences, WTP for harvest did not vary significantly between classes—that is, the Krinsky-Robb 95% confidence intervals associated with WTP for each Bluefin Tuna size class overlapped between the two classes. Overall, WTP for the average 2015 trip differed significantly between the two classes (Figure 2). Interestingly, for Class 2 members, who were significantly less likely to have taken a Bluefin Tuna trip in the previous five years, WTP for the average 2015 trip (\$49.90) was less than the average estimated cost per Angling permit holder for a 2015 Bluefin Tuna trip (\$534); this can be attributed to the low harvest levels associated with the average trip in 2015.

Consumer surplus for the 2015 recreational Bluefin Tuna fishery as a whole was estimated to be \$14.01 million, reflecting the difference between aggregate WTP for the average 2015 Bluefin Tuna trip (\$22.75 million) and aggregate estimated 2015 Bluefin Tuna trip expenditures (\$8.74 million).¹¹ Given an estimate of 78.5 mt for private-angler

¹¹ Based on survey responses, 61.8% of active Bluefin Tuna fishermen were estimated to be in Class 1, and 38.2% in Class 2. These percentages were used for purpose of weighting consumer surplus by class (see Equation 11).

Bluefin Tuna landings in 2015,¹² consumer surplus was calculated to be \$80.98 per pound of harvest.

Class-specific estimates of angler compensating surplus largely reflect the stark difference in preferences between classes (Table 9). For example, a complete fishery closure would result in a loss of over \$1700 in welfare per trip for Class 1 anglers, a result of the significant benefits that Class 1 anglers derive from the fishery from aspects other than harvest (whose 2015 levels were relatively low). However, a fishery closure would generate no significant loss of benefits for Class 2 given the already-low harvest levels (and thus low WTP) associated with the 2015 average trip.

DISCUSSION

Drivers of class membership

Our results clearly demonstrate a segmentation in preferences among U.S. east coast Bluefin Tuna anglers, indicating substantial heterogeneity in derived welfare among anglers while also providing key insights regarding how changes to regulations and fishery conditions (e.g., costs, fish distribution) could impact effort and harvest. Preference heterogeneity appears to largely be driven by income and recent (within the past five years) Bluefin Tuna targeting (or lack thereof), both of which are logical in the context of the fishery. Regulations governing recreational Bluefin Tuna harvest have generally been strict since the mid-2000s (one to three fish per vessel per day [77 FR 21015, 04/09/2012; 79 FR 25707, 05/06/2014]); as a result, individuals who highly value harvest but not catch-and-release (i.e., Class 2 members) have thus perhaps not been

¹² The 78.5 mt estimate was calculated by taking the total amount of Angling category landings for Bluefin Tuna in 2015 (113.1 mt, obtained from the HMS Management Division), and multiplying it by the estimated proportion of landings taken by Angling category permit holders as opposed to Charter/Headboat permit holders (69.4%, obtained from an LPS query for 2015).

compelled to target Bluefin in recent years—as evidenced by the 0.27 probability of taking a trip with 2015 average trip levels for Class 2 members (see Table 6). This idea was reinforced during pre-survey focus groups, when some anglers mentioned targeting Bluefin Tuna heavily when regulations were liberal in the early 2000s (e.g., in 2003, when vessels could retain 1 school, large school, or small medium-size Bluefin Tuna per person, or up to six per vessel, per day [68 FR 35822, 06/17/2003])¹³, but subsequently switching to other species with less restrictive harvest limits when Bluefin Tuna bag limits were reduced. For low-income anglers, meanwhile, it may not be feasible or worthwhile to target Bluefin Tuna with any regularity (or at all) given the high costs of the fishery coupled with relatively restrictive harvest regulations. Among low-income anglers (annual income < \$150,000) who had not targeted Bluefin Tuna in the previous five years, 34% of them indicated the high expense of Bluefin Tuna fishing as a reason for not recently targeting the species, compared to only 20% for high-income anglers ($P = 0.08$).

The finding that anglers with higher levels of income value catch-and-release fishing more highly is supported by previous studies of U.S. recreational anglers. In a survey of freshwater anglers in New York State, Connelly et al. (2001) used cluster analysis to identify seven types of anglers; a highly skilled group that targeted cold-water species and practiced catch-and-release had the highest average income of the seven groups. Grambsch and Fisher (1991) found that freshwater black bass anglers with annual income greater than the U.S. median were significantly more likely to practice catch-and-release than anglers with incomes below the median. Most notably, in a study of billfish

¹³ References for Federal Register notices pertaining to previous Bluefin Tuna regulations were provided by Sarah McLaughlin and Brad McHale of the NMFS HMS Management Division.

tournament anglers along the U.S. Atlantic and Gulf Coasts as well as Puerto Rico, Graefe and Ditton (1997) found that income was a significant predictor of whether an angler would release all billfish (anglers with higher income were more likely to release all billfish), and that income was the strongest predictor of the number of billfish kept (anglers with lower income kept more billfish). While Bluefin Tuna are a more sought-after food fish than billfish, a similar association with income and catch-and-release could presumably hold. In the present study, a Fisher exact test revealed that a significantly higher proportion of anglers with an annual income of over \$150,000 voluntarily release Bluefin Tuna (59%) compared to anglers with an annual income of less than \$150,000 (42%; $P = 0.03$).

The relatively high value attached to catch-and-release among higher-income anglers identified both in previous studies and through some of our questions may explain the continued avidity of this group despite increasingly restrictive Bluefin Tuna harvest regulations, suggesting a relatively inelastic response in effort to management strategies by Class 1 anglers. Interestingly, our model did not identify significant differences in WTP for harvest between Class 1 and Class 2—both groups consider harvest equally important. However, the additional value attached by Class 1 anglers to non-consumptive aspects of Bluefin Tuna fishing (catch-and-release, hooking and losing fish, and other factors captured by the ASC) appear to provide sufficient incentive for this group to continue Bluefin Tuna despite restrictive harvest regulations.

The lack of explanatory power of the consumptive orientation variables included in the model is possibly due to the fact that the Likert scale questions used to define these variables were only asked to individuals who stated that they had targeted Bluefin Tuna

in the previous five years, the latter being a dominant determinant of class membership. However, the fact that both the consumptive and non-consumptive orientation dummy variables are highly correlated with having targeted Bluefin tuna in the previous five years (Spearman's ρ is 0.39 and 0.36, respectively), and that only the targeting variable is significant in the model, suggests that recent Bluefin Tuna targeting behavior is likely a stronger driver of class membership. There are, however, two possible alternative reasons for the non-significance of the consumptive orientation factors: 1) the Likert scale questions used to define consumptive orientation may not have adequately captured angler attitudes; and/or 2) the stated consumptive attitudes of anglers (in Likert scale questions) may not have aligned with the preferences expressed in DCE responses. This latter possibility highlights a key strength of using DCEs for eliciting preferences; for example, a respondent may not consider themselves consumptively oriented when directly asked (resulting in non-consumptive responses to Likert scale questions), but when confronted with actual trip scenarios, may in fact select trip alternatives that allow greater opportunities for harvest.

WTP comparisons with previous studies

Our class-specific WTP estimates for harvest of a single Bluefin Tuna, which ranged from \$160.20 to \$360.01 across size ranges and angler classes, are generally higher than the marginal WTP for catch of an additional fish found in Johnston et al.'s (2006) meta-analysis of recreational fishing values obtained for diverse fisheries using various analytical methods (391 observations from 48 studies between 1977 and 2001), which found WTPs ranging from \$0.048 to \$612.79, with a mean of \$16.82. Species in the meta-analysis with higher WTPs (> \$100/fish) generally included popular food and

sportfish including salmon (e.g., Jones and Stokes Associates Inc. 1987, Morey et al. 1993) and big-game species such as billfish and sharks (e.g., Schuhmann 1996) (reviewed in Johnston et al. 2006). In addition, our estimates are similar to Duffield et al.'s (2012) WTP estimate of \$276.44 for catching a blue marlin among private-boat Hawaiian anglers (the survey did not distinguish between harvested and released fish). Given their elite status as both a food and sportfish, the high WTP estimated for Bluefin Tuna harvest is not surprising.

Class 1 WTPs for Bluefin Tuna fishing trip characteristics were found to be generally similar to values for other sportfish for which significant non-harvest benefits are derived. For example, Duffield et al. (2012) also found that Hawaiian anglers were willing to pay \$166.45 to see a marlin and \$128.72 to hook and lose a marlin—60% and 47% of WTP for catch, respectively. The importance of these non-consumptive aspects, both in terms of WTP and in terms of relative importance compared to catch, is similar to Class 1 members in the present study, who demonstrated a WTP of \$118.89 for hooking and losing a Bluefin Tuna—35-74% of WTP for Bluefin Tuna harvest, depending on size class. Similarly, in their discrete choice survey of southeastern U.S. anglers, Carter and Liese (2012) found WTP for releasing an additional King Mackerel due to having reached the bag limit (\$37.62) to be nearly half the WTP for King Mackerel harvest (\$77.59).¹⁴ While the WTP values for Bluefin Tuna are higher, the relative proportion of WTP for catch-and-release compared to harvest (21-77%, depending on size class) for Class 1 is similar to that shown for King Mackerel. Thus, for Class 1 anglers, Bluefin Tuna, in addition to being a highly desirable food fish, are also a valuable game fish that,

¹⁴ In Carter and Liese's (2012) experimental design, 1 fish was the smallest number of fish that could be kept; WTPs here therefore reflect marginal WTP for the second fish caught and are therefore likely less than the WTP for the first fish.

like Blue Marlin and King Mackerel, can provide significant benefits even in the absence of catch and/or harvest.

For Class 2 members, harvest is the primary factor driving choice, and preference for harvest (and aversion to catch-and-release) is even stronger than in other studies for coveted food fish. In the same study that found relatively high WTP for King Mackerel release compared to harvest, Carter and Liese (2012) calculated a WTP for harvesting Red Snapper and grouper species (\$80.40 and \$62.97, respectively) more than eight times the value of releasing the fish due to bag limit restrictions (\$9.95 and \$6.86, respectively). While both Red Snapper and grouper are considered highly desirable food species, anglers still placed some value on catch-and-release, compared to the negative WTP values exhibited by Class 2 Bluefin Tuna anglers.

Applications to management

We found that the recreational Bluefin Tuna fishery resulted in an aggregate consumer surplus of over \$14 million for 2015. This estimate reflects the total net benefits that anglers derived above and beyond trip expenditures—a recreational analog to profit obtained by a commercial fishery. Aggregate consumer surplus estimates for recreational fisheries are generally scarce in the literature due to lack of available expenditure and valuation information. It is worth noting that our estimate does carry significant caveats—for example, the assumption that Bluefin Tuna trips in 2015 cost roughly the same as all tuna trips (Bluefin Tuna and other species) along the U.S. east coast in 2011, and the fact that the relative proportion of anglers in each class who had targeted Bluefin Tuna in the past five years is equivalent to the relative proportion of Bluefin Tuna trips taken by members of each class in 2015. Nevertheless, our estimate

provides a reasonable starting point for comparison with previous research as well as consideration of allocation questions within the U.S. Bluefin Tuna fishery.

Using responses from a contingent valuation survey of recreational Bluefin Tuna anglers (both private and charter) in Hatteras, NC, Stoll and Ditton (2006) estimated an individual annual consumer surplus of \$344 for maintaining the quality of the Bluefin Tuna fishery with the regulations in place at the time—because anglers averaged 0.97 trips per year, this value essentially amounted to a per-trip consumer surplus. While this value is quite different from the consumer surplus estimates generated for each class in the present study (\$1684.72 and -\$484.40 for Class 1 and Class 2, respectively), it does fall in between the two, and raises the possibility that the median estimate of \$344 may represent an aggregation of substantial heterogeneity in preferences among Bluefin Tuna anglers such as those identified in the present study.

Perhaps of greater policy relevance than aggregate consumer surplus in the fishery is the marginal consumer surplus, estimated to be \$80.98 per pound of harvested Bluefin Tuna. When considering the allocation of a fishery's quota among competing sectors—for example, commercial and recreational—resource economists have generally relied on some version of the equimarginal principle, which dictates that an efficient allocation of the resource occurs when the marginal benefit of additional quota is equal among sectors. In 2015, commercial ex-vessel prices (revenue) of Bluefin Tuna landed in the United States ranged from \$5.75-\$7.27 per pound (NOAA 2017), meaning that marginal profit was even lower (ex-vessel price minus expenses). Based on the equimarginal principle alone, it would appear economically efficient to increase the Angling category share of the U.S. Bluefin Tuna quota. However, it is important to

remember that since the probability of Class 1 anglers' taking a trip given 2015 average values was 0.96, additional effort resulting from increased stock abundance (catchability), Angling category allocation and/or liberalized regulations would likely come from the more consumptively-oriented Class 2 (whose probability of taking a trip given 2015 average values was only 0.27). Because Class 2 consumer surplus for the average 2015 trip was -\$484.10, substantial increases in harvest (and thus allocation) would be needed to result in a positive marginal consumer surplus for Class 2, while Class 1 effort (and surplus) likely would not change markedly with higher harvest levels, though there would be some increase due to Class 1's positive WTP for harvest. As a result, increasing allocation levels to the recreational Angling category may not significantly improve the efficiency of the U.S. Bluefin Tuna fishery as a whole.

While the model was effective at explaining the sources of heterogeneity among recreational Bluefin Tuna anglers, those sources—income and recent Bluefin Tuna targeting—do not initially appear to be as salient to management as, for example, regional heterogeneity. However, what our results do show is a large amount of latent, or potential, effort in the fishery: the Class 2 anglers (approximately 47% of all Angling permit holders) who have not targeted Bluefin Tuna recently, but who could plausibly reenter the fishery if conditions—fish availability, regulations, and costs—made it a worthwhile endeavor. With the most recent Atlantic Bluefin Tuna stock assessment indicating that the species is no longer experiencing overfishing (ICCAT 2017), managers should be wary that even a small increase in daily Bluefin Tuna bag limits could result in a large and sudden increase in participation and harvest. Their consideration of the utility function of Class 2 anglers (and thus the “tipping point” at

which inactive anglers could reenter the fishery) could inform the degree to which regulations should be liberalized in order to maintain landings within the designated sub-quota.

Our application of a latent class logit model to decisions made by recreational Bluefin Tuna anglers revealed distinct heterogeneity in preferences among anglers, with important implications for management of this overfished species. The use of latent class models, as opposed to more conventional random parameters models, could prove useful in other recreational fishery scenarios where class-specific management—for example, regionally or by gear type—is a feasible strategy. Our results could also help inform, through the estimation of compensating surplus, the comparative welfare impact of management alternatives that would meet similar biological goals (though models and assumptions regarding catch, harvest, and other conditions such as resource access would be required [See Holzer and McConnell 2014]). By doing so, managers could best maximize the welfare of these user groups while maintaining fishing mortality within biologically acceptable limits.

ACKNOWLEDGMENTS

The authors thank Brad McHale and Sarah McLaughlin of the NMFS Atlantic Highly Migratory Species Management Division, as well as 12 recreational Bluefin Tuna anglers who participated in focus groups, for their advice regarding survey development and their review of survey materials. In addition, we are grateful to Kristy Wallmo and Clifford Hutt (NMFS) for their experimental design and modeling guidance. We also thank QuanTech, Inc. for survey distribution and response collection, and *On The Water* magazine for assistance with outreach to increase response rates. Support for this project

was provided by NMFS Saltonstall-Kennedy Grant 15GAR020 and by a NMFS/Sea Grant Fellowship in Marine Resource Economics (NA15OAR4170179). This article is contribution number XXXX from the Virginia Institute of Marine Science, College of William & Mary.

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Table 1. Attributes and attribute levels included in discrete choice experiments (DCEs) presented to recreational Bluefin Tuna anglers.

Attribute	Number of levels (values)
Daily bag limit: school	4 (0, 1, 2, 3)
Daily bag limit: large school/small medium	4 (0, 1, 2, 3)
Annual bag limit: large medium/giant	2 (0, 1)
Catch: school	3 (0, 1, 2)
Catch: large school/small medium	3 (0, 1, 2)
Catch: large medium/giant	3 (0, 1, 2)
Number of fish hooked and lost	3 (0, 1, 2)
Individual trip cost	3 (\$200, \$400, \$600)

Table 2. Attribute levels for the “average” 2015 recreational Bluefin Tuna trip taken along the U.S. east coast.

Bluefin Tuna trip characteristics	2015 average trip
Daily bag limit: school	2
Daily bag limit: large school/small medium	1
Daily bag limit: large medium/giant	1
Released: school	0.07
Released: large school/small medium	0.07
Released: large medium/giant ^a	0
Harvested: school	0.06
Harvested: large school/small medium	0.06
Harvested: large medium/giant	0.001
Number of fish hooked and lost	0.06
Individual trip cost	\$534

^a While some large medium/giant Bluefin Tuna were undoubtedly released by recreational anglers during 2015, the LPS did not intercept any anglers who did so (which is not surprising given that such an event is relatively rare). As a result, while recognizing that this estimate is lower than the actual value, we include the LPS estimate of 0 here.

Table 3. Sample frame and responses by state.

State	Total Angling permit holders	Eligible Sample Frame		Responses (at least one DCE)	
		No. of permit holders	Percent of total sample	No. of permit holders	Percent of responses
Maine	425	82	3.3	40	4.1
New Hampshire	186	38	1.5	8	0.8
Massachusetts	2,470	483	19.4	188	19.2
Rhode Island	539	107	4.3	41	4.2
Connecticut	574	115	4.6	56	5.7
New York	1,822	327	13.2	110	11.2
New Jersey	2,713	538	21.6	224	22.9
Delaware	750	149	6.0	69	7.0
Maryland	1,044	208	8.4	72	7.3
Virginia	908	180	7.2	71	7.2
North Carolina	1,314	258	10.4	101	10.3
Total	12,745	2,485	100	980	100

Table 4. Models fitted to angler DCE responses. “CL” refers to conditional logit; “LCM” refers to latent class model; and “DNC” indicates that a model failed to converge to a stable negative log-likelihood.

Model	Number of parameters	Log-likelihood	AIC	BIC
CL	12	-5740.48	11504.96	11579.75
2-class LCM	31	-4857.03	9776.06	9927.58
LCM with > 2 classes	31+19*M	DNC	DNC	DNC

Table 5. Parameter estimates for 2-class latent class logit model fit to DCE data. A single asterisk denotes significance at $p = 0.05$; a double asterisk denotes significance at $p = 0.01$.

