



INTERNATIONAL DOCTORAL
SCHOOL OF THE USC

Gregory
Verutes

PhD Thesis

An Evaluation of International
Policies and Local Management
Strategies to Reduce Marine
Mammal Bycatch

Santiago de Compostela, 2022



DOCTORAL THESIS

**AN EVALUATION OF
INTERNATIONAL POLICIES
AND LOCAL MANAGEMENT
STRATEGIES TO REDUCE
MARINE MAMMAL BYCATCH**

Gregory Michael Verutes

**INTERNATIONAL PHD SCHOOL OF THE UNIVERSITY OF SANTIAGO DE COMPOSTELA
Ph.D. PROGRAMME IN MARINE SCIENCE, TECHNOLOGY, AND MANAGEMENT**



SANTIAGO DE COMPOSTELA
2022



DECLARACIÓN DO AUTOR DA TESE

An Evaluation of International Policies and Local Management Strategies to Reduce Marine Mammal Bycatch

D. Gregory Michael Verutes

Presento a miña memoria de tese de doutoramento, seguindo o procedemento axustado ao Regulamento, e declaro que:

1. A memoria de tese inclúe os resultados da elaboración do meu traballo.
2. De selo caso, na tese faise referencia ás colaboracións que xeroutivo este traballo.
3. A tese é a versión definitiva presentada para a súa defensa e coincide coa versión enviada en formato electrónico.
4. Confirmo que a tese non incorre en ningún tipo de plaxio doutros autores nin de traballos presentados por min para a obtención doutros títulos.

En Santiago de Compostela, 23 de Xaneiro de 2022

Gregory M. Verutes



AUTORIZACIÓN DOS DIRECTORES DA TESE

**An Evaluation of International Policies and
Local Management Strategies to
Reduce Marine Mammal Bycatch**

D. Carlos Sebastián Villasante
D. Graham John Pierce

INFORMAN:

Que a presente tese ,se correspoñdese co traballo realizado por D. Gregory Michael Verutes, baixo a nosamiña dirección, e autorizamoso a súa presentación, considerando que reúne os requisitos esixidos no Regulamento de Estudos de Doutoramento da USC, e que como directores desta non incorre nas causas de abstención establecidas na Lei 40/2015.

En Santiago de Compostela, 23 de Xaneiro de 2022

Carlos Sebastián Villasante

Graham John Pierce



Gregory Michael Verutes

**AN EVALUATION OF
INTERNATIONAL POLICIES
AND LOCAL MANAGEMENT
STRATEGIES TO REDUCE
MARINE MAMMAL BYCATCH**

Campus Do Mar Ph.D. Program



**SANTIAGO DE COMPOSTELA
2022**



For my father, George.



Contents

Acknowledgements	19
Contributions	21
Resumo (Galego).....	23
Summary (English).....	35
Abstract	47
1 SETTING THE SCENE.....	53
1.1 INTRODUCTION.....	53
1.1.1 Ocean data and monitoring innovations	55
1.1.2 Marine mammals, fisheries, and their interactions.....	57
1.1.3 Species distribution models	58
1.2 THEORETICAL CANVAS	59
1.2.1 Embracing complexity in marine mammal conservation research.....	59
1.2.2 Advancing policy and practice to manage marine mammal bycatch	61
1.3 AIM AND RESEARCH QUESTIONS	63
1.4 METHODOLOGICAL APPROACH.....	63
1.5 REFERENCES.....	64
2 USING GIS AND STAKEHOLDER INVOLVEMENT TO INNOVATE MARINE MAMMAL BYCATCH RISK ASSESSMENT IN DATA-LIMITED FISHERIES. 71	
2.1 INTRODUCTION.....	71
2.2 METHODS	74
2.2.1 Engage stakeholders and acquire existing knowledge	75
2.2.1.1 Areas of interest and subregions	76
2.2.1.2 Fishing activities and gear usage	77
2.2.1.3 Environmental and marine mammal sightings data.....	78
2.2.2 Build bycatch scenarios	79
2.2.2.1 Habitat suitability.....	80
2.2.2.3 Seasonality	81
2.2.2.4 Fishing extent and intensity	81
2.2.3 Assess and visualize bycatch risk and data uncertainty	82
2.2.3.1 Expert evaluation	84
2.2.3.2 Spatially explicit criteria	84
2.2.3.3 Measuring bycatch risk.....	87
2.2.3.4 Characterizing uncertainty of data sources	87
2.3 RESULTS.....	88

2.3.1 Visualizing bycatch risk	88
2.3.2 Capturing expert knowledge.....	92
2.3.3 Characterizing uncertainty.....	92
2.3.4 Emergent patterns and findings	93
2.4 DISCUSSION	95
2.4.1 Limitations and simplifications	96
2.4.2 Future directions.....	97
2.5 CONCLUSION.....	99
2.6 REFERENCES	99
2.7 SUPPORTING INFORMATION.....	105
2.7.1 Methodology and Scoring Scheme.....	105
2.7.1.1 Methods and tool for risk assessment	105
2.7.1.2 Spatial data on species for the spatial overlap criterion.....	105
2.7.1.2.1 <i>Dugongs</i>	107
2.7.1.2.2 <i>Irrawaddy dolphins</i>	107
2.7.1.3 Rankings for resilience criteria	109
2.7.1.3.1 <i>Dugongs</i>	109
2.7.1.3.2 <i>Irrawaddy dolphins</i>	110
2.7.1.4 Literature review for scoring the remaining exposure and consequence criteria	110
2.7.1.4.1 <i>Exposure</i>	111
2.7.1.4.2 <i>Consequence-sensitivity</i>	112
2.7.2 Limitations and simplifications	112
2.7.3 Supplementary References	113

3 MODELING SEASONAL DISTRIBUTION OF IRRAWADDY DOLPHINS (ORCAELLA BREVIROSTRIS) IN A TRANSNATIONAL IMPORTANT MARINE MAMMAL AREA	129
3.1 INTRODUCTION.....	129
3.2 METHODS	132
3.2.1 Study area	132
3.2.2 Boat surveys	132
3.2.3 Environmental variables.....	134
3.2.4 Seasonal habitat models.....	136
3.2.5 Model tuning, variable selection, and suitability thresholds	137
3.2.6 Model evaluation and statistical tests	139
3.3 RESULTS.....	141
3.3.1 Group size and seasonal habitat patterns.....	142
3.3.2 Spatially explicit seasonal habitat models	144
3.4 DISCUSSION	147
3.4.1 Emergent patterns of habitat suitability.....	147
3.4.2 Limitations and simplifications	149
3.4.3 Conservation and management opportunities.....	150
3.5 CONCLUSION.....	151
3.6 REFERENCES	152
3.7 SUPPORTING INFORMATION.....	158