	Class 1		Class 2	
	β	S.E.	β	S.E.
X variables				
Daily bag: S	0.292**	0.080	0.0950	0.058
Daily bag: LS/SM	0.208**	0.065	-0.051	0.053
Annual bag: LM/G	0.518**	0.119	0.140	0.095
Catch: S	0.230**	0.078	0.092	0.059
Catch: LS/SM	0.197**	0.071	-0.202**	0.059
Catch: LM/G	0.122*	0.058	-0.121*	0.048
Legal harvest: S	0.296**	0.107	0.342**	0.078
Legal harvest: LS/SM	0.621**	0.087	0.754**	0.077
Legal harvest: LM/G	0.581**	0.129	0.602**	0.110
Hooked and lost	0.219**	0.040	0.056	0.036
Trip cost	-0.002**	0.0003	-0.002**	0.0002
No-trip ASC	-2.647**	0.271	0.223	0.186
Z variables				
Consumptive	0	--	-0.014	0.203
Non-consumptive	0	--	-0.195	0.208
High income	0	--	-0.363*	0.147
New England	0	--	-0.086	0.178
NY/NJ	0	--	-0.131	0.175
Target Bluefin Tuna	0	--	-0.964**	0.195
Intercept	0	--	0.783**	0.154
Latent class probability	0.528		0.472	

Table 6. Marginal effects of a one-unit change in trip attribute levels on trip probability, given 2015 average Bluefin Tuna trip levels. “S” refers to school-size fish; “LS/SM” refers to large school/small medium-size fish; “LM/G” refers to large medium/giant-size fish; “C&R” refers to catch-and-release. A single asterisk denotes a marginal probability statistically significant at a 95% confidence level based on 10,000 draws of the parameter vector; bold denotes a significant difference in marginal probability between classes.

Factor	Class 1	Class 2
2015 average trip probability	0.955*	0.266*
Marginal effects		
C&R 1 S	0.009*	0.018
C&R 1 LS/SM	0.008*	-0.037*
C&R 1 LM/G	0.005*	-0.023*
Harvest 1 S	0.019*	0.092*
Harvest 1 LS/SM	0.026*	0.118*
Harvest 1 LM/G	0.023*	0.103*
Hook and lose 1 fish	0.009*	0.011
\$100 increase in trip cost	-0.009*	-0.039*

Table 7. Output of multiple linear regression of the log-odds of posterior Class 2 membership as a function of Z parameters. A single asterisk denotes significance at $p = 0.05$; a double asterisk denotes significance at $p = 0.01$. Adjusted $R^2 = 0.1116$. F-statistic = 21.5 ($p = 2.2e-16$).

Variable	Estimate	Marginal effect of Class 2 probability
Intercept	6.9088**	--
Consumptive	-0.1075	--
Non-consumptive	-0.3626	--
High Income	-1.7015**	-0.218
New England	-0.1963	--
NY/NJ	-0.5864	--
Target Bluefin Tuna	-5.7609**	-0.446

Table 8. Class-specific willingness to pay (WTP) for Bluefin Tuna trip attributes. A single asterisk denotes a WTP significantly different from 0 at a 95% confidence level based on 10,000 draws of the parameter vector; bold denotes a significant difference in WTP between classes.

	Class 1	Class 2
Catch: S	\$123.09*	\$44.11
Catch: LS/SM	\$104.52*	-\$97.04*
Catch: LM/G	\$64.71*	-\$58.64*
Legal harvest: S	\$160.20*	\$162.98*
Legal harvest: LS/SM	\$338.46*	\$360.01*
Legal harvest: LM/G	\$315.33*	\$288.58*
Hook and lose	\$118.89*	\$26.71
No trip (Option C)	-\$1438.35*	\$111.50

Table 9. Class-specific compensating surplus (base case: 2015 levels). A single asterisk denotes compensating surplus significantly different from 0 at a 95% confidence level based on 10,000 draws of the parameter vector; bold denotes a significant difference in compensating surplus between classes.

Change from 2015 fishery	Class 1	Class 2
No LM/G harvest	-268.00*	-17.09
Catch-and-release only	-675.76*	-38.32
Fishery closure	-1708.90*	-149.14*

This section of the questionnaire presents four bluefin tuna fishing trip scenarios involving different bag limits, catch, and trip costs. For each scenario, imagine that you could either take one of the two trips described, or not go bluefin tuna fishing. Which option would you prefer? Note: For each option, you would only be allowed to harvest fish according to the stated regulations for that option.

Bluefin tuna size classes*:
 School: 27" - < 47"
 Large School/Small Medium: 47" - < 73"
 Large Medium/Giant: 73" +
 *All fish sizes are curved forked length (CFL).

Definitions			
Bag limits: The number of bluefin tuna of each size class that you are allowed to keep.	Legal harvest: The number of fish caught (brought to the boat) that you are legally allowed to keep based on fish size and stated bag limits.	Hooked and lost: The number of bluefin tuna you hook that are lost before being brought to the boat.	Trip cost to you: Your share of expenditures for the fishing trip (e.g., fuel, bait, tackle, ice, food, parking).

Scenario # 1

FEATURES	OPTION A	OPTION B	OPTION C
Bag limits (per vessel)	0 School per day 0 Large School/Small Medium per day 1 Large Medium/Giant per year	3 School per day 0 Large School/Small Medium per day 1 Large Medium/Giant per year	Do not go bluefin tuna fishing.
Catch	2 School 2 Large School/Small Medium	1 School 2 Large Medium/Giant	
Legal harvest	None	1 School 1 Large Medium/Giant	
Hooked and lost	0	2	
Trip cost to you	\$600	\$600	

	<u>OPTION A</u>	<u>OPTION B</u>	<u>OPTION C</u>
Please indicate the option you like the BEST → (Select one):	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
Please indicate the option you like the LEAST → (Select one):	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>

Figure 1. Sample DCE presented to recreational U.S. east coast Atlantic Bluefin Tuna anglers. Since the fishery is managed using English units rather than metric units, curved fork lengths were provided in inches.

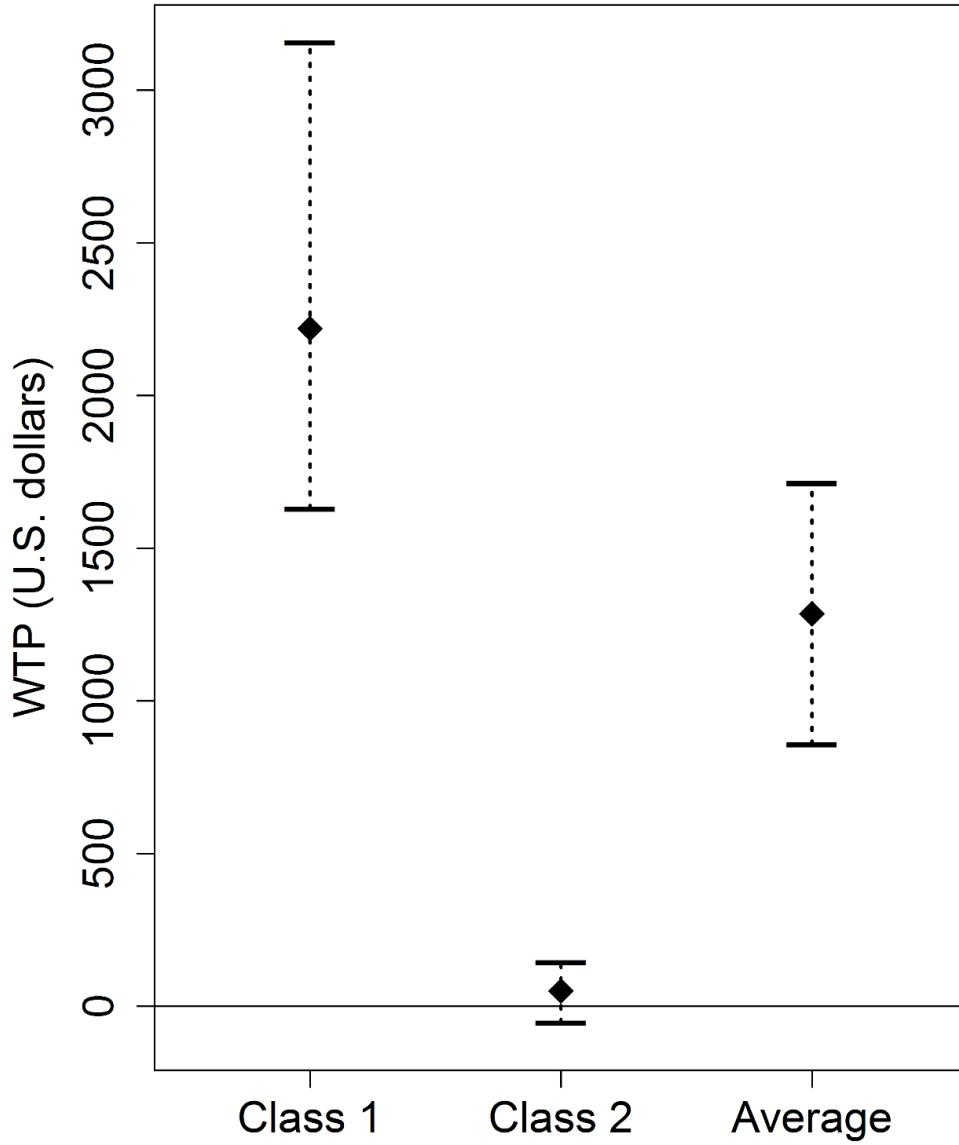


Figure 2. WTP for the average 2015 Bluefin Tuna trip by class and overall. Diamonds represent the mean values and dashed lines indicate the 95% Krinsky-Robb confidence intervals based on 10,000 random draws.

APPENDIX: Responses to non-DCE survey questions

Examination of non-DCE survey questions provided an initial framework for exploring angler attitudes and preferences to test in choice modeling efforts (Table A1). For example, there appeared to be strong segmentation by region, with anglers from New England coastal states (n = 333) exhibiting distinct angling behaviors and preferences as compared to those from the New York/New Jersey (n = 334) or Mid-Atlantic (Delaware, Maryland, Virginia, and North Carolina; n = 313) regions. New England anglers generally had higher incomes, targeted Bluefin Tuna more frequently (both in terms of trips per season and having targeted Bluefin Tuna in recent years), were less consumptively oriented, and targeted Bluefin Tuna closer to port than anglers from other regions. This apparent heterogeneity was used to inform individual-specific Z variables to incorporate into the latent class model.

While attitudes regarding the importance of harvest showed a high degree of variation among respondents, anglers appeared broadly willing to accept some degree of reduction in harvest if it meant increased fishery quality in future years: 78.3% of respondents agreed or strongly agreed with the statement, “I would be willing to accept a lower daily Bluefin Tuna bag limit if doing so would help further rebuild Bluefin Tuna stocks and allow for greater future fishing opportunities.” At the same time, however, a majority of anglers (59.3%) agreed or strongly agreed that they would never target Bluefin Tuna if they were not allowed to harvest fish.

Table A1. Responses to non-DCE questions used to inform latent class choice modeling. For questions with responses that varied significantly by region, the bolded values differ significantly from the non-bolded values (only the region-specific values that significantly differ from one another are shown).

Variable	Description (sample size)	Value	New England	NY/NJ	Mid-Atlantic
Age	Mean in years (1129)	56	--	--	--
Income	% with annual income > \$150,000 (965)	37.8%	41.9%	--	30.4%
Years targeting HMS	Mean in years (1111)	14.7	--	--	--
Bluefin Tuna targeting	% who have targeted Bluefin Tuna in last five years (1143)	61.9%	76%	66.1%	43.5%
2015 trips targeting Bluefin Tuna	Mean in number of trips (711) ^a	3.12	4.2	2.6	2.1
Distance from port fished	% who fish for Bluefin Tuna < 25 miles from port (686)	30.8%	54.4%	10.9%	19.7%
Voluntarily release Bluefin Tuna	% who ever voluntarily release Bluefin tuna (683)	51.4%	--	--	--
Consumptive orientation	% with consumptive orientation (670)	39.3%	21.6%	57.3%	41.6%
Season length preference	% who prefer short, high-harvest season (685)	38.8%	22%	53%	46.8%

^a Only includes anglers who stated that they had targeted Bluefin Tuna in the previous five years.

Table A2. Percent of individuals in each class (absolute class assignment) who exhibit specific individual characteristics. A single asterisk denotes a significant difference in percentage between classes at $p = 0.05$; a double asterisk denotes significance at $p = 0.01$.

Variable	Description	Class 1 (n = 523)	Class 2 (n = 457)
Target Bluefin Tuna	% who have targeted Bluefin Tuna in last 5 y	78.8%**	55.7%**
New England	% New England permit holders	36.7%	30.9%
NY/NJ	% NY/NJ permit holders	35.6%	32.4%
Mid-Atlantic	% Mid-Atlantic permit holders	27.7%*	37.0%*
Consumptive orientation	% with consumptive orientation ^a	35.2%	37.3%
Non-consumptive orientation	% with non-consumptive orientation ^a	33%	28.2%
High income	% with annual income > \$150,000	38.1%*	28.6%

^a Sample size is only those in each class who have targeted Bluefin Tuna in the last five years (412 for Class 1; 255 for Class 2).

CHAPTER III

Decision Making in a Mixed Commercial-Recreational Fishery for Atlantic Bluefin Tuna

ABSTRACT

Stated choice random utility frameworks have emerged as a valuable tool for eliciting the preferences and values of fishermen, but their static nature enables respondents to know choice outcomes prior to choice selection, potentially confounding results. To evaluate the importance of uncertainty in decision making, we applied a contingent sequential stated choice survey to bluefin tuna fishermen off the U.S. east coast, who are allowed to fish either commercially or recreationally on a trip-by-trip basis. Respondents completed an online survey in which they were presented two fishing trip choice scenarios, each of which asked them to make multiple choices regarding fish disposition, with the recognition that each decision might impact future choice sets on that trip. We describe our application of a random parameters logit model with correlated random parameters used to identify key factors governing disposition decisions, evaluate the impact of inertia (habit formation), and forecast future harvest patterns.

Keywords: Choice experiment, inertia, uncertainty, allocation

INTRODUCTION

Stated choice modeling in fisheries

Stated choice random utility models have been used to identify preferences and values in numerous non-market and environmental settings, including recreational fisheries (e.g., Hanley, Wright, and Adamowicz 1998, Aas, Haider, and Hunt 2000, Wallmo and Edwards 2008). These models often utilize data collected through surveys that employ discrete choice experiments (DCEs), in which respondents are presented with several multi-attribute alternatives—for example, fishing trips with varying levels of catch, harvest limits, and cost—and are asked to select their most preferred alternative (e.g., Oh et al. 2005, Carter and Liese 2012). These studies provide valuable information regarding preferred management alternatives for a given sector (Aas, Haider, and Hunt 2000), as well as guidance for optimal allocation among competing sectors (Lew and Larsen 2012).

While such stated choice models can provide critical welfare estimates and valuable insight into the tradeoffs that individuals make between attributes, one shortcoming of the static DCE approach is the ex-post nature of the choice scenarios: the respondent is able to choose between hypothetical fishing trips while already knowing the outcome of each trip. The trip, in other words, is considered a static good consisting of a bundle of attributes and attribute levels already known to the decision maker. Actual fishing decisions, however, take place in the context of uncertainty with regard to the outcome (i.e., fishing success) associated with a particular decision, and individual fishermen must evaluate the risks associated with each choice (Gates 1984, Holland 2008). A more dynamic approach is needed in order to capture such uncertainty and

measure its effects on fishermen decision making, which ultimately impacts patterns of fishing mortality (Wilén et al. 2002).

A dynamic approach also lends itself to an examination of habit formation among respondents, and the degree to which their preferences are (or are not) stable. While discrete choice random utility models in which respondents answer multiple DCEs often account for repeated choices by estimating the joint probability of a choice sequence (e.g., Carter and Liese 2012, Lew and Larson 2012), the error terms (unobservable portion of utility) associated with each choice are considered independent and preferences are assumed to be fixed across choices (Train 2009). The concept of inertia—the degree to which a current choice is affected by previous behavior—is rarely explicitly accounted for in fisheries settings. In modeling demand for recreation alternatives and transportation modes, however, inertia has proven to be an important driver of decision making (Adamowicz 1994, Cantillo, Ortúzar, and Williams 1997, Cherchi and Maca 2011, Morikawa 1994). In the context of fisheries, inertia could be interpreted as behavioral insensitivity to circumstances, with high-inertia individuals maintaining a given behavior or set of behaviors (e.g., target species, spatial and temporal fishing decisions, fishing mode) even as conditions change. Conversely, low-inertia individuals might be considered opportunistic, adapting behavior to prevailing conditions in order to maximize a certain objective such as harvest level or profit.

Mixed commercial-recreational fisheries

In the United States, commercial and recreational fisheries are most often considered together in the context of competition for finite fishery resources. While National Standard 4 of the Magnuson-Stevens Fishery Conservation and Management

Act calls for fair and equitable allocation of fishing privileges (C.F.R. §600.310, Plummer, Morrison, and Steiner 2012), Kearney (2002) posited that conflict between recreational and commercial fishery sectors is inevitable in developed nations. Indeed, controversies over allocation have repeatedly arisen for numerous species that are targeted by both groups, such as Pacific salmon (Berman, Haley, and Kim 1997), red drum (Thurman and Easley 1992, Schuhmann and Easley 2000), and Gulf of Mexico snappers and groupers (Gentner 2013, Agar and Carter 2014). Economic theory, typically drawing on the equimarginal principle, has been employed to help inform the resolution of such allocation conflicts for decades (e.g., Bishop and Samples 1980, Easley and Prochaska 1987, Easley 1992).

A tacit assumption of such analyses has been the distinct and mutually exclusive nature of commercial and recreational stakeholder groups (i.e., each fisherman belongs to one group or the other), but there are examples of U.S. fisheries in which individual fishermen partake in both the commercial and recreational sectors for a given species or species complex (referred to here as a mixed commercial-recreational fishery), complicating management efforts. In pelagic fisheries off Hawaii, for example, fishermen who possess a Commercial Marine License are able to fish both recreationally and commercially, and often do so on a trip-by-trip basis according to market and fishery conditions, thus blurring the distinction between the two sectors (Adams 1978, Pooley 1993, Miller 1996, McConnell and Haab 2001, Duffield et al. 2012). According to a survey of Hawaiian small-boat pelagic fishermen by Hospital, Bruce, and Pan (2011), over 30% of respondents who self-classified as “recreational” had sold fish in the previous year (often to cover trip costs), making it difficult to track and manage sector-

specific harvest while also presenting an obstacle to potential future allocation of harvest between sectors.

The fishery for Atlantic bluefin tuna (*Thunnus thynnus*) along the U.S. east coast from Maine to North Carolina presents a particularly unique and challenging case of a mixed commercial-recreational fishery given the species' high profile and value, the complex domestic allocation structure, and the United States' accountability to the International Commission for the Conservation of Atlantic Tunas (ICCAT). The bluefin tuna quota allocated to the United States by ICCAT (1,059 mt for 2017 [ICCAT Rec. 16-08]) is domestically apportioned among fishery sectors according to the 2006 Consolidated Atlantic Highly Migratory Species (HMS; billfish, sharks, swordfish, and tunas) Fishery Management Plan (NMFS 2006) (Table 1). The commercial and recreational fisheries for bluefin tuna are separated by the size classes targeted. Recreational anglers (i.e., Angling category permit holders), who cannot legally sell bluefin tuna, are restricted to the harvest of bluefin tuna measuring from 27 inches to less than 73 inches curved fork length (CFL), with the exception of one annual trophy of 73 inches CFL or greater per vessel per year (64 FR 29090, 5/28/1999). Commercial fishermen, meanwhile, are only allowed to harvest fish measuring greater than 73 inches CFL (64 FR 29090, 5/28/1999).

While available permit types generally correspond to the fishery's allocation categories, a notable exception is the HMS Charter/Headboat (CHB) permit, which allows the permit holder to fish either under the Angling (recreational) or General (commercial handgear) categories on a trip-by-trip basis (but not on the same trip), thereby contributing landings to both sub-quotas (64 FR 29090, 5/28/1999). This permit

structure was developed to reflect the historical practice of charter boat operators in the fishery to fish commercially for bluefin tuna when not operating as a charter vessel (60 FR 25665, 5/12/1995). In 2016, 263 CHB permit holders (approximately 11% of all CHB permit holders from Maine to North Carolina), sold at least one bluefin tuna under the General category (U. Forest-Bulley, NMFS, pers. comm.). Because of the size class specifications for bluefin tuna regulations, the size of the first fish harvested frequently dictates trip type. While the CHB permit was initially intended for for-hire captains, anyone who possesses a valid Merchant Marine License or Uninspected Passenger Vessel License is allowed to obtain one (64 FR 29090, 5/28/1999), and private anglers may wish to obtain this permit given both its flexibility to fish commercially and its more liberal recreational harvest regulations compared to Angling category permit holders (i.e., higher bag limits in order to attract customers for charter captains) (FR 82 19615, 4/28/2017). The extent to which permit holders utilize this flexibility, as opposed to fishing exclusively in either a commercial or recreational manner, is unknown.

Because the CHB permit holder group has no quota allocation of its own, it directly competes with recreational anglers in possession of an Angling category permit and with commercial fishermen in possession of a General category permit. From 2002 to 2015, CHB permit holders annually harvested approximately 24-43% of the annual Angling category quota and 19-46% of the annual General category quota (K. Goldsmith, NMFS, pers. comm; NMFS Fisheries Statistics Division, pers. comm.) (Figure 1). The CHB permit category thus represents a significant “swing” group whose behavior can substantially impact the volume and size distribution of U.S. bluefin tuna landings. For example, if numerous CHB permit holders elect to fish commercially (i.e., under the

General category) for a given year, the risk of overharvesting the General category sub-quota—and the U.S. bluefin tuna quota as a whole—increases. Meanwhile, per international agreement, no more than 10% of the United States’ annual quota (balanced over a two-year period) can consist of juvenile bluefin tuna measuring between 27 and 47 inches CFL (ICCAT Rec. 14-05); if a large proportion of CHB permit holders fish recreationally, that threshold could be exceeded. Understanding how fishery conditions such as regulations and expected fish size might affect CHB permit holders’ decisions to fish commercially or recreationally for bluefin tuna is critical for improving the ability of managers to predict permit holders’ relative contributions to the Angling and General category sub-quotas, and by extension, to the U.S. bluefin tuna quota as a whole.

In this study, we applied a unique choice modeling approach that examined decision making as conditions evolved over the course of a single fishing trip. We explored factors determining targeting and trip type decisions in the mixed commercial-recreational fishery for Atlantic bluefin tuna, while also investigating the potential impacts of inertia (previous behavior) and uncertainty (e.g., fish size) on such decisions. In particular, we examined the degree to which fishermen are opportunistic—that is, harvesting whatever bluefin tuna are available to them regardless of size or disposition options—versus having strong, defined preferences for harvesting under the General or Angling category (i.e., strong inertia). Lastly, we sought to identify potential preference heterogeneity among bluefin tuna fishermen that could explain and predict harvest patterns in this highly valued fishery.

METHODS

The contingent sequential stated choice (CSSC) survey

We conducted an online stated choice survey of CHB permit holders from Maine to North Carolina that asked respondents to choose their most preferred options for simulated bluefin tuna fishing trip scenarios. To capture evolving conditions over the course of a single fishing trip, we developed what we call a contingent sequential stated choice (CSSC) survey, in which respondents were asked to make up to three decisions for each trip (Figure 2): 1) whether or not to take paying charter clients bluefin tuna fishing (or not go bluefin tuna fishing at all); 2) how to dispose of a first fish caught (retain under Angling, retain under General, or release); and 3) how to dispose of a second fish caught (retain under Angling, retain under General, or release). Respondents did not know how many fish they would catch (if any) over the course of a trip scenario. Given the size-differentiated nature of the commercial and recreational Atlantic bluefin tuna fisheries and the prohibition on retaining fish for both commercial and recreational purposes on the same trip, in many cases deciding to keep the first fish would bind the respondent to either a commercial or recreational trip and thereby restrict disposition options for subsequent fish (Figure 3). For instance, if a respondent kept a bluefin tuna measuring less than 73 inches CFL under the Angling category, a subsequent fish measuring 73 inches CFL or greater could not be retained under the General category, and could only either be released or retained under the Angling category as the vessel's annual trophy (if regulations permitted). Permit holders were thus compelled to make decisions while in a position of uncertainty regarding future catch (both size and quantity), providing insight into how uncertainty may affect preferences and decision making.

Experimental design

Attributes and attribute levels for the trip scenarios were developed in conjunction with CHB permit holders and NMFS HMS Management Division staff to reflect those factors believed to affect the decision to fish for bluefin tuna in a given manner (Table 2). For the first choice of whether to go bluefin tuna fishing and whether to take paying clients (assuming that willing charter clients were available), five attributes, each with two to four levels, were included: Angling daily bag limits for the school (27 - < 47 inches CFL) and large school/small medium (47 - < 73 inches CFL) size classes; Angling annual (trophy) bag limit for the large medium/giant (73+ inches CFL) size classes; the General daily bag limit for the large medium/giant size classes; and the anticipated size range of fish to be encountered (assuming that fish were available in the area). For the second choice of how to dispose of the first fish landed, a sixth attribute, the size of the first fish, was added to the choice set, and impacted which disposition options were available. For the final choice of how to dispose of the second fish landed, the size of the second fish was added as a seventh attribute, with bag limit levels potentially adjusted depending on the disposition of the first fish.¹

Because presenting a full factorial experimental design that included all levels of all attributes was not practical (3,456 simulated trips), macros in SAS software (SAS 9.3; SAS Institute, Inc., Cary, NC USA) developed by Kuhfeld (2010) were used to develop a fractional factorial design capable of efficiently estimating parameters (Louviere, Hensher, and Swait 2000). A key objective of the study was to examine decision making and tradeoffs with regard to harvest under the Angling or General category; therefore, the

¹ While bag limits were potentially adjusted across decisions within a single trip, they were not adjusted across trips within a survey, as the two trips were considered independent. For example, if a respondent chose to retain their annual trophy bluefin tuna measuring 73 inches CFL or greater on the first trip, such a decision did not necessarily mean that the trophy category would be closed on the second trip.

survey was designed so that respondents would frequently have to choose the disposition category for a given fish—in other words, scenarios in which a fish could be harvested under either category. Frequently, deciding to harvest a fish under one category or the other would restrict disposition options for subsequent fish. Restrictions were built into the construction of the trip scenarios so that actual fish size always fell within the range of anticipated fish size, and also that the aggregate Angling bag limit for fish measuring less than 73 inches CFL never exceeded three fish, as had typically been the case during the several years prior to survey development. In addition, scenarios in which a fish would have to be released without any prior decision making on the part of the respondent (e.g., a 45 inch CFL fish when the school-size bag limit is 0) were not included. A total of 20 alternatives, each representing a single simulated trip scenario (i.e., up to three choices), was generated and blocked into 10 blocks of two trips each. Respondents were thus never required to make more than six choices over the two trip scenarios, similar to the number used in other stated choice surveys, in order to reduce the risk of respondent fatigue (Bennett and Adamowicz 2001, Hicks 2002, Oh et al. 2005, Carter and Liese 2012).

In addition to the trip scenarios, surveys included a series of questions that asked permit holders about their bluefin tuna fishing behavior and experience, attitudes concerning the management of the fishery, and demographic characteristics. Responses to these questions were used to explore drivers of heterogeneity in trip decision making as well as to examine consistency between stated use of the CHB permit and trip scenario choices (i.e., convergent validity [Freeman 2003]). Prior to survey delivery, focus groups were held with CHB permit holders in Hyannis, MA, Toms River, NJ, and Nags Head,

NC, in which attendees beta tested the online survey to ensure comprehension and compatibility with a variety of mobile devices (e.g., laptops, smartphones, and tablets). The survey was approved by the College of William and Mary's Protection of Human Subjects Committee (Protocol # PHSC-2015-11-19-10758-amscheld).

Survey delivery

Survey distribution and collection were conducted by the survey research firm Quantech, Inc. (Rockville, MD USA) from April-August 2016. Names and contact information for all CHB permit holders as of December 31, 2015 (n = 2410) with a listed primary port from Maine to North Carolina (Maine, New Hampshire, Massachusetts, Rhode Island, Connecticut, New York, New Jersey, Delaware, Maryland, Virginia, and North Carolina) were obtained from the HMS Management Division and shared with Quantech. For each state, permit holders were randomly assigned to one of the 10 survey blocks while maintaining an equal number of each survey version in each state to the extent possible.

Given the complex nature of the survey, with attribute levels and available alternatives able to vary over choices within a trip scenario, a web survey was used. To contact CHB permit holders and invite them to participate, a mixed-mode approach modified from Dillman, Smyth, and Christian (2009) was employed consisting of up to five contacts over five weeks: an initial email invitation with a unique survey link (for the 86% of permit holders with a valid email address); a reminder email invitation; a mail invitation with a survey link and unique access code; a postcard reminder; and a final reminder email. To increase response rates, several measures were taken in accordance with recommendations from focus group attendees and previous published studies.

Correspondence materials explicitly mentioned that the study was being led by the Virginia Institute of Marine Science (VIMS), as focus group attendees suggested that aligning the study with an academic organization (rather than a government agency) would increase responses. Because low-odds, high-reward lotteries have been shown to be the most-cost effective way to increase response rates (Gajic, Cameron, and Hurley 2012), permit holders were entered into a random drawing to win one of two \$500 cash prizes upon completing the survey. In addition, permit holders were informed that following the study's conclusion, respondents would receive a summary of survey findings.

Choice modeling

While respondents were asked to make up to three decisions for each trip scenario, only responses to the latter two decisions—the dispositions of the first and second fish caught—were modeled, given the interest in understanding and predicting harvest decisions among members of this permit holder group. Responses to the first question—whether or not to take paying clients on a given trip—were used as a means to contextualize subsequent choices, as the presence of clients on board might impact permit holder behavior (e.g., a permit holder may be more compelled to retain a fish under the Angling category for clients). However, given the presumed diversity of CHB permit holders (some of whom may never take paying clients), imposing whether or not clients were on board as an initial attribute was not considered a reasonable approach, as it would not necessarily provide an appropriate or reasonable context for subsequent bluefin tuna harvesting decisions (Swait et al. 2002).

To model CSSC responses, a random utility theoretic approach was used, which assumes that an individual will select the alternative (harvest under the General category, harvest under the Angling category, or release) that maximizes his or her underlying utility function. For individual n , the overall utility U of alternative (harvest disposition) i can be decomposed into an observable component V_{ni} and a random error component ε_i not captured by the model; alternative i will be selected if its associated utility is greater than that for all other available alternatives j . In this study, for a given choice scenario the number of available disposition alternatives varied from one (i.e., the fish had to be released) to three according to the size of the fish, the Angling and General category bag limits, and any constraints placed on available alternatives by previous choices on that trip.² The observable component of utility V_{ni} can be written as βx_{ni} , where x_{ni} is a vector of the attributes in alternative i , and β is a vector of associated utility parameters (Train 2009). If each unobserved component of utility ε_i is assumed to follow an independent and identical extreme value type I distribution, the probability of individual n choosing alternative i can be expressed by the multinomial logit (MNL):

$$P_{ni} = \frac{e^{\beta x_{ni}}}{\sum_j e^{\beta x_{nj}}}. \quad (1)$$

An extension of the multinomial logit, the random parameters logit (RPL), allows each random parameter β associated with factor x to vary across each respondent n according to a specified mixing distribution (Train 2009):

$$P_{ni} = \int \left(\frac{e^{\beta' x_{ni}}}{\sum_j e^{\beta' x_{nj}}} \right) f(\beta) d\beta. \quad (2)$$

² Choice scenarios in which the only possible alternative was to release the fish (i.e., there was no choice, which would only occur as a consequence of previous decisions) were not included in the model.

This general form, which allows for unrestricted substitution patterns across alternatives, random taste variation across respondents, and correlation in errors across decisions, has been used in numerous stated choice studies of fishermen (e.g., Carter and Liese 2012, Lew and Larson 2012). For this study, in which a diverse group of bluefin tuna fishermen were suspected to utilize the CHB permit in different ways, the RPL was considered a potentially critical tool for quantifying the degree of heterogeneity among respondents, which could be used for forecasting future behavior.

To account for the panel nature of the data—each respondent was able to make up to four decisions (over two trips) regarding the disposition of bluefin tuna—the log-likelihood function included the product of individual mixed logit probabilities across t choice occasions:

$$\ln L = \sum_{n=1}^N \ln \left\{ \prod_{t=1}^T \left[\int \left(\frac{e^{\beta' x_{ni}}}{\sum_j e^{\beta' x_{nj}}} \right) f(\beta) d\beta \right] \right\}. \quad (3)$$

While the model described in Equation 3 accounts for correlation in unobserved factors across the multiple fish disposition decisions that an individual makes through the course of the survey by allowing for heterogeneous individual preferences, it does not distinguish between decisions within a given simulated trip and decisions that occur on separate trips. In order to allow for correlation in unobserved factors at the trip level (i.e., the multiple decisions on a single trip), the random parameters in the model, which were associated with trip-specific attributes and assigned normal distributions, were permitted to be correlated with one another (Hensher and Greene 2003, Hess and Train 2017). In order to do so, we specified the individual-specific random coefficients $\beta'_n \sim N(b, \Omega)$,

with b representing the mean across individuals and Ω representing the covariance matrix where off-diagonal elements are allowed to be non-zero. The vector of random coefficients can then be written as $\beta'_n = b_n + L\mu_n$, in which L denotes a lower triangular Choleski factor of Ω and μ represents a vector of independent standard normal deviates (Revelt and Train 1998, Train 1998, Carter and Liese 2012).

In addition to including trip-specific attributes as factors in the model, alternative- and individual-specific dummy variables were also included to examine hypotheses believed to be relevant to managing this mixed commercial-recreational fishery (Table 3). Of particular interest was evaluating the level of opportunism among respondents—for example, if the first fish caught was harvested regardless of size, even if doing so bound the respondent to an Angling or General category trip. Conversely, the effect of inertia (i.e., habit formation) was investigated through the addition of dummy variables describing decision making on previous choice occasions (Adamowicz 1994, Morikawa 1994). Inertia was investigated on two levels. First, for both scenarios, respondents' stated primary trip type orientation for bluefin tuna (Angling or General)—which can be considered a revealed preference—was included as a factor in deciding whether to harvest a fish under the Angling or General category. Second, for the second trip scenario, the first trip type was included as a factor. Together, these variables examined the level of consistency in trip type selection regardless of trip-level attributes.

Model fit for the standard MNL, the RPL without correlated random parameters, and the RPL with correlated random parameters was assessed using Akaike's Information Criterion (AIC; Akaike 1973) and the Bayesian Information Criterion (BIC; Schwarz 1978). The RPLs with and without correlated random parameters were further compared

using three tests: the Wald test; the Lagrange multiplier test (a.k.a. score test); and the likelihood ratio test. All model estimation was performed using the “mlogit” package (Croissant 2013) in the statistical programming software R (R Core Team 2016).

To estimate the marginal effects of trip- and individual-specific variables on the probability of disposing of a fish in a given manner, the bootstrapping method of Krinsky and Robb (1986) was used, based on 10,000 random draws from a multivariate normal distribution with a mean set at parameter means (b_n for the RPLs) and a covariance matrix corresponding to the model’s variance-covariance matrix. Marginal effects—the effect of a single unit change in a continuous variable (e.g., fish size, bag limits), or the discrete change of a dummy variable from 0 to 1 (e.g., for individual-specific variables)—were then calculated by estimating the difference in disposition probability associated with a marginal change in the variable of interest while holding other variable levels constant at mean values.

Because a key objective of this study was to forecast how harvest patterns might change as a function of both fishery conditions (fish size, bag limits) and the characteristics of participating fishermen (e.g., primary trip type orientation, geographic location), varying levels of the factors included in the model were combined to generate realistic mock decision scenarios that could be experienced by fishery participants. For each of these mock scenarios, the same 10,000-row Krinsky-Robb matrix used to estimate marginal probabilities was used to generate a distribution of harvest probabilities, providing insight into both the anticipated behavior of permit holders and potential variability in responses.

RESULTS

Response rate and characteristics of respondents

Out of 2,394 eligible respondents, 788 permit holders completed the survey, for an effective response rate of 32.9%. The proportion of respondents by state was similar to the proportion of permit holders by state, suggesting that responses were generally not biased based on geographic location, although Fisher exact tests revealed that Rhode Island permit holders were significantly over-represented and that North Carolina permit holders were significantly under-represented ($p < 0.01$) (Table 4). Responses to general questions regarding demographics, bluefin tuna fishing behavior and use of the CHB permit revealed striking heterogeneity (Table A1). Despite the permit's being originally intended for for-hire captains, of those who answered that they had targeted bluefin tuna in the past five years, only slightly more than half (56%) indicated that they had captained a charter trip targeting bluefin tuna during that time. The most common primary bluefin tuna trip type indicated by respondents was private recreational (39.9% of respondents), followed by charter recreational (33%), private commercial (23.7%) and charter commercial (charters on which the intent is to catch and sell a large medium or giant-size bluefin tuna; 3.4%), meaning that over 70% of respondents primarily fished recreationally and over 60% of respondents primarily fished for bluefin tuna without paying clients on board.

Responses also suggested significant heterogeneity in permit use by geographic region. New England permit holders were far more likely to have targeted and sold commercial-sized bluefin tuna, while New York/New Jersey-based permit holders largely targeted school-size bluefin tuna recreationally. In addition, a greater proportion of New York/New Jersey permit holders supported the idea of a separate sub-quota for the CHB

category—perhaps a result of the fact that they tend to directly compete with the Angling category for landings of juvenile bluefin tuna, as opposed to fishing under both the Angling and General categories.

Of the 577 respondents who elected to go bluefin tuna fishing for both scenarios (i.e., did not select the “Do not go bluefin tuna fishing” option for either scenario), 14% chose to harvest fish under the Angling category for both trips, 23% chose to harvest fish under the General category for both trips, 29% chose to harvest fish under the General category on one trip and under the Angling category on the other trip, and 34% chose to release all bluefin tuna on at least one trip. Stated primary trip types generally aligned with the types of trips selected in choice scenarios, suggesting convergent validity (Table 5).

Of respondents who indicated that they had taken paying clients on a bluefin tuna charter in the previous five years and completed at least one scenario trip ($n = 358$), 69.8% chose to take clients on at one least scenario trip, compared to 32.2% of respondents who had not taken clients in the previous five years ($n = 289$) (Fisher exact test: $p < 0.0001$). In addition, 82.3% of respondents who had ever sold a bluefin tuna and who completed at least one scenario trip ($n = 247$) chose to harvest a fish under the General category on at least one trip, compared to 43% of respondents who had never sold a bluefin tuna ($n = 398$) (Fisher exact test: $p < 0.0001$).