4 ADVANCING THE IMPLEMENTATION OF POLICIES TO MONITOR AND REDUCE SMALL CETACEAN BYCATCH.....	163
4.1 INTRODUCTION	163
4.2 BACKGROUND.....	167
4.2.1 Legislative context.....	169
4.2.1.1 European Union	169
4.2.1.2 United States of America	171
4.2.2 Case studies	172
4.2.2.1 Common dolphins (<i>Delphinus delphis</i>) of the Bay of Biscay	173
4.2.2.2 Harbor porpoise (<i>Phocoena phocoena</i>) subpopulation of the Baltic Proper	175
4.2.2.3 Harbor porpoises of the U.S. Gulf of Maine.....	177
4.3 COMPARISONS AMONG CASE STUDIES AND REGIONS	181
4.3.1 Enabling and limiting conditions for reducing cetacean bycatch.....	184
4.3.1.1 Community involvement	185
4.3.1.2 Data collection	187
4.3.1.3 Quantitative analysis.....	189
4.3.1.4 Governance	191
4.3.1.4.1 <i>Monitoring and evaluation</i>	191
4.3.1.4.2 <i>Mitigation measures</i>	192
4.4 DISCUSSION	194
4.4.1 Necessary steps to make E.U. measures comparable to the U.S. MMPA.....	196
4.4.2 Advancing bycatch management through risk assessment.....	198
4.4.2.1 Bycatch monitoring and reporting	199
4.4.2.2 Spatio-temporal patterns of bycatch risk	200
4.4.2.3 Management and action plans.....	204
4.5 CONCLUSION.....	206
4.6 REFERENCES	208
5 CONCLUSIONS.....	219
5.1 RESULTS SYNTHESIS	219
5.2 CONTRIBUTION TO RESEARCH, POLICY, AND MANAGEMENT.....	221
5.3 PERSPECTIVES AND RECOMMENDATIONS.....	223



List of figures

- Figure 1.** The three dimensional complexity landscape represented by three axes: (A) data availability (x-axis), (B) conceptual complexity (y-axis), (C) analytical complexity (z-axis), where circle size denotes analytical complexity (larger circles represent higher analytical complexity)..... 60
- Figure 2.** Three field sites selected in Southeast Asia..... 74
- Figure 3.** Subregions based on management, conservation, geopolitical and ecological similarities across the three SE Asian field sites. 77
- Figure 4.** Inventory of environmental, biological, and fisheries data summarized by site, year, and season for each field site. 79
- Figure 5.** Bycatch risk assessment conceptual model and tool process diagram. 83
- Figure 6.** Estimated bycatch risk in three field sites (A-C). (A) Sibiu-Tinggi Islands, Johor, Malaysia (SBTI) for dugongs, (B) Kuching Bay, Malaysia (KUCG) during the dry season, pre-monsoon and post-monsoon, B1-3 respectively, and (C) Kien Giang Biosphere Reserve, Vietnam (KGBR) for Irrawaddy dolphins. 90
- Figure 7.** Plots and bar charts summarizing drivers and emergent patterns of bycatch risk..... 91
- Figure 8.** The study area: (A) situated in the Eastern Gulf of Thailand, including the Kien Giang-Kep Archipelago Important Marine Mammal Area (red color) and (B) The riverine inputs to the Kep Archipelago (Kampot and Giang Rivers). 133
- Figure 9.** Irrawaddy dolphin occurrences recorded during the 2-year survey period (October 2017 through September 2019). 134
- Figure 10.** Histogram plots of (A) water depth, (B) distance to offshore islands, and (C) distance to river mouths. 142
- Figure 11.** Box and dot-density plots of the habitat characteristics and group size of Irrawaddy dolphins as sighted in Kep waters during the four seasons in terms of: (A) water depth, (B) distance to offshore islands, (C) distance to river mouths, (D) sea surface temperature, (E) chlorophyll-a concentration, and (F) group size. 143
- Figure 12.** Maps of Irrawaddy dolphin habitat suitability based on the best performing models projected to seasonal midpoints for months between 2018 and 2019: (A1) December, (A2) January, and (A3) February 2019 of the dry season; (B) April 2019, pre-monsoon; (C) May to September 2019 of the summer monsoon; and (D) October 2018, post-monsoon. 146



List of tables

Table 1. Summary of each field site, including focal species, situational context, and partner(s).	76
Table 2. Fishing methods and corresponding gear categories identified in each SEA field site.	78
Table 3. Definitions and scoring bins for the exposure, consequence, and Spatially Explicit Criteria (SEC).	85
Table 4. Diagnostic to characterize data uncertainty based on where existing information fits along a spectrum of green-yellow-red (highest to lowest data quality, respectively).	88
Table 5. Classification of data input uncertainty in three SEA field sites..	93
Table 6. Summary of candidate environmental data used to build SDMs in Maxent.....	137
Table 7. On-effort Irrawaddy dolphin sightings and encounter rates by season for the survey period, from October 2017 to September 2019.	138
Table 8. Fitting functions and environmental variables used to build final SDMs, after model tuning, by season.	141
Table 9. Presences used to fit seasonal SDMs and performance statistics.	145
Table 10. Strategies to monitor, research, and mitigate small cetaceans, fisheries, and bycatch.	167
Table 11. Case study summaries of current issues, strategies, and opportunities to advance the implementation of policies and agreements and reduce cetacean bycatch.....	180
Table 12. Existing information from international policies, agreements, scientific advice, and the literature for the three case studies mapped to certain bycatch risk exposure and consequence attributes as introduced by Verutes et al. (2020).....	202



Acknowledgements

To my parents, George and Della, for everything. They taught me how to read and write, algebra, hard work, dedication, and most importantly, to do what I love. To my siblings and in-laws, Tina, Tom, Chris, and Janet, for being my backstop. To Sebastián, for helping navigate a new culture in Spain and unforeseen challenges during the COVID-19 pandemic. To Graham and Begoña, for their willingness to contribute with ideas and suggestions that greatly improved this thesis. To Melissa, for inspiring me to value and fight for nature and its beauty that others too often take for granted. To my amazing colleagues in Southeast Asia whose willingness to share their data, time, passion for conserving marine mammals, and sense of humor were essential for this study. To representatives of the MareCet Research Organization, Kien Giang Biosphere Reserve, Vietnam Marine Megafauna Network, Sarawak Dolphin Project, Marine Conservation Cambodia, and Associação para a Investigação do Meio Marinho, for kindly granting interviews, participation in workshops, and other field exercises that greatly enriched this research. To Rebecca, Andrew, and Ellen, for having created the conditions for an important part of the fieldwork for this thesis to materialize.

To all the people who fought, and to all those who continue to fight, for the more sustainable use of our oceans and harmony between people and nature. Without them, many of the most amazing places on this planet would have already faded into obscurity.

Gracias. Obrigado. Thank you.





Contributions

This thesis benefited from collaborations with numerous individuals, who supported me during the design, engagement, analytical, and outreach phases of the research.

Chapter 2

Verutes, G. M., Johnson, A. F., Caillat, M., Ponnampalam, L. S., Peter, C., Vu, L., Junchompoo, C., Lewison, R. L., Hines, E. M. (2020). Using GIS and stakeholder involvement to innovate marine mammal bycatch risk assessment in data-limited fisheries. *PloS one*, 15(8), e0237835. doi: 10.1371/journal.pone.0237835

Conceived and designed the experiments: EH RL GV MC AJ. **Performed the experiments:** GV MC LP CP LV EH. **Analyzed the data:** GV MC EH. **Contributed to the writing of the manuscript:** GV RL AJ EH MC LP. **Project conception and management:** EH GV AJ. **Species gear interaction scoring:** LP CP CJ LV. **Data processing:** GV MC. **Habitat modeling:** MC GV EH. **Bycatch risk modeling:** GV. **Project delivery:** EH GV AJ RL.

Chapter 3

Verutes, G. M., Tubbs, S. E., Selmes, N., Clark, D. R., Walker, P., & Clements, O. (2021). Modeling Seasonal Distribution of Irrawaddy Dolphins (*Orcaella brevirostris*) in a Transnational Important Marine Mammal Area. *Frontiers in Marine Science*. doi: 10.3389/fmars.2021.617921

Conceived and designed the experiments: GV ST. **Performed the experiments:** GV ST. **Analyzed the data:** GV NS ST. **Contributed with data:** ST NS DC PW OC. **Wrote the manuscript:** GV ST NS.

Chapter 4:

Verutes, G. M., Leaper, R., Johnson, A. F., Lewison, R. L., Reiblich, J., Santos, M. B., Villasante, S., Pierce, G. J. (in prep.). Advancing the Implementation of Policies to Monitor and Reduce Small Cetacean Bycatch.

Conceived the policy analysis: GP GV. **Reviewed and analyzed the data:** GV GP. **Contributed to the writing of the manuscript:** GV GP RL JR AJ RLL MBS SV.



Resumo (Galego)

É posible deseñar e aplicar un marco de avaliación para avaliar as interaccións prexudiciais entre os mamíferos mariños e as pesqueiras utilizando só a información existente? Esta é a principal pregunta que intento responder nesta tese. De forma máis ampla, investigo as formas en que as políticas internacionais se traduciron, ou non, en estratexias de xestión eficaces para o seguimento e mitigación da captura incidental de mamíferos mariños nas pesqueiras con datos limitados.

A captura incidental, a captura incidental de especies non obxectivo en artes de pesca activas, foi recoñecida como unha ameaza para a megafauna mariña durante décadas (Coe et al., 1984; NRDC, 1992; Perrin et al., 1994). É un tema que merece ser entendido en profundidade, xa que a captura e retirada accidental por parte das pesqueiras é unha das ameazas humanas máis importantes para os mamíferos mariños (Reeves et al., 2013). Na década de 1960, aproximadamente 350.000 golfiños morreron ao ano na pesquería de atún de cerco do Pacífico Tropical Oriental (Joseph, 1994). A introdución de varias innovacións, como un "panel Medina" de seguridade de mallas pequenas e un procedemento de retroceso para liberar golfiños enredados das redes de pesca, xunto coa aprobación da Lei de Protección de Mamíferos Mariños dos Estados Unidos (MMPA) en 1974, reduciu efectivamente a captura incidental (Barham et al., 1977). A pesar dos avances para abordar un problema internacional complexo en particular en pesqueiras, unha estimación recente da captura incidental de mamíferos mariños suxire que máis de 300.000 animais morren cada ano polas pesqueiras mundiais (WWF, 2009). Hoxe avaliamos os efectos da captura incidental utilizando datos de cantidade e calidade limitadas e nun tempo de resposta lento despois da captura. Unha mala comprensión dos impactos da pesca nas poboacións locais de mamíferos mariños pode levar a unha xestión errónea.

A pesca a pequena escala (SSF en inglés) é fundamental para as economías e os medios de subsistencia locais (FAO, 2021), aínda que estas actividades están pobremente controladas e reguladas a nivel mundial (Pauly e Zeller, 2016). A grande extensión espacial de SSF e a abundancia relativamente baixa de certas poboacións de mamíferos mariños impiden a

capacidade dos científicos e das organizacións de conservación para avaliar rapidamente o risco e identificar áreas prioritarias para a conservación e xestión da vida salvaxe. Precísase unha ferramenta de avaliación cohesionada para illar os principais motores do risco de captura incidental (por exemplo, as interaccións especies-pesqueiras no espazo e no tempo) e identificar as áreas e estacións de maior preocupación, ao tempo que se identifican oportunidades para a investigación, a educación e a mellora dos datos. Antes de pasar ás preguntas específicas de investigación que formulo nesta tese, describo os temas de investigación tratados en contexto.

Aproximación teórica

Dadas as crecentes presións sobre os recursos mariños derivadas dun conxunto de actividades humanas en expansión e intensificación na economía oceánica actual (Halpern et al., 2015), a conservación da megafauna mariña adoita depender da información xeoespacial (baseada na localización) e do coñecemento das partes interesadas para protexer a diversidade biolóxica. Os esforzos para xestionar especies ameazadas, vulnerables e en perigo de extinción, incluído o 25% dos mamíferos mariños clasificados como tales pola Lista Vermella da UICN (Nelms et al., 2021), poderían mellorarse con coñecementos especializados para realizar análises xeoespaciais, compromiso das partes interesadas e establecer enfoques máis sistemáticos para a recollida e avaliación de datos (Hines et al., 2020; Wade et al., 2021). Esta tese inspírouse no lenzo teórico introducido por Lewison et al. (2018), que postula que primeiro debemos recoñecer, a complexidade inherente dos sistemas socio-ecolóxicos acoplados para despois captar os valores das partes interesadas e acceder aos datos e ferramentas necesarios para avanzar na investigación da conservación da megafauna mariña.

ABRAZAR A COMPLEXIDADE NA INVESTIGACIÓN DA CONSERVACIÓN DE MAMÍFEROS MARIÑOS

Os enfoques de sistemas complexos (CSA) son unha combinación de técnicas conceptuais, analíticas e computacionais que se poden aplicar a problemas ambientais "perversos", como as capturas incidentais da pesca (Lewison et al., 2018). Estes problemas perversos normalmente carecen dunha única solución e teñen un alto grao de incerteza científica (Balint et al., 2011). Como metodoloxía de investigación, os CSA adoitan ser intensivos en datos e difíciles de implementar en ambientes con datos limitados. Cando se traballa en países en desenvolvemento ou a nivel comunitario, os datos sobre especies mariñas e pesqueiras adoitan ser inaccesibles, de

baixa calidade ou dispersos entre varias fontes. Mesmo nos lugares onde se dispón de estimacións de poboacións, como os Estados Unidos e a Unión Europea, as lagoas nos datos sobre o esforzo pesqueiro e as taxas de encontro limitan a capacidade de cuantificar o risco de captura incidental na pesca en mamíferos mariños residentes e outras especies de megafauna sensibles (Soykan et al., 2008; Bellido et al., 2011). Precísanse técnicas conscientes da complexidade para caracterizar mellor os riscos para a vida salvaxe e identificar oportunidades para reducir a captura incidental porque recoñecen factores non lineais e impredecibles que inflúen nos cambios no medio mariño (Hazen et al., 2013) e na relación dinámica entre humanos e sistemas ecolóxicos (Lewison et al., 2018).

Os datos espacialmente explícitos ofrecen unha valiosa fonte de información para a investigación sobre a conservación dos mamíferos mariños e a xestión da captura incidental. A probabilidade dun evento de captura incidental está relacionada cos cambios na superposición de especies e pesqueiras e coas condicións específicas nas que se atopan os animais. O coñecemento da distribución espacial das especies mariñas é fundamental á hora de deseñar áreas protexidas e de implementar accións de xestión (por exemplo, Grech e Marsh, 2007; Carlen et al., 2018). Para este fin, os modelos de distribución de especies (SDM) son unha ferramenta cada vez máis popular para identificar o hábitat crítico e a distribución xeográfica (Redfern et al., 2006; Gegr et al., 2013). Algúns SDM, como os métodos de máxima entropía (Maxent; Phillips et al., 2006), son particularmente axeitados para xestionar situacións con datos de especies só de presenza. Ao aproveitar os avistamentos de animais dispoñibles, os datos de observación da terra e o coñecemento de expertos locais, os SDM examinan os posibles impactos sobre as especies en condicións ambientais cambiantes. Axudan a contextualizar as asociacións chave de hábitat en función de parámetros ecolóxicos coñecidos e pódense utilizar para apoiar a planificación da conservación e a xestión adaptativa tanto a curto como a longo prazo.