Model specification

The RPL model, both with and without correlated random parameters, provided a significantly better fit to the data than did the MNL according to both information criteria (Table 6). Including correlation among random parameters provided a better fit than not

including correlation according to AIC but not BIC, likely because BIC imposes a larger penalty for additional parameters than does AIC. Similarly, both the likelihood ratio test ($p = 0.0007$) and score test ($p = 0.0009$) rejected the null hypothesis that the random parameters were uncorrelated, but the Wald test did not ($p = 0.11$). While results were mixed regarding which RPL model was better suited to the data, we elected to use the model with correlated random parameters for subsequent analyses given its higher level of support from both information criteria and the model fit tests, in addition to the fact that correlation among random parameters was intuitive and allowed us to account for intra-trip correlation in unobserved factors.

Parameter estimates for the RPL with correlated random parameters are provided in Table 7. The model provided strong evidence for heterogeneity in preferences among CHB permit holders. With the exception of the FishSize variable, both the parameter mean and standard deviation estimates for all random coefficients were significant. The random parameter estimates for FirstFish and AntSize_Small_Ang indicated that while some permit holders appeared to be opportunistic, harvesting whatever bluefin tuna they were able to, others demonstrated clear preferences for harvesting under the General or Angling category. The mean value for FirstFish was positive and significant, indicating that, on average, a fish was more likely be harvested if it was the first fish of the trip, regardless of what category such harvest would fall under. For 14% of respondents, however, the FirstFish variable was less than 0, meaning that a fish's being the first of a trip was actually a negative inducement to harvest. Similarly, while the mean coefficient for AntSize_Sm_Ang was positive and significant, the coefficient was estimated to be

negative for 37% of respondents, who were less likely to harvest a fish under the Angling category when the anticipated fish size was less than 75 inches CFL.

For both bag limit variables, parameter estimates were positive, suggesting that an increase in a category's bag limit increased the probability of harvesting under that category. However, large and significant standard deviations for each variable indicated that the parameter estimates for the General and Angling category bag limits were less than 0 for 28% and 32% of the respondent population, respectively. In other words, for some individuals, the probability of harvesting under a given category decreased when the bag limit for that category increased. For FishSize, the mean value was slightly negative and significantly different from 0, but the standard deviation was not, meaning that larger bluefin tuna were slightly less likely to be harvested (under either category) compared to smaller fish.

Several random parameters were significantly correlated with one another. The positive correlation between the bag limit variables indicated that those who responded positively to an increase in the bag limit for one category (i.e., became more likely to harvest under that category) tended to also respond positively to an increase in the bag limit for the other category. The negative correlation between the FirstFish and FishSize parameters suggested that individuals more likely to harvest a fish if it was the first of the trip—that is, the opportunists—were less likely to harvest a fish as fish size increased. The negative correlation between the General bag limit and FishSize parameters, meanwhile, indicated that individuals whose probability of harvesting under the General category increased with an increasing bag limit also tended to have a reduced probability of harvesting a fish as fish size increased.

Non-random factors included in the model suggested strong inertia effects among some respondents—in particular, those who tended to harvest under the General category—as well as geographic heterogeneity in harvest tendencies. Respondents who indicated that their primary trip type was commercial (either private or charter) and who had previously sold a bluefin tuna were significantly more likely to harvest a fish under the General category. In addition, if the harvest of a fish bound a respondent to an Angling trip (e.g., if the fish was less than 73 inches CFL), those who were primarily General category fishermen were significantly less likely to harvest, demonstrating a marked preference for commercial harvest. Similarly, respondents who indicated that they primarily fished recreationally were more likely to harvest under the Angling category, though significance was marginal ($p = 0.05$). The type of trip chosen for the first trip scenario, however, was not a significant predictor of the type of trip chosen for the second trip scenario for either category. Geographic heterogeneity was demonstrated by the positive and significant dummy variables associated with the release alternative for the New England and Mid-Atlantic regions, indicating that respondents from the New York/New Jersey region were significantly more likely to harvest a fish, regardless of available disposition options.

Marginal effects and mock scenarios

The marginal probabilities of harvest associated with the factors included in the model are shown in Table 8. FirstFish had the highest marginal probability of all factors; if the fish was the first of the trip, the probability of its being harvested under the Angling or General category increased by 55% and 43%, respectively. Having clients on board, anticipating catching bluefin tuna ranging from 45-75 inches CFL, and being from New

York or New Jersey increased the probability of harvesting a fish under the Angling category by 31%, 18%, and 18%, respectively. For harvesting under the General category, having previously sold a bluefin tuna (35%) and being a primarily General category bluefin tuna fisherman (30%) had the largest marginal effects other than FirstFish.

Mock scenario results (Figure 4) indicated that harvest patterns for bluefin tuna of a given size could vary dramatically based on both fishery conditions and the individual characteristics of the permit holder. The mean probability of a New/New Jersey permit holder's harvesting a 60 inch fish under the Angling category with clients on board and a liberal Angling bag limit (four fish) (Scenario A) was 0.96; for the same fish caught by a New England permit holder without clients on board, a strict Angling bag limit (one fish), and no expectations regarding fish size (Scenario B), meanwhile, the mean probability of harvest was 0.16. For an 80 inch fish caught by a New England permit holder who primarily fished under the General category and had previously sold a bluefin tuna, when the General bag limit was high (four fish) and the Angling trophy category was closed (Scenario C), the mean probability of harvest under the General category was 0.99. Meanwhile, for a fish of the same size caught by a Mid-Atlantic permit holder who primarily fished under the Angling category and had never sold a bluefin tuna, when the General bag limit was strict (one fish) and the trophy category was closed (Scenario D), the mean probability of harvest under the General category was 0.62. While harvest probabilities for the 10,000 draws were tightly clustered for Scenarios A and C, they were spread broadly in Scenarios B (ranging from 0.023 to 0.55) and D (ranging from 0.25 to

0.90), underscoring that while predicting harvest patterns with some degree of precision may be possible in some circumstances, high uncertainty can persist in others.

DISCUSSION

This study applied a stated choice approach in which respondents made multiple within-trip decisions regarding bluefin tuna disposition. Results revealed substantial heterogeneity in how fishermen respond to uncertainty regarding catch outcomes for a given trip. Specifically, permit holders who were primarily commercially oriented appeared to exhibit stronger inertia and more well-defined harvest preferences, and were willing to forgo the opportunity to retain a fish under the Angling category in order to have a later opportunity to retain a fish under the General category. Conversely, those who identified as recreationally oriented (~73% of all respondents) appeared more opportunistic and averse to uncertainty, and were more inclined to harvest whatever fish were made available regardless of disposition option rather than risk not catching (and retaining) any subsequent fish.

Inertia versus opportunism

The finding that respondents who primarily fished in a commercial manner were less willing to harvest a fish recreationally than vice versa is not wholly surprising given the expectation of income generation (either to cover expenses or turn profit) among those who typically fish commercially—the harvest of an Angling category fish thus may be considered a loss. The interpretation that primarily commercially fishermen are less likely to harvest a fish for recreational purposes is consistent with Hospital, Bruce, and Pan's (2011) survey of Hawaii small-boat fishermen, which found that full-time commercial fishermen (> 50% of personal income derived from fishing) on average did

not sell fish on only 4% of trips, while part-time commercial fishermen (< 50% of personal income derived from fishing but had sold fish in the previous 12 months) did not sell fish on 38% of trips.

However, for those who primarily fish recreationally, the experience of catching a fish for commercial sale—plus the money obtained from its sale—may make such an alternative appealing even as the prospect of obtaining a fish for personal consumption is forgone. Additionally, it should be noted that while fish harvested under the General category are typically sold, it is technically legal to harvest a fish under the General category and not sell it as long as either: 1) a federally permitted seafood dealer affixes a dealer tag to the fish and reports the landing to NMFS; or 2) the vessel operator contacts a NMFS enforcement agent, providing the necessary reporting information (S. McLaughlin, NMFS, pers. comm.). This provision, included as a harvest option (“Retain under General category, but do not sell”) in the CSSC scenarios where applicable, might further explain the additional tendency of primarily recreational permit holders to harvest under the General category, as doing so could provide a means for harvesting a fish measuring more than 73 inches CFL for personal consumption even when the Angling trophy category is closed.³ An exception to the general pattern of increased opportunism among those who primarily fish recreationally may be for CHB permit holders who take paying clients, in which case the marginal probability of harvesting a fish under the Angling category increased by over 30%.

³ Respondents chose to harvest under the General category but not sell in about 17% of all instances in which harvesting under the General category was the selected alternative. Because no data are available regarding whether fish harvested under the General category are sold or not, it is unknown whether this frequency is representative of what occurs in the fishery.

While inertia was detected between stated primary trip type and the trip type selected in each of the scenarios, the RPL model did not provide evidence of inter-trip inertia—that is, the harvest disposition chosen in the first trip scenario did not significantly impact the choice of harvest disposition on the second trip. In the MNL model, which did not allow for individual preference heterogeneity or account for the multiple choice occasions that could be experienced by an individual, the choice of fish disposition on the first trip was shown to be a significant predictor of fish disposition on the second trip. This finding suggests that the preferences of respondents were consistent throughout the scenarios. Since the RPL model indicated that primary stated trip type significantly impacted harvest disposition under both the Angling and General categories, we can infer that inertia occurred between stated primary trip type (i.e., the revealed preference) and selected trip types in scenarios, but that the selected trip type in the first scenario did not affect the selected trip type in the second scenario after accounting for preference heterogeneity. Long-term habit formation thus does appear to play an important role in predicting harvest behavior when outcomes are uncertain, at least for some respondents.

Counterintuitive findings

A few parameter estimates from the model initially appear counterintuitive, but can be explained when considered in the context of the fishery and its participants. The finding that between a quarter and a third of respondents had negative coefficients associated with the bag limit variables could be due to the fact that for some individuals, a high bag limit is likely a signal of high stock abundance and fish availability. As a result, fishermen might choose to “hold out” for larger fish (either for higher yield when

fishing recreationally, or higher profit when fishing commercially), and thus may be compelled to release a fish in the lower range of a given size class. A second explanation may be that, to some fishermen, a high bag limit may suggest that management strategies are too lax for effectively conserving the bluefin tuna stock, leading them to voluntarily release fish that they would otherwise be allowed to keep. This behavior is more likely for recreational than commercial fishermen, but considering that nearly three quarters of respondents primarily fish for bluefin tuna recreationally, such a mindset could have contributed to model results. Such a conservation ethic among recreational anglers may also explain why some respondents had a negative coefficient associated with *AntSize_Sm_Angling*, which suggests that some anglers prefer to catch and release small bluefin tuna rather than harvest them.

The negative coefficient associated with *FishSize*—albeit two orders of magnitude smaller than that associated with *FirstFish*—could be a result of the fact that the majority of the respondent population was recreationally oriented and thus primarily able to retain fish measuring less than 73 inches CFL. While this group was more opportunistic than those who primarily fished commercially, there was some evidence of inertia among recreational anglers as well, with those who primarily fished recreationally more likely to harvest under the Angling category, which in turn meant harvesting smaller fish. Notably, both the *FishSize* and *PrimAng_Ang* coefficients were only significant in the RPL model, and not the MNL model: only when allowing for heterogeneous preferences that are consistent across choices did evidence of inertia and a slight aversion to larger fish by recreationally oriented fishermen become apparent.

Interpreting correlated random parameters

Allowing random variables to be correlated provided further insight into the contrast between opportunists and high-inertia individuals in situations with uncertain outcomes. For example, the significant positive correlation between the General and Angling bag limit parameters makes sense in that more opportunistic permit holders are likely to respond positively to any increase in allowable harvest, whereas those with well-defined preferences (for Angling or General category harvest) will likely be inclined to continue harvesting in a given manner regardless of the bag limit levels for the two categories. Given that the majority of respondents indicated that they were primarily recreational anglers, and that this group was more characterized by opportunism, the strong correlation identified in the model is not surprising. The negative correlation between the General bag limit and FishSize might be explained by the fact that, as mentioned previously, those who are less likely to harvest larger fish are likely more recreationally oriented, and thus not likely to respond to increases in the General bag limit unless the increase is large enough to induce individuals in this opportunistic group to fish commercially. The negative correlation between FirstFish and FishSize can be explained similarly: recreationally oriented individuals, who are more likely to harvest a smaller fish, are also more likely to harvest the first fish of the trip, providing further evidence of opportunism.

Regional effects

The region that appears to be most harvest-oriented—and whose harvest behavior thus may be most sensitive to fishery conditions—is the New York/New Jersey region, whose respondents were significantly more likely to harvest a fish than were respondents from the New England or Mid-Atlantic regions. It is important to consider, however, that

responses to general questions indicated that New York/New Jersey permit holders were significantly more likely to target school-size bluefin tuna and significantly less likely to target large medium or giant-size bluefin tuna compared to New England or Mid-Atlantic permit holders. From 2012-2016, estimated catch (harvest and release) of large medium and giant-size bluefin tuna in the New York/New Jersey region was quite small, ranging from 0-87 fish (with percent standard errors of 70-100%), or 0-4.2%, of total estimated U.S. catch for these size classes (pers. comm., NMFS, Fisheries Statistics Division, 2017). The ability of New York/New Jersey permit holders to retain large medium or giant-size bluefin tuna in the scenarios thus represents a potential issue with respect to content validity, in that the scenario specified may be unfamiliar to the respondent, meaning that they do not necessarily have well-defined preferences (Freeman 2003). This notion was reinforced during Toms River, NJ, focus group discussion, in which attendees mentioned that they rarely encountered bluefin tuna measuring larger than 73 inches CFL. That being said, attendees also indicated that if such fish did become available, they would happily retain and sell them under the General category. While it is unclear how exactly permit holders in this region would react to an influx of larger bluefin tuna, stated preferences derived from the model suggest that, if regulations permitted, harvest of bluefin tuna under the General category could rise dramatically, complicating efforts to maintain General category harvest—and overall U.S. bluefin tuna harvest—within internationally specified limits. This challenge underscores the need to integrate biological information regarding fish size and spatial distribution with fishermen behavior and preferences, as suggested by Fulton et al. (2010) and Hunt, Sutton, and Arlinghaus (2013).

CONCLUSION

The application of a CSSC survey approach to CHB permit holders was an effective means for characterizing the decision making of fishermen across a diverse population in a mixed commercial-recreational fishery when trip outcomes are uncertain. The incorporation of inertia variables and correlated random parameters allowed us to test for stability of preferences and to account for correlation in unobservable factors across multiple fish disposition choices over the course of a single trip. By considering prevailing fishery conditions (i.e., fish size and geographic distribution), the regulatory setting, and the individual characteristics of respondents, we were able to investigate aggregate harvesting behavior across the range of the fishery on the U.S. east coast in order to improve the ability of managers to forecast harvest patterns in this unique fishery. Future work should consider additional variables that might impact the decision to fish in a given manner, including bluefin tuna ex-vessel prices, weather conditions, and the availability of and regulations for other species in the area. In addition, factors driving the dichotomy in opportunistic harvesting behavior between commercially and recreationally oriented permit holders should be explored.

ACKNOWLEDGMENTS

The authors are grateful to Brad McHale and Sarah McLaughlin of the NMFS HMS Management Division for their advice regarding survey development and their review of survey materials. We thank Kristy Wallmo and Clifford Hutt (NMFS) for their guidance regarding experimental design and modeling approaches. Dr. John Graves (VIMS) provided valuable input regarding survey design and reviewed several drafts of the manuscript. The participation of 20 CHB permit holders at three focus groups was

essential for gaining feedback on survey content, and we are appreciative of their efforts. We also thank *On The Water* magazine for assistance with survey outreach as well as QuanTech, Inc. for survey distribution and response collection. Funding for this project was provided by NMFS Saltonstall-Kennedy Grant 15GAR020 and by a NMFS/Sea Grant Fellowship in Marine Resource Economics (NA15OAR4170179). This article is contribution number XXXX from the Virginia Institute of Marine Science, College of William & Mary.

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Table 1. Atlantic bluefin tuna permit structure and quotas.

	Angling	General	Harpoon	Purse Seine	Longline	Trap	Reserve	Charter/ Headboat
Percent of quota ^a	19.7%	47.1%	3.9%	18.6%	8%	0.1%	2.5%	--
2017 sub- quota (mt) ^b	195.2	466.7	38.6	184.3	148.3	1	24.8	--
Permits (Oct 2016) ^c	12,716	2,532	9	5	280	--	--	2,463

^a The U.S. baseline Atlantic bluefin tuna for 2017 was 1,058.89 mt.

^b The baseline tonnage allocated to each sector is not exactly the percentage of the overall U.S. baseline quota because 68 mt of the baseline quota are allocated to the Longline category quota, outside of the allocation framework, to account for bluefin tuna dead discards. (Source: 80 FR 52198, 8/28/2015)

^c Permit holder numbers for the Angling, General, Harpoon, and Charter/Headboat categories only include permit holders located in states from Maine south to North Carolina, where the directed fishery for Atlantic bluefin tuna occurs. Permit holder numbers for the Purse Seine and Longline categories were not available by state and represent permit holders from all Atlantic and Gulf-of-Mexico states. (Source: NMFS 2017)

Table 2. Attribute levels for contingent sequential stated choice (CSSC) survey. Fish size attributes are in curved fork length.

Attribute	Number of levels (values)
Angling daily bag limit: school	3 (0, 1, 2)
Angling daily bag limit: large school/small medium	3 (0, 1, 2)
Angling annual bag limit: large medium/giant (trophy)	2 (0, 1)
General daily bag limit	4 (1, 2, 3, 4)
Anticipated fish size (inches)	3 (45-75, 60-85, 75-100)
First fish size (inches)	4 (45, 70, 75, 90)
Second fish size (inches)	4 (0 [no 2nd fish], 60, 75, 85)

Table 3. Factors included in the model.

Factor name	Description	Associated alternative	Distribution (if random)
BagLim_Gen	General bag limit	General	Normal
BagLim_Ang	Angling bag limit (all size classes combined)	Angling	Normal
AntSize_Sm_Ang	Anticipated size 45-75 inches	Angling	Normal
FirstFish	First fish of trip	Angling, General	Normal
FishSize	Fish length in inches	Angling, General	Normal
Clients_Ang	Clients on board	Angling	--
FirstTripAng_Ang	First trip Angling	Angling	--
FirstTripGen_Gen	First trip General	General	--
BindGen_PrimGen	Harvest binds to General trip, primarily commercial bluefin tuna fisherman	General	--
BindGen_PrimAng	Harvest binds to General trip, primarily recreational bluefin tuna fisherman	General	--
BindAng_PrimGen	Harvest binds to Angling trip, primarily commercial bluefin tuna fisherman	Angling	--
BindAng_PrimAng	Harvest binds to Angling trip, primarily recreational bluefin tuna fisherman	Angling	--
NewEngland_Rel	Primary port in New England	Release	--
MidAtl_Rel	Primary port in Mid-Atlantic	Release	--
SellComm_Gen	Has previously sold a bluefin tuna	General	--
PrimaryAng_Ang	Primarily a recreational bluefin tuna fisherman	Angling	--
PrimaryGen_Gen	Primarily a commercial bluefin tuna fisherman	General	--

Table 4. Geographic distribution of survey respondents. Asterisks denote states whose proportion of respondents was significantly different from their proportion of the eligible sample frame according to Fisher exact tests ($p < 0.01$).