Tamén existen técnicas de baixo custo dispoñibles para caracterizar a localización e o nivel de esforzo na SSF (por exemplo, Stewart et al., 2010; Johnson et al. 2017) e documentar a distribución dos mamíferos mariños ameazados e os impactos específicos da pesca (p. ex., Pilcher et al., 2017). Medir a superposición das actividades de SSF e os hábitats adecuados de mamíferos mariños identificados polos SDM pode servir como punto de partida para caracterizar espacialmente o risco de captura incidental en situacións limitadas de datos (Wade et al., 2021). Por exemplo, Briscoe et al. (2014) baseáronse unicamente nos datos de avistamentos publicados

e en parámetros xeofísicos, como a distancia á costa e a profundidade da auga, para construír un SDM para dugongos (*Dugong dugon*) e estimar a probabilidade de presenza de especies en lugares previamente non investigados. Partindo deste enfoque nas pesqueiras con datos limitados do sueste asiático e de América Latina, os investigadores de mamíferos mariños identificaron áreas e estacións de maior risco de captura incidental aproveitando os coñecementos expertos locais sobre a distribución de pesqueiras artesanais e a densidade do tipo de artes (Hines et al., 2020; Costanza et al., 2021).

A CAPTURA INCIDENTE DA PESCA: A DIMENSIÓN HUMANA

A implicación da industria, o goberno, as institucións científicas e outras partes interesadas relevantes nos procesos de xestión pesqueira é esencial para o éxito da conservación (Berkes et al., 2001; Macher et al., 2018). A investigación existente suxire que os enfoques participativos para facilitar a colaboración multisectorial son máis propensos a fomentar a resolución de problemas, a co-crear coñecemento e a construír a confianza da comunidade (Trimble e Berkes, 2013; Verutes e Rosenthal, 2014). O valor da implicación das partes interesadas é unha mensaxe que se repite a miúdo, e difícil de acadar mesmo no “Take Reduction Plan” do MMPA dos Estados Unidos (McDonald et al., 2016). Para xestionar a captura incidental, a participación dos posuidores de coñecementos locais ten o potencial de identificar estratexias para equilibrar os beneficios da redución do risco de captura accidental e os custos da actividade pesqueira alterada para os medios de vida dos pescadores (Lewison et al., 2011; Read, 2021). A comunicación aberta e un entendemento mutuo entre pescadores, xestores e científicos teñen un enorme potencial para producir resultados positivos coas iniciativas de conservación.

A política pesqueira dirixida á conservación da biodiversidade ten un forte compoñente humano, xa que afecta ás comunidades que dependen directa ou indirectamente das áreas a protexer. A capacidade dos xestores para equilibrar eficazmente múltiples obxectivos, moitas veces en competencia, depende da comprensión das percepcións, necesidades e valores que teñen os diferentes grupos de interese sobre estas políticas; é dicir, como as persoas afectan e se ven afectadas por unha intervención concreta. O obxectivo último é unha distribución xusta e equitativa dos custos e beneficios nesas compensacións, que contribúa a uns resultados máis equilibrados para as persoas e a natureza. A falta de marcos de avaliación que consideren as complexidades mencionadas anteriormente, en particular, as dependencias do contexto espazo-

temporal e os conflitos entre a conservación da biodiversidade e os obxectivos pesqueiros, dificultou o desenvolvemento e implementación de estratexias de xestión de capturas incidentais nas pesqueiras con datos limitados.

Obxectivos e cuestións de investigación

Como podemos avanzar para abordar este problema perverso da captura incidental de mamíferos mariños conectando cunha comunidade de partes interesadas e realizando unha visión compartida para reducir a súa aparición mentres se mantén a produtividade da pesca? Esta tese pretende avanzar na investigación e xestión de captura incidental en contextos limitados de datos co mantra: debemos utilizar mellor os datos existentes.

A limitada dispoñibilidade de datos para caracterizar a distribución espazo-temporal de especies ameazadas que interactúan con pesqueiras problemáticas retardou o progreso en moitas rexións do mundo como América Latina, África e o sueste asiático (Alfaro-Shigueto et al., 2010; Moore et al., 2010; Teh et al., 2013). Ademais, houbo accións limitadas na Unión Europea (UE) para abordar niveis extremadamente altos de mortalidade inducida por capturas incidentais ou a ameaza de extinción de certas especies de mamíferos mariños (Peltier et al., 2020, Carlén et al., 2021). A pesar da dispoñibilidade de programas de seguimento regulares, métodos de investigación e asesoramento científico para actuar na UE (por exemplo, SAMBAH et al., 2016; Hammond et al., 2017; ICES, 2020), isto non garante que as estratexias de xestión identificadas para mitigar a captura incidental de mamíferos mariños se implementen e fagan cumprir de forma efectiva (Dolman et al., 2021; Rogan et al., 2021). Ademais, e moitas veces xustaposta a estas condicións limitantes de escaseza de datos e un proceso de implementación de políticas estancado, está o comentario antigo, "quizais deberíamos volver e recoller máis información". O enfoque e as ferramentas desenvolvidas aquí están deseñadas para contrarrestar esta narrativa.

En liñas xerais, a pesca é rica en datos. Existen infinidade de organizacións, iniciativas e ferramentas deseñadas para supervisar as frota globais, rastrexar estatísticas e analizar as actividades pesqueiras (por exemplo, a Organización para a Alimentación e a Agricultura (FAO), Sea Around Us, Global Fishing Watch). Os datos sobre pesqueiras e os impactos localizados da captura incidental das pesqueiras sobre as poboacións e os hábitats de mamíferos mariños son sen dúbida máis escasos (Soykan et al., 2008; Shester e Micheli, 2011; Chuenpagdee et al., 2019). Aínda que para algunhas partes interesadas nunca pode haber datos suficientes para

xustificar a participación nos procesos de xestión, as situacións de escasez de información non ofrecen excusas para a inacción. Necesitamos analizar a información que temos mentres se producen problemas; en caso contrario, as actividades científicas e de xestión seguirán rezagadas. Esta postura non implica que os achados dun inventario inicial de pesqueiras problemáticas ou da avaliación da captura incidental representen a resposta final para un lugar determinado. Ao integrar os datos existentes e o coñecemento experto local, son posibles novas formas de participación comunitaria e análises cuantitativas. En definitiva, o enfoque suxerido pode poñer aos xestores no camiño cara a unha investigación consciente da complexidade e un seguimento específico para abordar as taxas de captura incidental insostibles.