State	Eligible Sample Frame		Responses (completed both scenarios) ^b	
	No. of permit holders ^a	Percent of total sample	No. of permit holders	Percent of responses
Maine	112	4.7	36	4.6
New Hampshire	88	3.7	39	4.9
Massachusetts	683	28.5	243	30.1
Rhode Island	74	3.1	48	6.1*
Connecticut	125	5.2	33	4.2
New York	274	11.4	79	10.0
New Jersey	461	19.3	152	19.3
Delaware	66	2.8	22	2.8
Maryland	120	5.0	32	4.1
Virginia	97	4.1	37	4.7
North Carolina	294	12.3	67	8.5*
Total	2394	100	788	100

^a As of December 31, 2015, when the sample frame was drawn.

^b Includes individuals who selected “Do not take a bluefin tuna fishing trip (target another species, or do not go saltwater fishing)” for one or both trips.

Table 5. Percentage of respondents who completed at least one choice scenario of a given trip type (rows), by stated primary trip type (columns). Maximum values per column in bold. Sample sizes denote the number of respondents who completed at least one trip scenario.

	Stated Primary: Charter General (n = 21)	Stated Primary: Charter Angling (n = 212)	Stated Primary: Private General (n = 154)	Stated Primary: Private Angling (n = 260)
Charter General	57.1%	27.4%	26.6%	17.7%
Charter Angling	19.0%	51.9%	19.5%	21.1%
Private General	38.1%	17.9%	68.2%	37.7%
Private Angling	9.5%	7.1%	9.7%	40.0%
Release all	19.0%	17.9%	15.6%	38.5%

Table 6. Comparison of model fit for multinomial logit (MNL) and random parameters logit (RPL) models. For the RPL models, the number of parameters refers to the number of non-random parameters in addition to hyperparameters characterizing random parameters.

Model	Number of parameters	Log likelihood	AIC	BIC
MNL	19	-1332.3	2702.6	2791.6
RPL	24	-1239	2526	2638.5
RPL, correlated random parameters	34	-1223.7	2515.4	2674.7

Table 7. Model estimates for the multinomial logit (MNL) and for the random parameters logit (RPL) with correlated random parameters. Models included choice observations from a total of 801 respondents (788 who completed the survey plus 13 who only completed one trip scenario). A single asterisk denotes significance at $p = 0.05$; a double asterisk denotes significance at $p = 0.01$. (*Table on next page*)

Table 7.

	MNL		RPL with correlated random parameters		
	β		β	σ_β	
Angling (intercept)	-1.777**		-1.828	--	
General (intercept)	-0.529		-0.449	--	
BagLim_Gen	0.298**		1.296**	2.167**	
BagLim_Ang	0.154*		0.447**	0.982**	
AntSize_Sm_Ang	0.779**		1.011**	3.035**	
FirstFish	1.434**		3.314**	3.022**	
FishSize	-0.006		-0.0384*	0.0260	
Clients_Ang	0.957**		1.748**	--	
FirstTripAng_Ang	0.999**		0.424	--	
FirstTripGen_Gen	0.801**		-0.310	--	
BindGen_PrimGen	0.011		0.0973	--	
BindGen_PrimAng	-0.678**		-0.406	--	
BindAng_PrimGen	-0.936**		-2.114**	--	
BindAng_PrimAng	0.270		0.298	--	
NewEngland_Rel	0.406**		1.014**	--	
MidAtl_Rel	0.507**		0.823**	--	
SellComm_Gen	1.289**		2.227**	--	
PrimaryAng_Ang	0.272		0.659*	--	
PrimaryGen_Gen	1.103**		1.912**	--	
Correlations (RPL)	BagLim_Gen	BagLim_Ang	AntSize_Sm_Ang	FirstFish	FishSize
BagLim_Gen	1	--	--	--	--
BagLim_Ang	0.665**	1	--	--	--
AntSize_Sm_Ang	-0.0685	-0.319	1	--	--
FirstFish	-0.176	-0.135	0.0783	1	--
FishSize	-0.686*	-0.770	0.201	-0.452**	1

Table 8. Marginal probabilities. A single asterisk denotes a value that is significantly different from 0 at $p = 0.05$; a double asterisk denotes a value that is significantly different from 0 at $p = 0.01$.

Factor change ^a	Marg. prob, Angling	Marg. prob, General
One-fish increase, General bag limit	-0.0266**	0.132**
One-fish increase, Angling bag limit	0.0861**	-0.0169**
Anticipated size small (45-75 in)	0.179*	-0.0345**
First fish of the trip	0.550*	0.431**
One-inch increase in fish size	-0.00673*	-0.00504*
Clients on board	0.304**	-0.0594**
First trip Angling	0.0828	-0.0160
First trip General	0.00938	-0.0552
Binding to General, primarily General category fisherman	--	-0.00237
Binding to General, primarily Angling category fisherman	--	-0.0776
Binding to Angling, primarily General category fisherman	-0.338**	--
Binding to Angling, primarily Angling category fisherman	0.0702	--
New England	-0.102**	-0.0804
Mid-Atlantic	-0.0528	-0.0420
New York/New Jersey	0.175**	0.103**
Has previously sold a bluefin tuna	-0.0693**	0.347**
Primarily Angling category fisherman	0.116*	-0.0206
Primarily General category fisherman	-0.0589**	0.297**

^a Because fish under 73 inches CFL cannot be harvested under the Angling category, fish size used was different for marginal probabilities of factors associated with each alternative. For the factors associated with the Angling alternative, fish size was set to 60 inches CFL; for factors associated with the General alternative, fish size was 90 inches CFL.

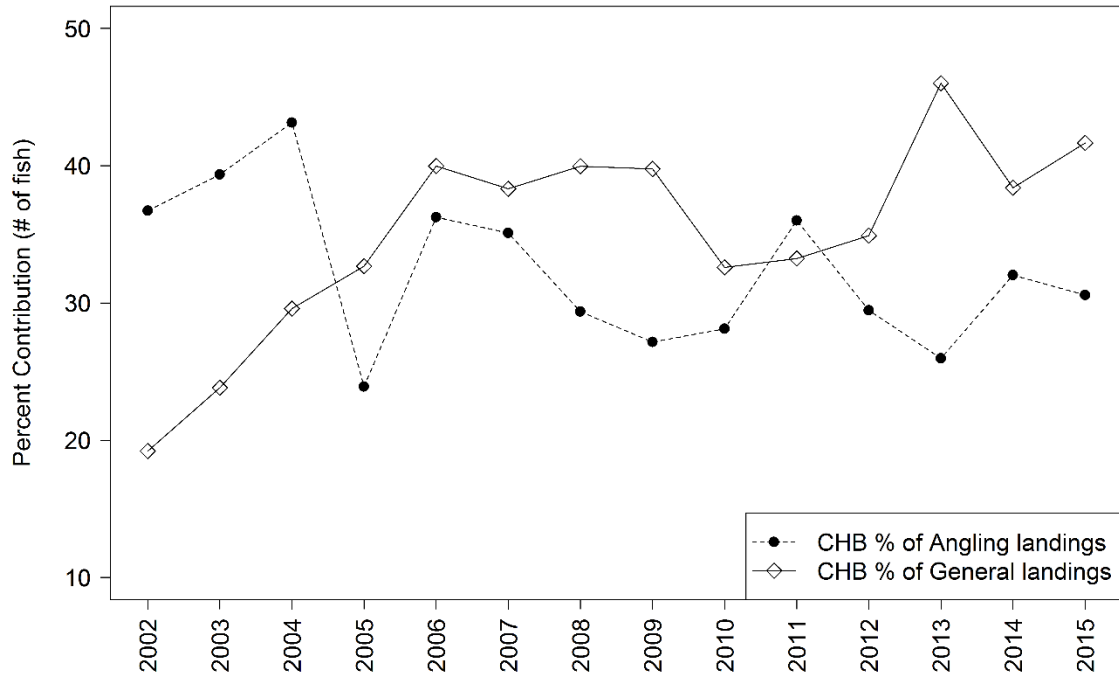


Figure 1. Bluefin tuna landings estimates (numbers of fish) by the Charter/Headboat (CHB) permit holder group as a percentage of the General and Angling category sub-quotas from 2002-2012. Numbers of fish are used as a proxy for weight because landings percentages in weight were only available for the General category (not shown here), but never differed from landings percentages by number by more than 5% for a given year. Angling category landings do not include fish harvested as annual trophies (≥ 73 inches CFL), which are generally less than 30 fish per year and would not meaningfully change percent contributions. A linear regression revealed a marginally significant, negative relationship between CHB permit holder percent contributions to the two groups ($R^2 = 0.29$; $p = 0.05$), suggesting shifts in effort between the two categories. A steady increase in contribution percentages for both categories from 2002-2004 likely reflects increased acquisition of CHB permits following the establishment of the permit in its current form in 2002 (67 FR 77434, 12/18/2002).

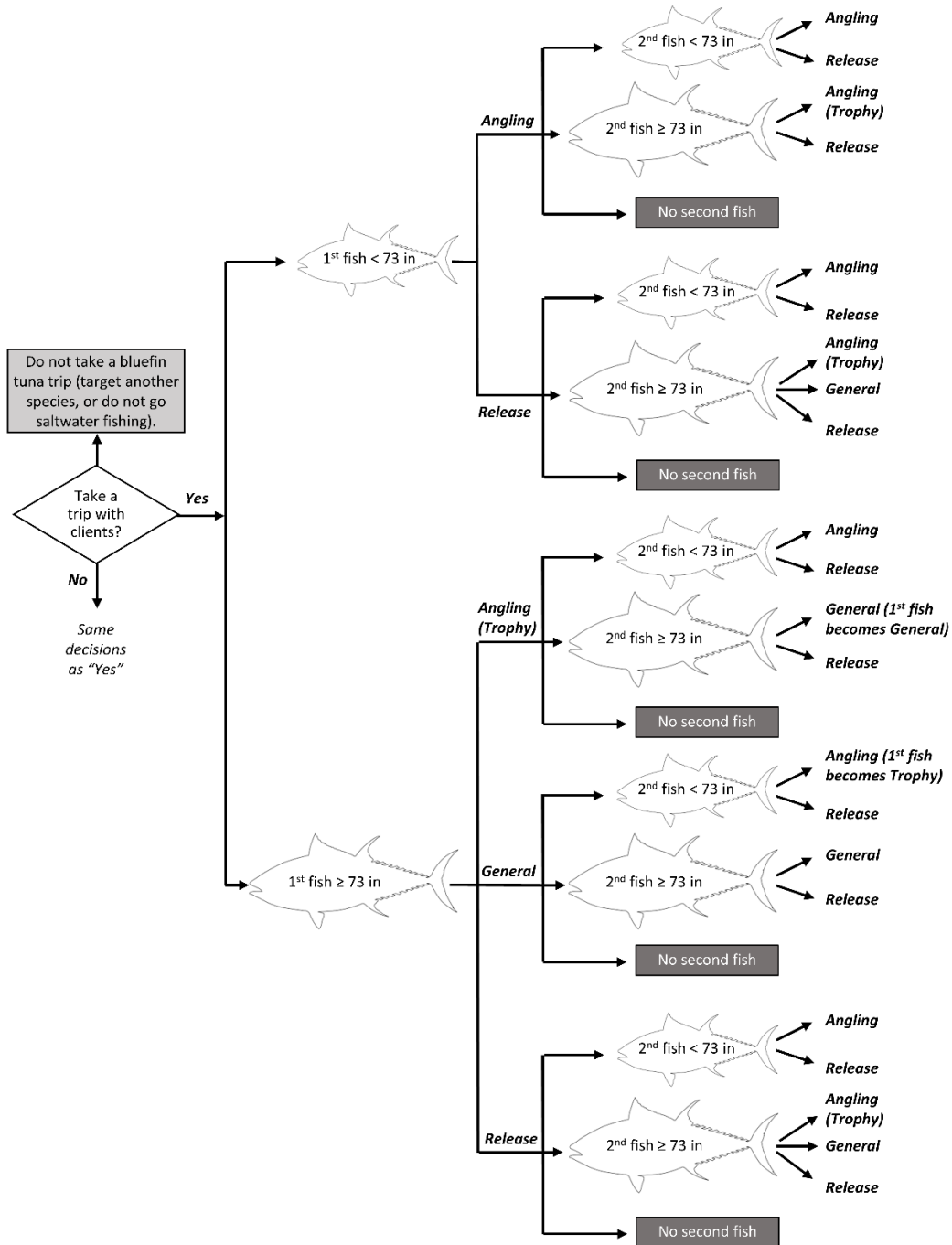


Figure 2. Decision tree for contingent sequential stated choice (CSSC) survey. Respondents were not aware of how many fish they would catch on a given trip scenario. Note: Available disposition options above assume that Angling and General category bag limits permit harvest, which may or may not be the case in individual choice sequences.

Reminder of trip characteristics:		Disposition options	
Recreational Regulations	2 fish 27"-<47" CFL daily 1 fish 47"-<73" CFL daily 1 annual trophy (73"+ CFL)	<p>NOTE: Not all of these options will be available for each fish caught; options for disposition depend on regulations, the size of the fish, and the size of any fish previously harvested on the trip</p> <p>Retain under Angling category: Harvest a sub-73" fish for recreational (non-sale) use by yourself or by your clients; report catch under Angling category.</p> <p>Retain under Angling category as annual trophy: Harvest a 73"+ fish for recreational (non-sale) use by yourself or by your clients; report catch under Angling category.</p> <p>Retain under General category for commercial sale: Harvest a 73"+ fish for commercial sale; report catch under General category.</p> <p>Retain under General category, but do not sell: Harvest a 73"+ fish for some purpose other than commercial sale (e.g., personal or client consumption); report catch under General category.</p> <p>Release: Do not harvest the fish.</p>	
Commercial Regulations	4 fish over 73" CFL daily		
Size range of bluefin tuna that you expect to encounter	45" - 75" CFL		
Annual trophy already retained?	No		
Clients on board?	No		
Catch Disposition			
1 st bluefin tuna	<u>Length:</u> 70" CFL <u>You chose to:</u> Retain under Angling category		
2 nd bluefin tuna	Current question, see below		

*
You hook another bluefin tuna, which measures 75" CFL.

As the fish approaches the boat, which action would you most likely take?

Retain under Angling category as annual trophy
 Release the bluefin tuna

Resume later ◀ Previous Next ▶

Figure 3. Example of a fish disposition choice task during a simulated fishing trip scenario. In this instance, the respondent selected to retain their first fish under the Angling. As a result, when a fish measuring more than 73 inches is caught, as above, the option to harvest the fish under the General category is unavailable; the respondent can only either retain it as the annual Angling trophy or release it.

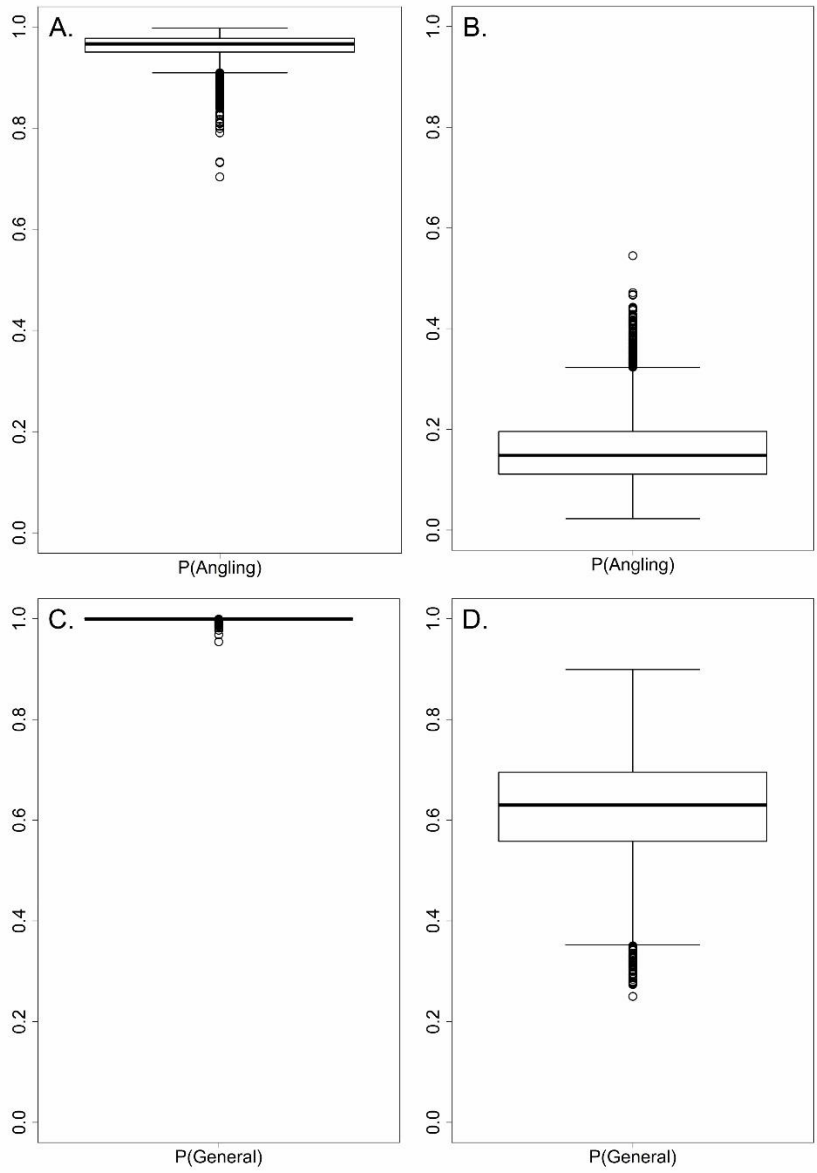


Figure 4. Disposition probabilities for four bluefin tuna fishing scenarios based on 10,000 random draws (in all scenarios, the fish is the first fish of the trip):
 Scenario A: NY/NJ permit holder; clients are on board; Angling category bag limit is 4; anticipated size 45-75 inches CFL; fish size 60 inches CFL.
 Scenario B: New England permit holder; clients are not on board; Angling category bag limit is 1; anticipated size not 45-75 inches CFL; fish size 60 inches CFL.
 Scenario C: New England permit holder; primarily a General category fisherman; has previously sold a bluefin tuna; Angling trophy category is closed; General category bag limit is 4.
 Scenario D: Mid-Atlantic permit holder; primarily an Angling category fisherman; has never sold a bluefin tuna; Angling trophy category is closed; General category bag limit is 1.

APPENDIX

Table A1. Demographic and bluefin tuna fishing behavior/attitude characteristics of respondents, broken down by geographic region. Superscripts with different numbers indicate values that are significantly different from one another ($p = 0.05$), based on either permutation tests (for continuous data) or Fisher exact tests (for categorical data).

Variable	Description (sample size)	Value	New England	NY/NJ	Mid-Atlantic
Age	Mean in years (769)	55	54 ^a	57 ^b	54
Years targeting HMS	Mean in years (802)	19.2	17.2 ^a	22.7 ^b	19.2 ^a
Bluefin tuna targeting	% who have targeted bluefin tuna in last five years (856)	81.9	88.6	78.4	70.0
Bluefin tuna avidity	Mean number of trips targeting bluefin tuna in 2015 (688)	7.5	9.8 ^a	3.9 ^b	5.5 ^c
Target school-size bluefin tuna	% who target school-size (27 - < 47 in CFL) bluefin tuna (694)	42.2	29.4 ^a	72.8 ^b	34.5 ^a
Target large medium or giant-size bluefin tuna	% who target large medium or giant-size (73+ in CFL) bluefin tuna (694)	48.4	63.8 ^a	17.8 ^b	47.9 ^a
Charter for bluefin tuna	% who operated a charter for bluefin tuna in previous five years (666)	55.6	54.4	57.8	55.8
Charter recreational	% whose primary bluefin tuna trip type is charter recreational (675)	33.0	24.1 ^a	44.7 ^b	43.0 ^b
Private commercial	% whose primary bluefin tuna trip type is private commercial (675)	23.7	31.6 ^a	26.3 ^a	6.4 ^b
Retained and sold bluefin tuna	% who have ever retained and sold a bluefin tuna (672)	37.9	50.1 ^a	18.1 ^b	30.1
Season length preference	% who prefer short, high-harvest recreational season* (667)	29.7	14.4 ^a	56.7 ^b	34.5 ^c
Support separate CHB quota	% who agree with the statement, "There should be a separate bluefin tuna sub-quota for the HMS Charter/Headboat category" (366)	53.0	37.4 ^a	78.7 ^b	57.1

* Respondents were asked if they would prefer a short (two-month) bluefin tuna season with a high recreational retention limit (three fish from 27 - < 73 inches CFL per vessel per day) or a long (six-month) season with a low recreational retention limit (one fish from 27 - < 73 inches CFL per vessel per day).

CHAPTER IV

Performance of a Low-Cost, Solar-Powered Pop-Up Satellite Archival Tag for Assessing

Post-Release Mortality of Atlantic Bluefin Tuna (*Thunnus thynnus*) Caught in the U.S.

East Coast Light-Tackle Recreational Fishery

ABSTRACT

Background: Pop-up satellite archival tags (PSATs) are a valuable tool for estimating mortality of pelagic fishes released from commercial and recreational fishing gears. However, the high cost of PSATs limits sample sizes, resulting in low-precision post-release mortality estimates with little management applicability. We evaluate the performance of a lower-cost PSAT designed to enable large-scale post-release mortality studies. The tag uses solar rather than battery power, does not include a depth sensor, and transmits daily summaries of light and temperature data rather than high-resolution habitat profiles, contributing to a substantially lower per-unit price. We assessed the tag's ability to detect mortality while also estimating the post-release mortality of juvenile (119-185 cm) Atlantic bluefin tuna (*Thunnus thynnus*) caught using light-tackle angling methods along the U.S. east coast.

Results: Using high-resolution data from previously deployed PSATs and environmental information from the general tagging location, we established parameters to infer mortality for Atlantic bluefin tuna using only daily summary data. We then deployed 22 PSATs, programmed to pop off after 31 days (thus providing 30 full daily summaries), on Atlantic bluefin tuna caught using light tackle off the coasts of Massachusetts and North Carolina, USA, in 2015 and 2016. Data were recovered for 15 tags with deployments ranging from seven days (premature shedding) to 95 days (failed pop-off), and indicated that tagged fish spent sufficient time near the surface to keep the solar-powered tags fully charged. Fourteen fish demonstrated strong temporal changes in temperature indicating vertical movement in the water column, consistent with survival. One fish was predated upon after 17 days, likely by a shortfin mako, and was considered a natural mortality, resulting in a post-release mortality estimate of 0%.

Conclusions: While low reporting rates complicated inferences about post-release mortality, the concept of using species-specific mortality parameters coupled with a reduced dataset shows promise as a cost-effective tool for detecting post-release mortality using PSATs. In addition, findings suggest that catch-and-release angling is a viable conservation strategy for juvenile Atlantic bluefin tuna caught in the U.S. east-coast light-tackle fishery.

Keywords: Pop-up satellite archival tag, Atlantic bluefin tuna, post-release mortality, recreational fisheries.

BACKGROUND

Over the past several decades, satellite telemetry has emerged as a valuable tool for estimating mortality rates for a broad variety of terrestrial and aquatic species. These studies can not only provide key insight into a species' movement ecology and population dynamics [1, 2], but can also identify anthropogenic sources of mortality and inform conservation efforts for species of concern [3].

In the marine realm, pop-up satellite archival tags (PSATs) have been widely employed to detect and estimate post-release mortality of large pelagic fishes (istiophorid billfishes, tunas, swordfish, and sharks) caught with commercial and recreational fishing gears [4]. Such studies are critical for estimating overall fishing-induced mortality and effects on stock size and age structure [5], as well as for informing best practices to minimize post-release mortality [6-8]. PSATs are typically battery-powered and record environmental data such as light level, pressure (depth), and water temperature at regular, high-resolution intervals (often 5 min or less) for a specified deployment period before popping off the fish, floating to the surface, and transmitting archived data (or summaries of archived data) via the Argos satellite system (CLS/Argos, Toulouse, France). The habitat data can be used to readily distinguish surviving and dead fish [7, 9, 10].

While useful for detecting post-release mortality, most commercially available PSATs cost over \$3,000 each (e.g., High-Rate Archival X-Tag [MSRP \$3,600], Microwave Telemetry, Inc., Columbia, MD USA). Simulation experiments, meanwhile, have recommended that studies deploy a minimum of 100 PSATs to estimate post-release mortality within five percentage points of the "true" value [11]. However, given the operating budgets of most post-release mortality studies, the high cost per tag generally

results in small sample sizes, which can lead to low-precision estimates that are of reduced utility to management [12]. This lack of precision is especially notable given that post-release mortality rates are species-specific and can also vary within a species according to fish size, gear type, fishing method, and environmental conditions [13, 14]. As a result, there has been increased interest in developing lower-cost PSAT alternatives for detecting post-release mortality of pelagic species (e.g., SeaTag-LOT, Desert Star Systems, LLC, Marina, CA USA; sPAT, Wildlife Computers, Inc., Redmond, WA USA).

The Atlantic bluefin tuna (*Thunnus thynnus*) is widely targeted by recreational anglers aboard charter and private boats along the east coast of the United States from Maine to North Carolina, where the fishery is of considerable economic importance [15]. While a variety of fishing methods are used, over the past decade significant technological advances (e.g., braided fishing line) have resulted in increasing popularity of the light-tackle fishery, which we define as the targeting of Atlantic bluefin tuna by actively casting or jigging artificial lures, primarily with spinning tackle. The fishery has become internationally known as a light-tackle, big-game angling opportunity, and currently supports numerous specialized charter boat businesses and fishing tackle manufacturers. Participating anglers primarily target juvenile Atlantic bluefin tuna in the large school (119 - < 150 cm curved fork length [CFL]) and small medium (150 - < 185 cm CFL) size classes. In recent years, anglers have been permitted to retain one fish per vessel per day in these size classes combined (FR 82 19615, 4/28/2017), which in times of high fish availability can result in large numbers of estimated regulatory releases that from 2012-2016 ranged from 88% - 231% of the number of estimated fish harvested (pers. comm., National Marine Fisheries Service, Fisheries Statistics Division).

Post-release mortality of pelagic fishes is influenced by the cumulative impact of physical trauma (i.e. hook-induced tissue damage) and physiological stress, which are largely affected by the gear and method of capture [16]. Previous studies using PSATs have suggested low post-release mortality for bluefin tuna captured in recreational fisheries. Stokesbury et al. [17] deployed PSATs on large medium and giant (≥ 185 cm CFL) Atlantic bluefin tuna captured using bait rigged with barbless circle hooks in an experimental recreational fishery off the coast of Prince Edward Island, Canada, with fight times ranging from 6 to 79 minutes, and estimated a mortality rate of 3.4% (2 of 59 fish died after release). Marcek and Graves [18] observed a post-release mortality rate of 0% for 19 school-size (91 - < 119 cm CFL) Atlantic bluefin tuna tagged with PSATs after being caught using 23-91 kg trolling tackle and fought for 5.5 to 12 minutes. Most recently, Tracey et al. [19] deployed PSATs on 59 southern bluefin tuna (*Thunnus maccoyi*), primarily of sizes comparable to the school and large school size classes (91 - <150 cm CFL), caught while trolling artificial lures or drifting with natural baits with 15-37 kg tackle (fight times ranged from 3 to 118 minutes), estimating a post-release mortality rate of 19%. Only five of the 59 fish tagged were caught with treble hooks, but two of those fish died, suggesting that the use of treble hooks increases post-release mortality (though the small sample size precluded statistical testing). The study also conducted physiological sampling of 233 recreationally caught southern bluefin tuna, and found that physiological stress (but not post-release mortality) increased with fight time, as has been found for other pelagic species [7]. While numerous additional studies have deployed PSATs on bluefin tuna to assess movements and habitat utilization [e.g., 20, 21, 22], post-release mortality data from such research is likely not reflective of recreational

fisheries due to the use of angling and handling methods intended to minimize mortality [17].

The present study assesses the post-release mortality of juvenile (119 - < 185 cm CFL) Atlantic bluefin tuna caught in the light-tackle recreational fishery along the U.S. east coast, while simultaneously evaluating the reliability and performance of a newly-developed, low-cost PSAT. Reportedly longer fight times and the frequent use of treble hooks on artificial lures in the light-tackle fishery may increase physiological stress and physical damage, respectively, and could result in higher rates of post-release mortality than those found in previous studies. Successful performance of the PSAT, designed to detect post-release mortality for large pelagic fishes at a significantly reduced cost compared to other available PSATs, would enable larger study samples, providing high-precision estimates that could be incorporated into management efforts.

METHODS

Tag configuration

The Desert Star Systems SeaTag-LOT was used in this study. The SeaTag-LOT is powered by a solar-charged capacitor rather than a battery and does not contain a pressure (depth) sensor. Once a tag is fully charged, which takes approximately 30 minutes in full sunlight, enough solar power can be stored so that the tag will continue to record and archive data for up to three days in complete darkness. While the tag records light and temperature data at four-minute intervals, the SeaTag-LOT only archives and transmits daily summary data for four light- and temperature- related measurements: a) capacitor voltage (daily average); b) solar panel voltage (daily average); c) temperature (daily minimum, maximum, and average); and d) maximum daily change in temperature

per minute ($\Delta T \text{ min}^{-1}$, calculated by dividing the maximum change in temperature between measurements by four). In addition, the tag transmits day length and local apparent noon time for each day of deployment. The reduced quantity of data archived, lack of pressure sensor, and use of solar power rather than a battery contribute to the relatively low per-unit cost of this PSAT (\$899 for quantities of less than 50, or roughly one quarter the price of other commercially available PSATs).

Because the SeaTag-LOT only transmits daily summary data, it was necessary to consider how the tag should be configured to detect post-release mortality specifically for bluefin tuna off the U.S. east coast. Tag configuration included the development of thresholds, under which the tag would pop off prior to the scheduled deployment date, for three mortality scenarios: 1) a fish dies and sinks to the bottom in shallow water (i.e., on the continental shelf); 2) the fish/tag is eaten (scavenging or predation); or 3) a fish dies and sinks in water deeper than the tag's 1,200 m service depth.

For scenario 1, the maximum $\Delta T \text{ min}^{-1}$ recorded by the tag was used as an indicator of whether a fish was alive and moving vertically in the water column. High-resolution (~5 min) depth and temperature data transmitted from Microwave Telemetry High-Rate X-Tags previously deployed on school-size Atlantic bluefin tuna and white marlin (*Kajikia albida*) (J. Graves, unpubl.) were examined to determine the minimum $\Delta T \text{ min}^{-1}$ typically exhibited by a living fish moving vertically in the water column, which could distinguish it from a dead fish resting at a constant depth on the sea floor (or a shed tag floating on the surface). Surviving fish generally exhibited a daily maximum $\Delta T \text{ min}^{-1}$ well in excess of $0.2^\circ\text{C min}^{-1}$; data from tags deployed on school-size bluefin tuna, for example, indicated typical daily maximum $\Delta T \text{ min}^{-1}$ values between 1°C and 2°C . Tags

deployed on white marlin that subsequently died and rested on the bottom for several days, meanwhile, indicated maximum $\Delta T \text{ min}^{-1}$ values of less than 0.05°C . The release threshold was thus set for 72 hours with a maximum $\Delta T \text{ min}^{-1}$ of less than 0.2°C . If a tag were to pop off due to exceeding this threshold, an examination of temperature data during the low $\Delta T \text{ min}^{-1}$ interval could be examined to infer that the fish was dead and resting on the bottom in cool waters versus alive and maintaining a very stable depth distribution higher in the water column. A shed tag floating on the surface could be differentiated from a tag that popped off a dead fish because the former, when floating on the surface, would begin transmitting in an “On Fish”, rather than “Reporting,” status.

For scenario 2, a tag’s remaining in complete darkness for a certain minimum amount of time was considered an appropriate indicator of predation or scavenging. Ingestion of PSATs (and presumably the fish to which they were attached) by predators or scavengers is well-documented [8, 9, 18, 23], and tags generally remain inside the consumer’s stomach for at least several days before being egested, floating to the surface, and transmitting data. Given these findings, tags were programmed to release if maintained in complete darkness for 48 hours.

For scenario 3, a low-temperature threshold at which the tag would pop off of the fish before sinking below the tag service depth was determined through inspecting depth-temperature data collected off the coast of North Carolina’s Outer Banks via the World Ocean Database [24]. Depth-temperature data indicated that temperatures at 1,000 m depth were typically in the vicinity of 4.5°C . While Atlantic bluefin tuna have a broad thermal range and have been recorded in temperatures as low as 3°C [25], we judged it preferable to keep the low-temperature threshold conservative to minimize the risk of a

tag pressure housing failure. In addition, previous PSAT tag research along the east coast of North America has suggested that bluefin tuna in this region rarely encounter temperatures below 8°C [20, 26]. It is possible that a deep-diving, surviving fish could swim below a conservative low-temperature threshold and cause tag pop-off, erroneously indicating a mortality; in such a case, however, the tag would provide information (e.g., daily temperature ranges prior to pop-off) from which survival could be inferred. The low-temperature threshold for pop-off was thus set at 4.5°C. In addition to examining whether tags popped off due to exceeding the thresholds described above, daily summary data of light level and temperature were visually examined to infer whether a fish survived the deployment duration.

Tag deployment

PSATs were deployed on large school and small medium-size Atlantic bluefin tuna caught onboard recreational charter vessels using typical light-tackle methods during the 2015 and 2016 fishing seasons off the coasts of Massachusetts and North Carolina. The majority of tagged fish were caught using spinning tackle and braided line with a rated breaking strength of 36-45 kg; one tagged fish was caught on a conventional (revolving-spool) vertical jigging rod and reel with 36 kg breaking strength braided line. Artificial lures used to catch bluefin tuna included soft-plastic lures rigged with single J-hooks, hard-bodied lures rigged with either treble or single hooks, and metal jigs rigged with single “assist” hooks. In addition, on a few occasions fish were caught by casting live Atlantic mackerel (*Scomber scombrus*), rigged with a single J-hook, into a school of actively feeding Atlantic bluefin tuna using spinning tackle.

Atlantic bluefin tuna were fought, handled, and released in the manner typically practiced by each fishing vessel, with no input from the tagging researcher. Bluefin tuna were tagged regardless of condition, and following the method of Marcek and Graves [18], multiple fish were not tagged if hooked within 30 minutes of one another in order to avoid sampling from the same school of fish and maintain a random sample to the extent practicable. Methods of securing fish for unhooking and tagging included lip-gaffing (either maintaining the fish in the water or sliding it onboard through the vessel's tuna door [a door in the transom to facilitate the landing of large fish]) or holding the fish under the operculum while supporting it against the vessel's gunwale. Gear type, fight time (hooking to capture), total time (hooking to release), hooking location in the fish, fish length (CFL), sea surface temperature, release location, and other relevant factors were recorded for each fish. In addition, the condition of each fish was assessed using a modified version of the "ACCESS" condition scale developed by Kerstetter et al. [27]. Each fish's condition was rated from 0-8 by evaluating four characteristics on a scale of 0 (poor) to 2 (good): overall activity, color, body positioning, and bleeding (i.e., a score of 2 means little/no bleeding).

The PSATs used in this study were programmed to record light level and water temperature every four minutes over the course of 31 days (or 30 full daily summaries), after which they detached from the fish via an ignition release, floated to the surface, and transmitted data. Tags were light-activated and maintained in sunlight for at least 30 minutes prior to deployment to ensure a full solar charge. The PSATs were rigged with 16 cm of 91-kg test monofilament fishing line attached to a hydroscopic nylon intramuscular tag anchor, following Marcek and Graves [18]. Each tag anchor was

inserted to a depth of approximately 10 cm into the fish's dorsal musculature 10 cm posterior to the origin of the first dorsal fin and 5 cm ventral to the base of the first dorsal fin, where it was able to interlock with the pterygiophores supporting the dorsal fin [28]. After tagging, at the discretion of the fishing crew, some fish were revived boat-side prior to release using a lip gaff while slowly moving the vessel forward at about 2 kt.

PSATs will sometimes release from fish prior to the scheduled release date (i.e., are shed), which could occur during routine swimming (for example, if the tag anchor pulls out of the dorsal musculature), or due to other reasons, such as a predation event in which the tag, rather than being ingested by the predator, is dislodged and floats to the surface. It is important to establish a threshold deployment duration to determine which prematurely-released PSATs should be included in the post-release mortality estimate [18, 29]. While previous post-release mortality studies have indicated that most capture-induced mortalities tend to occur within 48 hours of release [6, 19, 30, 31], the five days following release has often been used as the interval during which mortalities would be considered angling-induced (as opposed to natural mortalities) [8, 18]. As a result, to avoid misinterpreting the fate of surviving fish from tags that released prematurely, only tags from fish that remained attached for five days or longer and whose summary data for the first five days were consistent with survival were included as survivors in the estimate of post-release mortality.

To determine the effect of sample size on the 95% confidence interval for the post-release mortality estimate, bootstrapping simulations based on 10,000 bootstrapped samples were performed using software developed by Goodyear [11]. For the purposes of bootstrapping, natural mortality M was assumed to be 0.14 yr^{-1} and age-independent, an

assumption similar to that used in the 2014 stock assessment for western Atlantic bluefin tuna conducted by the International Commission for the Conservation of Atlantic Tunas (ICCAT) Standing Committee on Research and Statistics [32]. The post-release mortality estimate for the light-tackle fishery was statistically compared with Marcek and Graves' [18] estimate for school-size Atlantic bluefin tuna caught in the troll fishery, as well as with Tracey et al.'s [19] estimate for southern bluefin tuna caught in the troll fishery, using Fisher's exact tests.

Net displacement for tagged fish was calculated as the first high-quality pop-off position estimate (Argos location code 1, 2, or 3). In some cases, a high-quality location was not transmitted in the period immediately (~8 hours) after pop-off, in which case the first reasonable location estimate received (Argos location code 0, A, or B) was used to calculate net displacement. The straight-line distance between tag deployment location and pop-off location was calculated using ArcGIS version 10.2.2 (ESRI, Redlands, California).

RESULTS

A total of 22 PSATs were deployed on Atlantic bluefin tuna caught on light tackle during 2015 and 2016 (Table 1). Five tags were deployed off the Outer Banks, North Carolina and 17 tags were deployed off Cape Cod and Martha's Vineyard, Massachusetts. Fish sizes ranged from 114-201 cm CFL (mean = 150 cm, SD = 26 cm) and fight times ranged from 4-78 minutes (mean = 21 min; SD = 20 min). The time that the fish's head was out of the water during the hook removal, measuring, and tagging process ranged from 0 minutes (fish tagged in the water) to 3 minutes (mean = 75 s; SD = 51 s).