Nesta tese formulo as seguintes preguntas de investigación para comprender e interrogar as influencias de varias capas sobre a captura incidental de mamíferos mariños nas pesqueiras con datos limitados, desde a política ata a xestión:

1. Podemos deseñar unha ferramenta de xestión que acceda ao coñecemento existente para avaliar escenarios estacionais de captura incidental de mamíferos mariños, e visualizar os riscos asociados e as incertezas dos datos? (**Capítulo 2**);
2. Somos capaces de utilizar datos de observación terrestre de alta resolución e dispoñibles a nivel mundial, como a temperatura da superficie do mar e a concentración de clorofila-a para construír modelos precisos que describan os procesos ecolóxicos que rexen a selección do hábitat dos golfinhos de Irrawaddy e prever a distribución estacional da especie? (**Capítulo 3**);
3. Qué obstáculos científicos, sociopolíticos e económicos limitaron a implementación de medidas para controlar e mitigar as taxas insostibles de captura incidental de pequenos cetáceos na Unión Europea e nos Estados Unidos? (**Capítulo 4**)

Estrutura da tese

Esta tese inclúe tres seccións de resultados. En primeiro lugar, presento a ferramenta de xestión pesqueira de Avaliación do Risco de Capturas Incidentais (ByRA) (**Capítulo 2**) como un marco analítico para as nacións costeiras de todo o mundo onde a sobrepesca e a destrución do hábitat son problemas cada vez máis graves. A ByRA documenta patróns emerxentes de interacción entre artes de pesca de alto risco e especies de mamíferos mariños vulnerables en situacións

limitadas de datos. Usando dúas especies de mamíferos mariños en Malaisia e Vietnam como caso de proba, a ByRA aproveita (1) as enquisas de campo existentes, (2) o compromiso participativo que inclúe unha ampla gama de partes interesadas e (3) a análise xeoespacial para proporcionar información espacialmente explícita estruturada sobre riscos e vulnerabilidades, mentres se ten en conta a incerteza dos datos. As saídas de mapas e táboas de resumo identifican superposicións previamente descoñecidas entre as actividades pesqueiras de alto impacto e o hábitat axeitado de mamíferos mariños en tres sitios de campo do sueste asiático. Estes casos proporcionan unha imaxe detallada do coñecemento existente e novo sobre a pesca artesanal con datos limitados e poden orientar futuros plans de investigación e acción para a recuperación e protección de especies de mamíferos mariños na rexión.

A continuación, un papel de distribución de golfinhos de Irrawaddy ilustra unha imaxe do que está en xogo dentro dunha Zona Importante de Mamíferos Mariños (IMMA) recentemente designada ao longo da fronteira marítima activa Vietnam-Camboxa se as actividades pesqueiras seguen diezmado as poboacións de megafauna e os seus hábitats (**Capítulo 3**). Este capítulo establece tres obxectivos para mellorar o coñecemento básico dunha poboación costeira de golfinhos de Irrawaddy (*Orcaella brevirostris*) que habita nas augas do arquipélago de Kep, Cambodia: (1) caracterizar a súa distribución espacial; (2) mapear a variación das ocorrencias estacionais e as preferencias do hábitat; e (3) estimar o nicho ecolóxico da poboación en función da influencia das variables oceanográficas (é dicir, a profundidade, a proximidade á costa e á desembocadura dos ríos, a temperatura da superficie do mar e a concentración de clorofila-a) na probabilidade prevista de distribución. Ao aproveitar os datos de observación da Terra dispoñibles a nivel mundial dentro do arquipélago Kien Giang-Kep IMMA, esta investigación ten como obxectivo informar a xestión espacial de áreas de alto conflito entre pequenos cetáceos e actividades humanas, en particular a pesca Ilegal, non Declarada e non Regulada (INDNR). Como este é o primeiro estudo de modelización do hábitat dos golfinhos de Irrawaddy ao longo da rexión fronteiriza camboyano-vietnamita, o coñecemento adquirido apoiará o deseño de medidas de conservación transfronteirizas e aumentará a comprensión da selección do hábitat dos golfinhos a unha escala máis ampla.

Finalmente, mediante a análise da política rexional, reúno o marco de xestión e as estratexias dispoñibles para controlar e mitigar a captura incidental de pequenos cetáceos na UE e as pesqueiras dos Estados Unidos (**Capítulo 4**). Este capítulo compara, tanto a nivel rexional

como local, como o compromiso comunitario e a investigación que implica directamente aos pescadores permite o acceso a coñecementos expertos e apoia o deseño e implementación de seguimento de captura incidental (por exemplo, observadores no mar, enquisas de abundancia), avaliación e mitigación. Usando tres casos prácticos con frota pesqueira transfronteirizas e altas taxas de captura incidental de cetáceos na UE e Estados Unidos, analizo o funcionamento dos instrumentos legais actuais con respecto aos ingredientes recoñecidos a nivel mundial para reducir de forma eficaz os niveis insostibles de captura incidental. Os ingredientes, *sensu* Lewison et al. (2011), inclúen a participación da comunidade, unha sólida recollida de datos e análises e unha sólida estrutura de goberno. Para cada caso, os golfinhos comúns (*Delphinus delphis*) no Golfo de Biscaia e as marsopas (*Phocoena phocoena*) do Báltico e do Golfo de Maine dos Estados Unidos analizo os factores habilitantes e limitantes para a xestión da captura incidental de pequenos cetáceos.

Contribución da tese de doutoramento

A principal contribución desta tese é mellorar a comprensión das múltiples dimensións que inflúen na captura incidental de mamíferos mariños. Existen patróns espazo-temporais na ocorrencia de captura incidental que se poden identificar, incluso en SSF con datos limitados. A ferramenta ByRA combina coñecementos expertos locais con análises baseadas en mapas para indicar áreas de solapamento entre artes de pesca de alto impacto e especies de mamíferos mariños. En particular, a capacidade de caracterizar e contabilizar a incerteza dos datos dentro da ferramenta permite aos xestores orientarse a áreas e especies específicas que necesitan un seguimento e desenvolver plans de acción claros que poidan mellorar a calidade da información ao longo do tempo. Realiza unha avaliación rápida desde a escala rexional ata a escala do caso de estudio e pódese adaptar a novas xeografía e especies mediante discusións con expertos locais, persoal das axencias, representantes da industria e científicos. Os resultados poden ser corroborados e comunicados ás partes interesadas das pesqueiras con datos limitados. A través deste proceso, os investigadores poden facilitar un compromiso público sólido para obter coñecemento das partes interesadas, axudar aos líderes políticos a comprender a situación e axudar aos xestores a adoptar novas medidas para controlar a captura incidental. Os resultados dos tres capítulos suxiren onde se reorientan mellor os esforzos de vixilancia da captura incidental para reducir o risco e orientar a investigación e a formación no uso de tecnoloxías

emerxentes que rastrexan os movementos das pesqueiras e das especies de mamíferos mariños ameazadas.

Recomendacións de xestión e política

Esta tese ofrece dúas recomendacións para prácticas e políticas de conservación de mamíferos mariños. Unha delas é que un proceso de compromiso científico-política é a miúdo o eslabón que falta para avanzar na implementación de políticas para a xestión da captura incidental da pesca. Especificamente para as pesqueiras con datos limitados, é necesaria a investigación dirixida pola comunidade que involucre pescadores e outras partes interesadas para acceder ao coñecemento non aproveitado e apoiar o deseño e implementación de estratexias apoiadas localmente para controlar e mitigar as capturas incidentais. Este tipo de compromiso implica reunións cara a cara para co-desenvolver métodos de avaliación, cubrir de forma iterativa as lagoas de coñecemento e impulsar o apoio para unha acción de xestión máis concreta. Por exemplo, os métodos de participación comunitaria desta investigación revelaron patróns previamente descoñecidos na aparición de capturas incidentais no sueste asiático. Tamén confirmaron a necesidade de ampliar a vixilancia a novas zonas nas que operan a pesca de alto impacto e outras actividades humanas.