Twenty of the 22 fish were caught on artificial lures, while two fish were caught on live mackerel rigged with a single J hook. Of the 20 fish caught on lures, 12 were caught on lures rigged with one or two single hooks, seven were caught on lures rigged with two treble hooks, and one was caught on a lure rigged with both a treble and single hook. Two of the 22 fish (9%) were hooked internally. For one bluefin tuna, caught on a live mackerel, the hook was not visible (i.e., was in the esophagus/stomach) and the line was cut. The second fish, caught on a lure with two treble hooks, was hooked both in the corner of the jaw and in the posterior section of the palate, just anterior to the first gill arch, and hooks were removed prior to release. Twenty fish were hooked in various external locations. Two fish (9%) exhibited heavy bleeding after capture from hook wounds in the ventral musculature; other fish exhibited light or moderate bleeding resulting from hook and lip-gaff wounds.

Fourteen of the 22 PSATs successfully transmitted data. Six of the 14 tags were shed prior to the scheduled pop-off date, with deployments ranging from seven to 25 days. In addition, one tag (Fish #10) failed to pop off after the scheduled deployment period, and ultimately was shed from the fish after 95 days, providing daily summary data throughout the deployment. One of the tags that failed to report (Fish #19) was physically recovered when it washed ashore in Nags Head, North Carolina, and 46 days' worth of data were recovered. A diagnostic analysis performed by the manufacturer revealed that the tag's electronics functioned normally, but that the burn chamber of the tag had been flooded, preventing pop-off. In addition, the antenna of the tag was broken off, impeding the transmission of data following shedding. As a result, pop-up location and net displacement information were not available. For five of the 15 tags for which

data were recovered, the number of daily summaries transmitted was fewer than the total number of days for which the tag was deployed, with the number of summaries ranging from 83%-93% of total deployment days. We suspect that this resulted from the fact that daily summaries were binned based on light rather than a 24-hour clock—as a result, consecutive calendar days spent by a bluefin tuna at depth could result in the generation of only a single “daily” summary.

Based on daily summary data for the reporting 14 tags and the one tag which was recovered, coupled with the thresholds established for three mortality scenarios, we inferred that 14 of 15 fish survived through the deployment period (Figure 1). Net displacement for surviving fish tagged off North Carolina in March of 2015 and 2016 (4 reporting tags) ranged from 35-377 km over deployment periods ranging from 23 to 95 days. For surviving bluefin tuna tagged off Massachusetts (10 reporting or recovered tags), net displacements ranged from 61-304 km over deployments ranging from seven to 30 days. Daily capacitor voltage from tags on surviving fish generally remained near the maximum (3.6 V) throughout deployment, indicating that the tag (and fish) spent a sufficient amount of time near the surface to keep the tag fully-charged and well above the minimum capacitor voltage of 2.2 V needed for full processing capability. Average solar panel voltage, meanwhile, was lower due to the tag’s spending a significant portion of each day in darkness (at night and when fish dove into deeper waters). Daily maximum $\Delta T \text{ min}^{-1}$ values were generally well in excess of the $0.2^\circ\text{C min}^{-1}$ threshold, with the exception of Fish #10 (Figure 2), which for five consecutive days had maximum daily $\Delta T \text{ min}^{-1}$ values below $0.2^\circ\text{C min}^{-1}$ (at which time pop-off should have occurred had it not failed), indicating a highly constricted thermal range. However, the water temperature

measurements corresponding to those days (16.7-19.3°C) suggest that the fish was high in the water column at a stable depth, rather than resting on the bottom (in which case temperatures would have been considerably lower). As a result, even in the event of pop-up as designed, inference of survival rather than mortality would have been possible.

The tag deployed on Fish #12, a 117 cm CFL bluefin tuna caught south of Martha's Vineyard, Massachusetts in August 2016, appears to have been consumed 17 days after capture. A short recorded day length on that date suggests that the tag—and presumably the fish—were ingested, at which time the tag ceased sensing light. Because the tags deployed in this study binned daily summaries based on light, only a single “daily” summary bin during the time for which the tag was inside the predator is available, indicating a stable temperature ranging from 21.89° C to 23.97° C (mean: 23.2° C) and a maximum $\Delta T \text{ min}^{-1}$ of 0.09° C. The tag was presumably egested after two days, when it floated to the surface and began transmitting due to having exceeded the darkness threshold (> 48 h in darkness). The mean temperature while the tag was in darkness slightly exceeded the maximum temperature recorded the day before the tag was ingested (22.9° C) and the day after the tag was egested (22.0° C). This fish was considered a natural mortality for the purposes of calculating post-release mortality due to the long interval between catch-and-release and putative mortality.

While bluefin tuna were primarily targeted using light-tackle jigging and casting methods during tagging trips, there were some occasions on which fish were captured using conventional trolling/bait-fishing tackle (collectively referred to as stand-up tackle), enabling comparisons of fight times between fishing methods. Fight times for fish caught on light tackle (including fish that were not tagged; $n = 41$; mean = 20 min; SD = 19 min)

increased with fish size, and did not differ significantly from fight times for nine fish that were caught on conventional stand-up tackle ($n = 9$; mean = 17 min; SD = 8 min) (Student's t test $p = 0.50$) (Figure 3). In addition, light-tackle fight times did not differ from those for 24 southern bluefin tuna tagged by Tracey et al. [19] corresponding to the large school and small medium size classes caught on conventional stand-up tackle ($p = 0.9$).

Estimates of post-release mortality were dependent on the treatment of the seven tags that did not report and were not recovered. When non-reporting and unrecovered tags were excluded from the analysis, the post-release mortality was estimated to be 0% because data from all 15 reporting/recovered tags indicated survival beyond the five-day threshold. Fisher exact tests revealed no significant differences between a 0% post-release mortality estimate and the recreational post-release mortality estimates for juvenile bluefin tuna from Marcek and Graves [18] (0%; $p = 1$) and Tracey et al. [19] (19%; $p = 0.2$). Assuming 0% post-release mortality, bootstrapping simulations based on 10,000 bootstrapped samples estimated the 95% confidence interval for the “true” post-release mortality rate based on 15 PSATs to range from 0% to 6.7%. In a more conservative analysis, in which the seven non-reporting and unrecovered tags were considered mortalities, the post-release mortality estimate increased to 31.8% (bootstrapped 95% confidence interval: 13.6% - 54.5%).

DISCUSSION

Post-release mortality

Based on data from reporting and recovered tags, our results suggest a low post-release mortality rate for large school and small medium-size Atlantic bluefin tuna caught

using light-tackle methods off the U.S. east coast. The bluefin tuna tagged in this study were subjected to a broad range of hooking locations with variable levels of bleeding and an assortment of handling methods. The data from all reporting and recovered tags were consistent with survival.

How non-reporting tags are interpreted can dramatically affect estimates of post-release mortality; if all non-reporting tags are interpreted to be mortalities, estimates can be biased substantially upward [11]. Given these concerns, previous studies using PSATs have either excluded non-reporting tags from post-release mortality estimates or have offered multiple estimates that exclude non-reporting tags and consider non-reporting tags to be mortalities [6, 30, 33]. The level of uncertainty that non-reporting tags introduce into estimates of post-release mortality highlights the critical importance of high reporting rates for these types of studies.

While we provide post-release mortality estimates that both include and exclude tags that did not report/were not recovered, we contend that only including the 15 tags for which data were recovered (i.e., our 0% post-release mortality estimate) is the most appropriate approach for estimating post-release mortality in this study. This investigation was one of the first uses of the Desert Star Systems SeaTag-LOT, and thus may have been particularly vulnerable to non-reporting tags. The recovery of a failed tag from a surviving fish (Fish #19), which had both a flooded burn chamber (impeding pop-off) and a broken antenna (impeding data transmission), along with data transmitted from another tag on a surviving fish (Fish #10) whose pop-off release mechanism failed, suggest that tag failure was not uncommon and likely was a factor for the other non-reporting tags.

The most plausible explanation for the one mortality observed in this study is that the tag (and fish) was consumed by a lamnid shark, most likely a shortfin mako (*Isurus oxyrinchus*), which were observed in the vicinity of the tagging location at the time of tagging. Predations on juvenile PSAT-tagged bluefin tuna by lamnids have been inferred in previous studies based on elevated, stable temperatures regardless of depth while the tag was in darkness [18, 19]. The temperatures recorded by the tag while in darkness correspond to stomach temperatures measured for seven juvenile mako sharks (mean temperatures 18.9-25.9°C; ambient sea surface temperature 18-21°C) by Sepulveda et al. [34]. According to Sepulveda (unpubl.), the degree of stomach temperature elevation may become minimal once sea surface temperatures exceed 20°C, which is consistent with the tag data.

It is important to distinguish any mortalities occurring after tagging as having been a result of the catch, tagging and release experience (i.e., a fishing mortality) or a natural mortality. Applying the five-day threshold to distinguish natural and fishing mortalities, we consider the predated fish to be a natural mortality since it occurred more than five days after release. Goodyear [35] has developed a method to estimate the median number of tag-days needed to observe a natural mortality on a PSAT-tagged fish using a Monte-Carlo estimation based on 1,000,000 trials. Applying a natural mortality estimate of 0.14 for western Atlantic bluefin tuna [32], the number of tag-days needed to observe a natural mortality with 50% probability was estimated to be 1,815 tag-days. A total of 444 full tag-days were observed in this study, approximately one-quarter of the number of tag-days needed to observe a natural mortality with 50% probability. While it is thus well within the realm of possibility that a natural mortality event would have been

observed over the course of this study, it cannot be discounted that behavior and survivability could be negatively impacted in the days following release—for example, due to long-term physiological stress, internal bleeding or infection, or the added stress of carrying a PSAT [8, 30, 36].

While fish in this study were caught on both single and treble hooks, and were subjected to varying levels of air exposure, no post-release mortalities were detected. No fish caught on treble hooks with reporting tags ($n = 5$) were inferred to have died, compared to the 40% post-release mortality rate ($n = 5$) reported by Tracey et al. [19] for southern bluefin tuna caught on treble hooks. Studies on other species have offered conflicting conclusions on the comparative effects of single versus treble hooks [13, 37, 38]. Although no post-release mortalities were observed in this study, treble hooks did typically lead to greater degrees of physical injury. In addition, fish caught with treble hooks typically required longer handling times in order to remove the hooks, as has been observed for other species [13]. Air exposure has been linked to increased post-release mortality in recreational fisheries [8, 39], and it is recommended as a best practice that treble hooks not be used when fish are to be released, and also that fish not be removed from the water during the unhooking process. Removal of Atlantic bluefin tuna from the water that are to be released is also prohibited by the U.S. National Marine Fisheries Service (NMFS) Highly Migratory Species Management Division (79 FR 71510, 12/2/2014).

We found that fight times for bluefin tuna caught on light tackle were not significantly different from those of fish caught on stand-up tackle. The lack of evidence that fight times are longer with light-tackle methods likely results from the fact that while

the rods and reels used are generally lighter in weight and fish are typically fought without the aid of a harness, the line's breaking strength is generally not different from that used in more standard bluefin tuna fishing practices.

Tag performance and recommendations

Fourteen of the 22 PSATs deployed in this study (63.6%) transmitted data. Marcek and Graves [18] and Tracey et al. [19], who also assessed the post-release mortality of juvenile bluefin tuna using PSATs scheduled for short-term (< 6 mo) deployments, observed reporting rates of 95% (20 tags) and 100% (59 tags), respectively, which are markedly higher than the present study's reporting rate. PSATs may not report for a variety of reasons. These include mechanical failure, which can prevent pop-off or data transmission; biofouling, which can result in negatively buoyant tags; pressure housing failure; and tag damage resulting from predation or scavenging [4, 9, 40]. In addition, some researchers have hypothesized that species such as bluefin tuna that undertake extensive vertical movements may induce expansion and contraction of the tag body, which could lead to failure [4, 41]. As noted above, a high tag reporting rate is critical for studies of post-release mortality; even if a tag is considerably less expensive than others and provides sufficient data for inferring post-release mortality, a high percentage of tag failures can negate these lower costs by introducing considerable uncertainty into results, thus compromising management advice.

Six of the 14 tags (42.9%) were shed from fish prior to the specified pop-off date, but data from the six tags indicated that fish were moving vertically in the water column prior to shedding, consistent with survival. Premature shedding of PSATs is well-documented in studies of large pelagic fishes [31, 40, 42]. The most plausible reason for

tag shedding was that the nylon tag anchor did not fully lock between dorsal fin pterygiophores when a tag was deployed [18]. Another possibility is that the threaded nylon bolt connecting the tag body to the nosecone/tether assemblage failed. The bolt is designed to shear when the tag ignition release is fired. However, the bolt could have been compromised (torqued) due to overtightening during tag preparation, or could have been sheared due to stresses during deployment.

In addition to addressing these issues resulting in low reporting and high shedding rates, we recommend that transmitted daily summaries for mortality tags correspond the tag's internal clock, rather than light levels. Daily summaries for the tag used in this study were based on light: A "day" ends when the tag has been in darkness for two hours, at which time the previous day's data is summarized and a new day begins. The new day will "end" following the tag's exposure to light and subsequent exposure to darkness for two consecutive hours. While helpful for geolocation purposes, this data structure can be confusing and lead to daily summary data based on days of differing lengths—especially if a vertically migrating fish dives into mesopelagic depths and multiple daily summaries for a single day are generated. Meanwhile, if a fish remains in relatively deep, dark waters for multiple days, a single daily summary for multiple calendar days will be generated, as happened in several instances during the present study. Similarly, if a tag is predated upon, only a single daily summary is generated, even if the tag is within the consumer's stomach for several days. Simply deriving daily summaries based on a 24 hour clock will provide a far more straightforward and uniform dataset for interpretation.

CONCLUSIONS

Catch-and-release recreational fishing for large school and small medium-size Atlantic bluefin tuna along the U.S. east coast appears to be a viable conservation strategy across fishing methods. Post-release mortality estimates using light tackle do not differ notably from previous studies employing different gear types, nor do fight times, which could be considered a proxy for physiological stress.

Despite a relatively high failure rate, which can complicate post-release mortality estimates and must be addressed, the Desert Star Systems SeaTag-LOT shows promise as an example of a low-cost tool for detecting post-release mortality. The maintenance of high solar capacitor voltage for tags deployed on Atlantic bluefin tuna suggests that solar power is a viable means of powering PSATs deployed on a range of pelagic species. The daily summary data appear to provide sufficient information to infer the fate of released fish, although in this study there were no detected mortalities resulting from exceeding the low temperature (sinking in deep water) or low $\Delta T \text{ min}^{-1}$ (resting on the bottom) thresholds. Studies on different species (or different size classes of a single species) will require the development of species-specific thresholds for pop-off. Future work should focus on improving tag design and deploying tags on other species to assess performance.

DECLARATIONS

Ethics approval: The experimental protocols used in this study were approved by the College of William & Mary's Institutional Animal Care and Use Committee (IACUC-2014-08-06-9715-jegrav and IACUC-2016-07-21-11321-jegrav).

Consent for publication: Not applicable.

Availability of data and materials: The datasets used and/or analyzed during the current study are available from the corresponding author on reasonable request.

Competing interests: The authors declare that they have no competing interests.

Funding: Funding for this research was provided by the International Women's Fishing Association, the NMFS-Sea Grant Joint Fellowship Program, the Norcross Wildlife Foundation, the Virginia Institute of Marine Science, and the Virginia Institute of Marine Science Foundation.

Authors' contributions: WG designed the study, conducted fieldwork, analyzed data, and drafted the manuscript; AS assisted in project planning and in drafting and editing of the manuscript; JG assisted with developing parameters for tag pop-off and study design, and contributed substantially to the drafting of the manuscript.

Acknowledgments: This study would not have been possible without the collaboration of numerous anglers and charter captains. We would like to thank anglers Sami Ghandour, Josh Lee, and Boyang Zhang, who graciously invited us on board their charters to deploy tags on any fish they intended to release. In addition, we are indebted to the numerous charter captains and crew who were kind enough to allow us on board and assist with tagging efforts. Captains included: Capt. Ned Ashby (*Sea Breeze*); Capt. Jim Ashley (*Endorfin*); Capt. Kenneth Brown (*Trophy Hunter*); Capt. David Goldman (Shore Catch Guide Service); Capt. Jesse Granitzki (*Bi-Op-Sea*); Capt. Willy Hatch (*Machaca*); Capt. Mike Hogan (*Grey Goose*); Capt. Cullen Lundholm (Cape Star Charters); Capt. Dom Petrarca (Coastal Charters Sportfishing); Capt. Andy Piland (*Good Times*); Capt. Bobby Rice (Reel Deal Fishing Charters); Capt. Dan Rooks (*Tuna Duck*); and Capt. Josh Zacharias (Outermost Angling Charters). In addition, we are grateful to Dr. Chugey Sepulveda (Pfleger Institute of Environmental Research) and Dr. Sean Tracey (University of Tasmania) for providing us with unpublished data to use in our analysis, and also thank Dr. Tracey for reviewing a draft of the manuscript. This article is contribution number XXXX from the Virginia Institute of Marine Science, College of William & Mary.

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Table 1. Catch and tag information for 22 Atlantic bluefin tuna caught with light-tackle recreational fishing gear off Massachusetts (MA) and North Carolina (NC) and tagged with pop-up satellite archival tags. Asterisks denote tags that were shed prior to the scheduled pop-off date.

Fish	Date Deployed	Location	Curved FL (cm)	Hooking Location ^a	Hook type ^b	Fight time (min)	Condition (0-8 scale)	Full days deployed on fish ^c	Minimum straight-line displacement (km)	Mean displacement per day (km)
1	3/9/15	NC	195	JC	S	37	6	30	61	1.97
2	3/19/15	NC	173	JC	T/S	37	5	30	173	5.58
3	3/22/15	NC	157	RF	S	23	7	---	DNR ^d	---
4*	8/10/15	MA	145	VM	T	16	5	7	96	12
5	9/18/15	MA	114	JC	S	8	6	30	61	1.97
6	9/18/15	MA	152	DP	S	21	7	---	DNR	---
7*	9/25/15	MA	157	JC	S	17	8	25	226	8.69
8*	9/28/15	MA	165	JC	S	21	8	25	275	10.58
9 ^e	9/28/15	MA	183	JC	S	72	7	27	259	9.25
10 ^f	3/1/16	NC	193	UJ	T	78	5	95	377	3.89
11*	3/9/16	NC	201	LJ	S	28	6	23	35	1.46
12 ^g	8/5/16	MA	117	JC	S	9	7	17	143	6.81
13	8/5/16	MA	135	JC	S	18	7	---	DNR	---
14	8/7/16	MA	137	JC/TH	T	7	7	---	DNR	---
15	8/7/16	MA	130	UJ	S	4	7	---	DNR	---
16	8/7/16	MA	122	JC	S	8	8	---	DNR	---
17	8/7/16	MA	132	JC	T	8	6	30	144	4.65
18*	8/7/16	MA	137	JC	S	8	6	9	130	13
19 ^h	8/7/16	MA	140	JC/VM	T	9	3	46	DNR	---
20*	8/8/16	MA	147	JC	S	20	8	21	304	13.82
21	8/27/16	MA	132	JC/DP	T	7	4	---	DNR	---
22 ⁱ	8/31/16	MA	127	JC	T	4	7	29	283	9.13

^a Hooking locations are deep (DP), jaw corner (JC), lower jaw (LJ), roof of mouth (RF), top of head (TH), upper jaw (UJ), and ventral musculature (VM).

^b Fish were caught with either single (S) or treble (T) hooks. (*Continued on next page*)

^c While the number of daily summaries acquired generally corresponded to the tag deployment duration, there were five instances in there were fewer daily summaries than deployment days: Fish 2 (25 summaries, 30 day deployment); Fish 10 (88 summaries, 95 day deployment); Fish 18 (8 summaries, 9 day deployment), Fish 20 (19 summaries, 21 day deployment), and Fish 22 (27 summaries, 29 day deployment).

^d “DNR” refers to tags that did not report.

^e The tag had been light-activated three days prior to deployment, and thus was only deployed for 27 days.

^f The tag did not pop off as scheduled, but was eventually shed after 95 days, when data for the duration of the deployment were transmitted.

^g The tag/fish was predated upon 17 days after deployment, and began transmitting 3 days later.

^h The tag did not transmit data but was physically recovered on a beach in Nags Head, North Carolina, and data were retrieved.

ⁱ The tag had been light-activated the day before deployment, and thus was only deployed for 29 days.

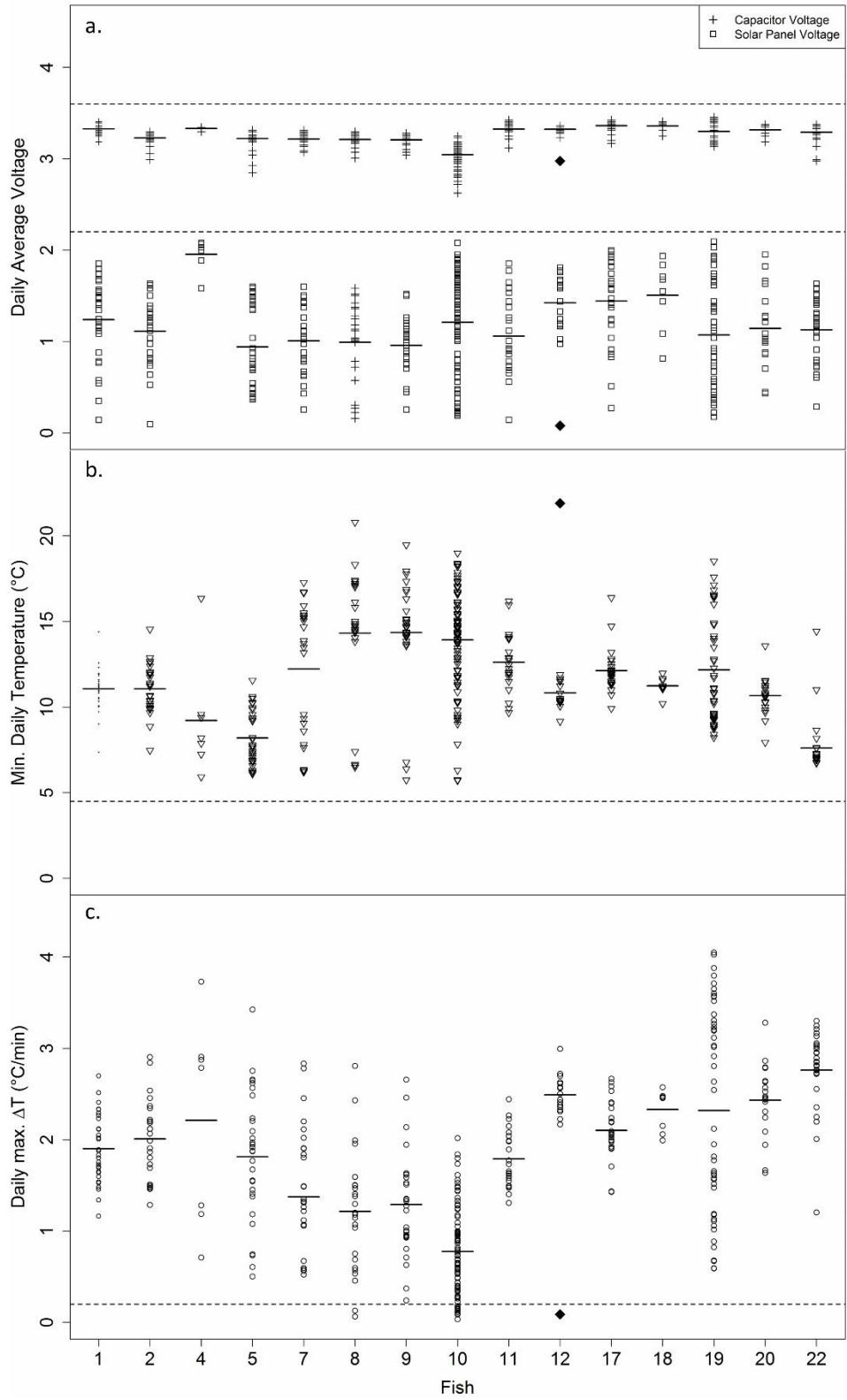


Figure 1. Data recovered from 15 pop-up satellite archival tags deployed on Atlantic bluefin tuna (*Full description on next page*).

Figure 1. Daily average solar panel and capacitor voltage (a), minimum daily temperature (b), and daily maximum $\Delta T \text{ min}^{-1}$ (c) for the 15 Atlantic bluefin tuna for whom data were recovered. Short horizontal solid lines represent the mean daily summary values for each fish. The horizontal dashed lines in (a) refer to the maximum and minimum solar capacitor voltages (3.6V and 2.2V); the horizontal dashed line in (b) refers to the minimum temperature threshold for pop-off (4.5° C); the horizontal dashed line in (c) refers to the daily maximum $\Delta T \text{ min}^{-1}$ threshold for pop-off (72 h at less than 0.2° C). The black diamonds for Fish#12 correspond to the daily summary data from when the tag/fish were presumably inside a lamnid shark, characterized by darkness (reflected by low solar panel voltage), a high minimum temperature, and a low daily maximum $\Delta T \text{ min}^{-1}$.

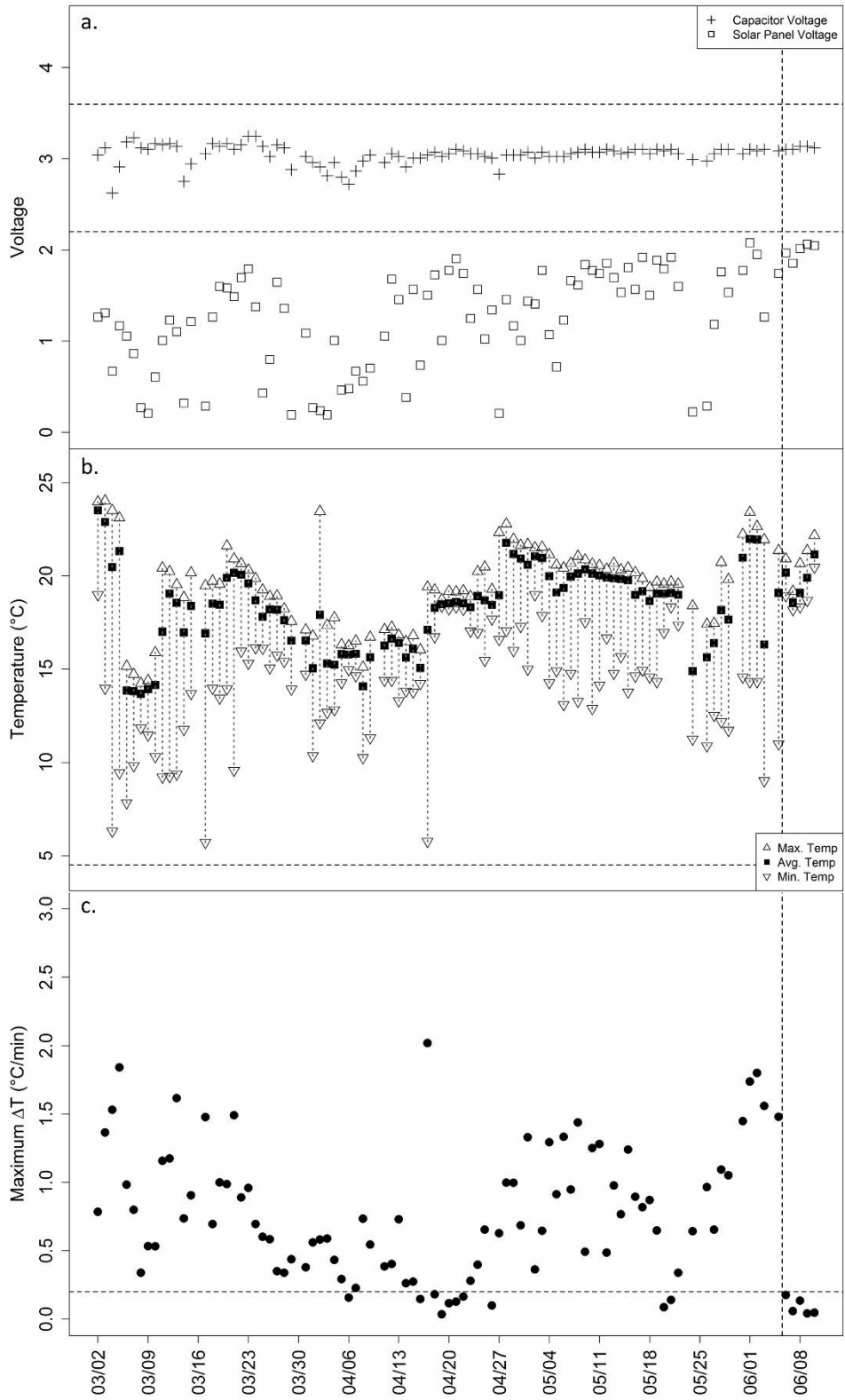


Figure 2. Daily summary data transmitted by SeaTag-LOT deployed on Fish #10 (*Full description on next page*).

Figure 2. Daily summary data for voltage (a), temperature (b), and daily maximum $\Delta T \text{ min}^{-1}$ (c) for a SeaTag-LOT deployed on Fish #10 (193 cm CFL) on 3/1/2016, which was shed after 95 days (indicated by the vertical dashed line) following failed pop-off after 30 days. Solar capacitor voltage is near the maximum voltage of 3.6 V (horizontal dashed line) throughout deployment, and is similar to voltage after shedding, indicating that the fish was spending sufficient time near the surface to keep the tag fully charged. The broad temperature range exhibited by the fish throughout the deployment indicates extensive vertical movement in the water column, which becomes much more compressed after tag shedding. Daily maximum $\Delta T \text{ min}^{-1}$ is generally maintained above the pop-off threshold of 0.2°C while the tag is on the fish, with the exception of five consecutive days in April, and decreases to below the threshold once the tag is shed and is floating at the surface.

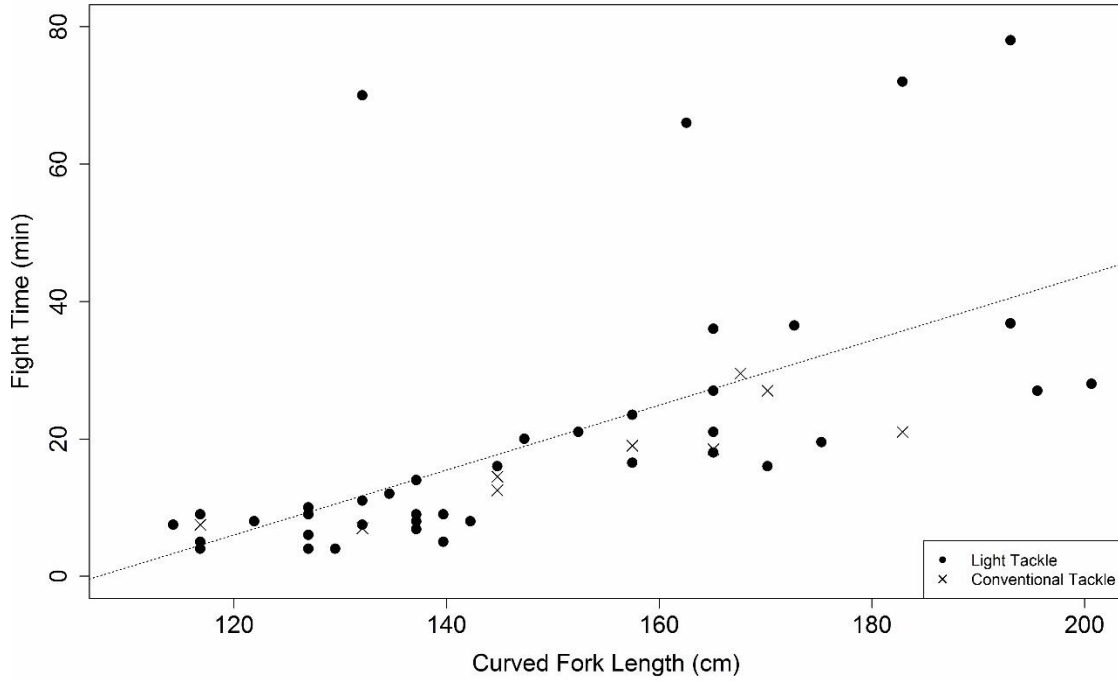


Figure 3. Fight times for Atlantic bluefin tuna caught using light-tackle (n = 41) and conventional (n = 9) fishing methods. Fight times did not significantly differ between the two gear types, and fight time was significantly correlated with fish size ($p = 2.3 \times 10^{-6}$; multiple $R^2 = 0.37$).

CONCLUSIONS

This dissertation provides a multidisciplinary perspective on the U.S. recreational Atlantic bluefin tuna fishery that aims to reduce implementation uncertainty—how fishermen will respond to changing fishery conditions—while linking behavior to fishing mortality outcomes. These findings can be used by the National Marine Fisheries Service (NMFS) Highly Migratory Species Management Division to better predict bluefin tuna harvest and mortality levels while maximizing angler wellbeing. In addition, given its highly cooperative nature, this research answers the call from the National Marine Fisheries Service (NMFS) to better engage with the recreational fishing community (NOAA 2015), which can improve regulatory compliance while also supporting active public involvement with management efforts.

Private recreational bluefin tuna anglers were shown to exhibit diverse preferences across the range of the fishery. However a common denominator among anglers was the high value placed on being able to harvest (or at least having the opportunity to harvest) bluefin tuna. Results clearly demonstrated that harvest was an integral motivator among anglers, even as some also placed a high value on non-consumptive components of the fishing experience. As a result, the NMFS HMS Management Division should prioritize maintaining some level of allowable harvest for this group, though managers should also be wary of the potential for large, non-linear increases in effort and harvest if regulations are liberalized to the point where highly consumptive-oriented anglers decide to enter the fishery.

Among fishermen who possessed the more flexible Charter/Headboat (CHB) permit, fishery conditions had differing impacts on the decision of individuals to fish commercially or recreationally, although those who primarily fished commercially were generally less likely to harvest fish recreationally than vice-versa. There were, however, a large number of permit holders who fished opportunistically (that is, landing fish in whatever manner was legal according to regulations), indicating the need for managers to be cognizant of the prevailing size classes and geographic distribution of bluefin tuna in a given year. Beginning in 2018, CHB permit holders who wish to maintain the ability to fish commercially will be required to obtain a commercial sale endorsement associated with their permit, which will improve managers' ability to assess potential commercial effort for a given location and time period (FR 82 57543, 12/06/2017). However, because the CHB permit (and sale endorsement), like the Angling category permit, does not have a cap on the number of participants and can be purchased online at any time, the potential for sudden increases in participation (and harvest) remains, underscoring the importance of the motivating factors described in this dissertation.

The finding that large school and small medium-size Atlantic bluefin tuna caught in the light-tackle recreational fishery experience low post-release mortality suggests that, as in the troll fishery for school-size bluefin tuna (Marcek and Graves 2014) and the natural bait fishery for large medium- and giant-size bluefin tuna (Stokesbury et al. 2011), catch-and-release is a viable conservation strategy. While this work is not expected to result in management changes, the high estimated survival rate of released bluefin tuna across size classes and gear types reinforces the notion that recreational fishing mortality for the species in U.S. waters predominantly results from harvest rather

than discard mortality. This inference can improve the U.S. negotiating position at the international level, as it is able to account for all sources of fishing mortality. In addition, it demonstrates that, for anglers who highly value catching and releasing bluefin tuna (identified in Chapter II), substantial economic welfare can be derived from the bluefin tuna fishery with minimal biological impacts on the resource.

An overarching theme of this dissertation was its strong level of collaboration and engagement with the recreational bluefin tuna fishing community, which fostered a dialogue that can improve management outcomes and provide a basis for future cooperative efforts. Between focus group attendees, survey respondents, anglers and captains who assisted with satellite tagging efforts, and those who facilitated outreach efforts, over 2000 fishery participants contributed to the completion of this research. By increasing transparency and accountability, cooperative fisheries research has proven beneficial for improving the credibility of scientific findings among fishermen while also legitimizing management strategies (Kaplan and McCay 2004). Conversely, if science and management are viewed with distrust, non-compliance with regulatory measures can result (Johnson and van Densen 2007), which in the case of the recreational Atlantic bluefin tuna fishery could take the form of disregarding size and bag limits, non-reporting of catch, refusal to respond to the Large Pelagics Survey (LPS), or fishing without the required permit, among others.

Given the large size of the recreational bluefin tuna angling population and its broad distribution along the U.S. east coast, as well as limited enforcement capacity, buy-in to management strategies is especially critical. By extensively engaging fishermen in the research process and subsequently communicating results through a variety of

avenues, any regulatory changes (or, in the case of Chapter IV, suggested best practices) resulting from this work are hoped to be met with understanding.

In sum, this work has provided the first in-depth insight into the human dimensions of recreational bluefin tuna fishermen along the U.S. east coast while also further demonstrating the viability of catch-and-release angling as an effective conservation approach. Having established a dialogue with fishery participants, a valuable next step would be improving accountability among fishermen for bluefin tuna fishing mortality, which Abbott (2015) highlights as a key for effective management of a recreational fishery. As described in Chapter I, limitations to the LPS and low compliance with the fishery's reporting requirement (Automated Landings Reporting System; ALRS) have hindered real-time tracking of harvest levels, both among recreational anglers (Angling and CHB permit holders) harvesting under the Angling category and CHB-permit holders harvesting under the General category.

Recent efforts to reduce the burden of reporting, such as the development of a smartphone app, will only be effective if fishermen are motivated to report and understand the benefits of doing so. In focus groups as well as in previous studies (NOAA 2013), it became evident that low reporting rates were frequently due to a combination of complacency, forgetfulness and mistrust—one focus group participant jokingly referred to the ALRS phone number as “1-800 CLOSE ME.” By better communicating to bluefin tuna fishermen that timely reporting of catch is needed to maintain compliance with internationally allocated quota and ensure future access to the fishery, a change in norms oriented toward higher compliance could result. In addition, exploring a shift in management of the fishery toward output controls, such as harvest

tags, could facilitate accountability, and has proven effective in Maryland and North Carolina as well as in a pilot program in Massachusetts (NOAA 2013, Abbott 2015). However, as with the current system, the effectiveness of output controls depends on buy-in of the recreational bluefin tuna fishing community.

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