En segundo lugar, sempre que a incerteza se caracterice e teña en conta con precisión, incluso a información de baixa resolución pode ser útil na investigación sobre a conservación dos mamíferos mariños. Hai unha clara necesidade de enfoques analíticos que garantan que a recollida de datos en situacións de escaseza de datos non se converta nun obstáculo para a investigación. Específicos para a xestión da captura incidental, pódense aplicar métodos que aproveitan a información existente sobre as distribucións dos animais, o esforzo pesqueiro e as taxas de interacción para caracterizar o risco de captura incidental e as incertezas dos datos asociados. Ao identificar as áreas de preocupación polas capturas incidentais e contabilizar a incerteza, os xestores poden tomar medidas inmediatas independentemente das limitacións de capacidade científica. Isto permite aos xestores adoptar tecnoloxías axeitadas para rastrexar os movementos de pesqueiras e mamíferos mariños con datos limitados e, sobre todo, adoptalos en lugares que serán informativos para a xestión.

A participación de grupos multisectoriais de partes interesadas nos procesos de xestión da biodiversidade é fundamental para o éxito da conservación. Non se pode esaxerar esta mensaxe sobre a importancia do compromiso comunitario. Os esforzos para promover un entendemento

compartido entre xestores mariños, científicos, pescadores e outras partes interesadas relevantes representan un enfoque de investigación de baixo custo, transparente e manexable para aumentar o coñecemento sobre problemas e solucións de captura incidental. Os obradoiros organizados no contexto desta tese demostran o valor de tal enfoque. Ao crear un ambiente para que os membros da comunidade comprendan o propósito da investigación científica e compartan os seus coñecementos, os participantes poderían presentar os seus propios valores, ideas e preocupacións de forma mais aberta. O uso de procesos participativos similares para xestionar as pesqueiras con dados limitados, onde os grupos marxinados están mellor representados, pode dar lugar a solucións de captura incidental que protexan a biodiversidade mariña e manteñan os medios de vida dos pescadores.

Palabras chave: mamíferos mariños; interaccións pesqueiras-especies; Sistema de Información Xeográfica; distribución de especies, Maxent, conservación da biodiversidade, xestión pesqueira; incerteza dos datos

Bibliografía

- Alfaro-Shigueto, J., Mangel, J. C., Pajuelo, M., Dutton, P. H., Seminoff, J. A., & Godley, B. J. (2010). Where small can have a large impact: structure and characterization of small-scale fisheries in Peru. *Fisheries Research*, 106(1), 8-17.
- Balint, P. J., Stewart, R. E., Desai, A., & Walters, L. C. (2011). *Wicked environmental problems: managing uncertainty and conflict*. Island Press.
- Barham, E. G., Taguchi, W., & Reilly, S. (1977). Porpoise rescue methods in the yellowfin purse seine fishery and the importance of Medina panel mesh size. *Marine Fisheries Review*, 39(5), 1-10.
- Berkes, F., Mahon, R., McConney, P., Pollnac, R., & Pomeroy, R. (2001). Managing small-scale fisheries. *Information management*, 92, 4-7.
- Bellido, J. M., Santos, M. B., Pennino, M. G., Valeiras, X., & Pierce, G. J. (2011). Fishery discards and bycatch: solutions for an ecosystem approach to fisheries management?. *Hydrobiologia*, 670(1), 317-333.
- Briscoe, D. K., Hiatt, S., Lewison, R., & Hines, E. (2014). Modeling habitat and bycatch risk for dugongs in Sabah, Malaysia. *Endangered Species Research*, 24(3), 237-247.
- Carlén, I., Thomas, L., Carlström, J., Amundin, M., Teilmann, J., Tregenza, N., et al. (2018). Basin-scale distribution of harbour porpoises in the Baltic Sea provides basis for effective conservation actions. *Biological Conservation*, 226, 42-53.
- Carlén, I., Nunny, L., & Simmonds, M. P. (2021). Out of sight, out of mind: how conservation is failing European porpoises. *Frontiers in Marine Science*, 8, 13.
- Chuenpagdee, R., Rocklin, D., Bishop, D., Hynes, M., Greene, R., Lorenzi, M. R., & Devillers, R. (2019). The global information system on small-scale fisheries (ISSF): a crowdsourced knowledge platform. *Marine Policy*, 101, 158-166.
- Coe, J. M. (1984). *Guidelines for reducing porpoise mortality in tuna purse seining (Vol. 13)*. National Oceanic and Atmospheric Administration, National Marine Fisheries Service.
- Costanza, A. B., Guidino, C., Mangel, J. C., Alfaro-Shigueto, J., Verutes, G., Caillat, M., et al. (2021). Participatory Risk Assessment of Humpback Whale (*Megaptera novaeangliae*) and Leatherback

- Turtle (*Dermochelys coriacea*) Bycatch in Northern Peru. *Frontiers in Marine Science*.
- Dolman, S. J., Evans, P. G. H., Ritter, F., Simmonds, M. P., & Swabe, J. (2021). Implications of new technical measures regulation for cetacean bycatch in European waters. *Marine Policy*, 124, 104320.
- FAO. (2021). *FAO Yearbook. Fishery and Aquaculture Statistics 2019*, Rome. Available at: <https://doi.org/10.4060/cb7874t>
- Grech, A., & Marsh, H. (2007). Prioritising areas for dugong conservation in a marine protected area using a spatially explicit population model. *Applied GIS*, 3, 1-14.
- Gregr, E. J., Baumgartner, M. F., Laidre, K. L., & Palacios, D. M. (2013). Marine mammal habitat models come of age: the emergence of ecological and management relevance. *Endangered Species Research*, 22(3), 205-212.
- Hammond, P. S., Lacey, C., Gilles, A., Viquerat, S., Boerjesson, P., Herr, H., et al. (2017). Estimates of cetacean abundance in European Atlantic waters in summer 2016 from the SCANS-III aerial and shipboard surveys. *Wageningen Marine Research*.
- Halpern, B. S., Frazier, M., Potapenko, J., Casey, K. S., Koenig, K., et al. (2015). Spatial and temporal changes in cumulative human impacts on the world's ocean. *Nature communications*, 6(1), 1-7.
- Hazen, E. L., Jorgensen, S., Rykaczewski, R. R., Bograd, S. J., Foley, D. G., et al. (2013). Predicted habitat shifts of Pacific top predators in a changing climate. *Nat. Clim. Change* 3, 234–238.
- Hines, E., Ponnampalam, L. S., Junchompoo, C., Peter, C., Vu, L., Huynh, T., et al. (2020). Getting to the bottom of bycatch: a GIS-based toolbox to assess the risk of marine mammal bycatch. *Endangered Species Research*, 42, 37-57.
- ICES. (2020). EU Request on Emergency Measures to Prevent bycatch of Common Dolphin (*Delphinus delphis*) and Baltic Proper Harbour Porpoise (*Phocoena phocoena*) in the Northeast Atlantic. ICES Special Request Advice, 2020, Available online at: https://www.ices.dk/sites/pub/Publication%20Reports/Advice/2020/Special_Requests/eu.2020.04.pdf
- Joseph, J. (1994). The tuna-dolphin controversy in the eastern Pacific Ocean: Biological, economic, and political impacts. *Ocean Development & International Law*, 25(1), 1-30.
- Johnson, A. F., Moreno-Báez, M., Giron-Nava, A., Corominas, J., Erisman, B., Ezcurra, E., & Aburto-Oropeza, O. (2017). A spatial method to calculate small-scale fisheries effort in data poor scenarios. *PLoS One*, 12(4), e0174064.
- Lewison, R. L., Soykan, C. U., Cox, T., Peckham, H., Pilcher, N., LeBoeuf, N., et al. (2011). Ingredients for addressing the challenges of fisheries bycatch. *Bulletin of Marine Science*, 87(2), 235-250.
- Lewison, R. L., Johnson, A. F., & Verutes, G. M. (2018). Embracing complexity and complexity-awareness in marine megafauna conservation and research. *Frontiers in Marine Science*, 5, 207.
- Macher, C., Bertignac, M., Guyader, O., Frangoudes, K., Frésard, M., Le Grand, C., et al. (2018). The role of technical protocols and partnership engagement in developing a decision support framework for fisheries management. *Journal of environmental management*, 223, 503-516.
- McDonald, S. L., Lewison, R. L., & Read, A. J. (2016). Evaluating the efficacy of environmental legislation: A case study from the US marine mammal Take Reduction Planning process. *Global Ecology and Conservation*, 5, 1-11.
- Moore, J. E., Cox, T. M., Lewison, R. L., Read, A. J., Bjorkland, R., McDonald, S. L., et al. (2010). An interview-based approach to assess marine mammal and sea turtle captures in artisanal fisheries. *Biological Conservation*, 143(3), 795-805.
- National Research Council (NRDC). (1992). *Dolphins and the tuna industry*. National Academies Press.
- Pauly, D., & Zeller, D. (2016). Catch reconstructions reveal that global marine fisheries catches are higher than reported and declining. *Nature communications*, 7(1), 1-9.
- Peltier, H., Authier, M., Dabin, W., Dars, C., Demaret, F., Doremus, G., et al. (2020). Can modelling the drift of bycaught dolphin stranded carcasses help identify involved fisheries? An exploratory study. *Global Ecology and Conservation*, 21, e00843.
- Perrin, W. F., Donovan, G. P., & Barlow, J. (1994). *Gillnets and cetaceans*. International Whaling Commission.
- Phillips, S. J., Anderson, R. P., & Schapire, R. E. (2006). Maximum entropy modeling of species

- geographic distributions. *Ecological modelling*, 190(3-4), 231-259.
- Pilcher, N. J., Adulyanukosol, K., Das, H., Davis, P., Hines, E., Kwan, D., et al. (2017). A low-cost solution for documenting distribution and abundance of endangered marine fauna and impacts from fisheries. *PLoS one*, 12(12), e0190021.
- Read, F. L. (2021). *Cost-benefit Analysis for Mitigation Measures in Fisheries with High Bycatch*. ASCOBANS Technical Series No. 2. ASCOBANS Secretariat, Bonn, Germany.
- Redfern, J. V., Ferguson, M. C., Becker, E. A., Hyrenbach, K. D., Good, C., et al. (2006). Techniques for cetacean–habitat modeling. *Marine Ecology Progress Series*, 310, 271-295.
- Reeves, R. R., McClellan, K., & Werner, T. B. (2013). Marine mammal bycatch in gillnet and other entangling net fisheries, 1990 to 2011. *Endangered Species Research*, 20(1), 71-97.
- Rogan, E., Read, A. J., & Berggren, P. (2021). Empty promises: The European Union is failing to protect dolphins and porpoises from fisheries by-catch. *Fish and Fisheries*, 22(4), 865-869.
- SAMBAH. (2016). Final report for LIFE+ project SAMBAH LIFE08 NAT/S/000261 covering the project activities from 01/01/2010 to 30/09/2015. Reporting date 29/02/2016. Available at: <http://www.sambah.org/Nysida-11.htm>
- Shester, G. G., & Micheli, F. (2011). Conservation challenges for small-scale fisheries: Bycatch and habitat impacts of traps and gillnets. *Biological Conservation*, 144(5), 1673-1681.
- Soykan, C. U., Moore, J. E., Zydalis, R., Crowder, L. B., Safina, C., & Lewison, R. L. (2008). Why study bycatch? An introduction to the Theme Section on fisheries bycatch. *Endangered Species Research*, 5(2-3), 91-102.v
- Stewart, K. R., Lewison, R. L., Dunn, D. C., Bjorkland, R. H., Kelez, S., Halpin, P. N., & Crowder, L. B. (2010). Characterizing fishing effort and spatial extent of coastal fisheries. *PLoS one*, 5(12), e14451.
- Teh, L. S., Teh, L. C., Hines, E., Junchompoo, C., & Lewison, R. L. (2015). Contextualising the coupled socio-ecological conditions of marine megafauna bycatch. *Ocean & Coastal Management*, 116, 449-465.
- Trimble, M., & Berkes, F. (2013). Participatory research towards co-management: lessons from artisanal fisheries in coastal Uruguay. *Journal of environmental management*, 128, 768-778.
- Verutes, G. M., & Rosenthal, A. (2014). Using simulation games to teach ecosystem service synergies and trade-offs. *Environmental Practice*, 16(3), 194-204.
- Wade, P. R., Long, K. J., Francis, T. B., Punt, A. E., Hammond, P. S., Heinemann, D., et al. (2021). Best Practices for Assessing and Managing Bycatch of Marine Mammals. *Frontiers in Marine Science*.
- World Wild Fund for Nature (WWF). (2009). Factsheet on Bycatch. Available at: https://wwfint.awsassets.panda.org/downloads/bycatch_factsheet.pdf

Summary (English)

Is it possible to design and apply an assessment framework for evaluating harmful interactions between marine mammals and fisheries using existing information only? This is the main question I attempt to answer in this thesis. More broadly, I investigate the ways in which international policies have, or have not, translated into effective management strategies for monitoring and mitigating marine mammal bycatch in data-limited fisheries.

Bycatch, the incidental capture of non-target species in active fishing gear, has been recognized as a threat to marine megafauna for decades (Coe et al., 1984; NRDC, 1992; Perrin et al., 1994). It is a topic that deserves to be understood in-depth, as incidental capture and removal by fisheries is one of the most significant human threats to marine mammals (Reeves et al., 2013). In the 1960s, approximately 350,000 dolphins were killed annually in the Eastern Tropical Pacific purse seine tuna fishery (Joseph, 1994). The introduction of several innovations, such as a small-mesh safety “Medina panel” and a backdown procedure to release entangled dolphins from fishing nets, together with the passage of the U.S. Marine Mammal Protection Act (MMPA) in 1974 has effectively reduced bycatch (Barham et al., 1977). Despite progress to address a complex international issue in particular fisheries, a recent estimate of marine mammal bycatch suggests more than 300,000 animals are killed by global fisheries each year (WWF, 2009). Today, we evaluate the effects of bycatch using data of limited quantity and quality and slow response time post-capture. A poor understanding of fisheries impacts on local marine mammal populations can lead to misguided management.

Small-scale fisheries (SSF) are critical to local economies and livelihoods (FAO, 2021), yet their activities are poorly monitored and regulated globally (Pauly and Zeller, 2016). The large spatial extent of SSF and relatively low abundance of certain marine mammal populations impede the ability of scientists and conservation organizations to rapidly evaluate risk and identify priority areas for wildlife conservation and management. A cohesive assessment tool is needed to isolate key drivers of bycatch risk (e.g., species-fishery interactions in space and time) and pinpoint areas and seasons of greatest concern, while also identifying opportunities for research, education, and data improvement. Before moving on to the specific research questions I

pose in this thesis, I put the research topics covered in context.

Theoretical Approach

Given the mounting pressures on marine resources from a variety of intensifying human activities in today's ocean economy (Halpern et al., 2015), marine megafauna conservation often relies on geospatial (location-based) information and stakeholder knowledge to protect biological diversity. Efforts to manage threatened, vulnerable, and endangered species – including the 25% of marine mammals classified as such by the IUCN Red List (Nelms et al., 2021) – could be enhanced with specialized expertise to conduct geospatial analyses, stakeholder engagement, and establish more systematic approaches for data collection and assessment (Hines et al., 2020; Wade et al., 2021). This thesis was inspired by the theoretical work introduced by Lewison et al. (2018), which posits that we must first acknowledge, and then account for, the inherent complexity of coupled socio-ecological systems to capture stakeholder values and access the necessary data and tools for advancing marine megafauna conservation research.

EMBRACING COMPLEXITY IN MARINE MAMMAL CONSERVATION RESEARCH

Complex systems approaches (CSA) are a combination of conceptual, analytical, and computational techniques that can be applied to “wicked” environmental problems, such as fisheries bycatch (Lewison et al., 2018). These wicked problems typically lack a single solution and have a high degree of scientific uncertainty (Balint et al., 2011). As a research methodology, CSA are often data-intensive and difficult to implement in data-limited environments. When working in developing countries or at the community level, data on marine species and fisheries are often inaccessible, low quality, or dispersed among multiple sources. Even in places where population estimates are available, such as the United States and European Union, gaps in data on fishing effort and encounter rates limit the ability to quantify the risk of fisheries bycatch on resident marine mammals and other sensitive megafauna species (Soykan et al., 2008; Bellido et al., 2011). Complexity-aware techniques are needed to better characterize risks to wildlife and identify opportunities to reduce bycatch because they acknowledge non-linear, unpredictable factors that influence changes in the marine environment (Hazen et al., 2013) and the dynamic relationship between human and ecological systems (Lewison et al., 2018).

Spatially explicit data offer a valuable source of information for marine mammal conservation research and managing bycatch. The probability of a bycatch event relates to changes in species-fishery overlap and the specific conditions under which animals are encountered. Knowledge of the spatial distribution of marine species is crucial when designing protected areas and implementing management actions (e.g., Grech and Marsh, 2007; Carlen et al., 2018). For this purpose, species distribution models (SDMs) are an increasingly popular tool to identify critical habitat and geographic distribution (Redfern et al., 2006; Gegr et al., 2013). Some SDMs, such as the maximum entropy methods (Maxent; Phillips et al., 2006), are particularly suited to handle situations with presence-only species data. By leveraging available animal sightings, earth observation data, and local expert knowledge, SDMs examine potential impacts to species under changing environmental conditions. They help to contextualize key habitat associations based on known ecological parameters, and can be used to support both near and long-term conservation planning and adaptive management.

There are also low-cost techniques available to characterize the location and level of effort in SSF (e.g., Stewart et al., 2010; Johnson et al. 2017) and document the distribution of threatened marine mammals and fishery-specific impacts (e.g., Pilcher et al., 2017). Measuring the overlap of SSF activities and suitable marine mammal habitats identified by SDMs can serve as a starting point for spatially characterizing bycatch risk in data-limited situations (Wade et al., 2021). For example, Briscoe et al. (2014) relied solely on published sightings data and geophysical parameters, such as distance to the shore and water depth, to build an SDM for dugongs (*Dugong dugon*) and estimate the probability of species presence in previously unsurveyed locations. Building on this approach in data-limited fisheries of Southeast Asia and Latin America, marine mammal researchers pinpointed areas and seasons of highest bycatch risk by tapping into local expert knowledge about SSF distribution and gear-type density (Hines et al., 2020; Costanza et al., 2021).

FISHERIES BYCATCH: THE HUMAN DIMENSION

The involvement of industry, government, scientific institutions, and other relevant stakeholders in fisheries management processes is essential for conservation success (Berkes et al., 2001; Macher et al., 2018). Research suggests that participatory approaches to facilitate multisectoral collaboration are more likely to encourage problem-solving, co-create knowledge, and build

community trust (Trimble and Berkes, 2013; Verutes and Rosenthal, 2014). The value of stakeholder involvement is an often-repeated message, and difficult to achieve even in the legally mandated Take Reduction Planning of the U.S. MMPA (McDonald et al., 2016). For managing bycatch, engaging local knowledge holders has the potential to identify strategies for balancing the benefits of bycatch risk reduction against the costs of altered fishing activity to fishers' livelihoods (Lewison et al., 2011; Read, 2021). Open communication and a mutual understanding between fishers, managers, and scientists has enormous potential to yield positive outcomes with conservation initiatives.

Fisheries policy directed towards the conservation of biodiversity has a strong human component, as it affects communities that depend directly or indirectly on the areas to be protected. The ability of managers to effectively balance multiple, often competing, objectives rely on an understanding of the perceptions, needs, and values those different stakeholders have about these policies; that is, how people affect and are affected by, a particular intervention. The goal is a just and equitable distribution of costs and benefits in those trade-offs, that contributes to more balanced outcomes for people and nature. The lack of assessment frameworks that consider the aforementioned complexities – in particular, spatiotemporal context dependencies and conflicts between biodiversity conservation and fisheries objectives – has hindered the development and implementation of bycatch management strategies in data-limited fisheries.

Objectives and Research Questions

How can we move forward in addressing this wicked problem of marine mammal bycatch by connecting with a community of stakeholders and realizing a shared vision for reducing its occurrence while sustaining fisheries productivity? This thesis aims to advance bycatch research and management in data-limited contexts with the mantra: *we must better use existing data*.

The limited availability of data to characterize the spatio-temporal distribution of threatened species interacting with problematic fisheries has slowed progress in many regions of the world such as Latin America, Africa, and Southeast Asia (Alfaro-Shigueto et al., 2010; Moore et al., 2010; Teh et al. 2013). In addition, there has been limited action in the European Union (E.U.) to address extremely high levels of bycatch-induced mortality or the threat of extinction to certain marine mammal species (Peltier et al., 2020, Carlén et al., 2021). Despite the availability of regular monitoring programs, research methods, and scientific advice to act in

the E.U. (e.g., SAMBAH et al., 2016; Hammond et al., 2017; ICES, 2020), this does not guarantee that the management strategies identified to mitigate marine mammal bycatch will be effectively implemented and enforced (Dolman et al., 2021; Rogan et al., 2021). Further, and often juxtaposed to these limiting conditions of data scarcity and a stalled policy implementation process, is the age-old comment, “maybe we should go back and collect more information.” The approach and tools developed here are designed to counter this narrative.

Broadly speaking, fisheries are data rich. There are myriad organizations, initiatives, and tools designed to monitor global fleets, track statistics, and analyze fishing activities (e.g., Food and Agriculture Organization (FAO), Sea Around Us, Global Fishing Watch). Data on SSF and localized impacts of fisheries bycatch on marine mammal populations and habitats are arguably scarcer (Soykan et al., 2008; Shester and Micheli, 2011; Chuenpagdee et al., 2019). While for some stakeholders there can never be enough data to justify participation in management processes, data-poor situations offer no excuses for inaction. We need to analyze the information we have while problems are happening; otherwise, science and management activities will continue to lag. This stance does not imply that findings from an initial inventory of problematic fisheries or bycatch assessment represent the final answer for a given location. By integrating existing data and local expert knowledge, new forms of community involvement and quantitative analyses are possible. Ultimately, the suggested approach can put managers on a path towards complexity-aware research and targeted monitoring to address unsustainable bycatch rates.

I propose the following research questions to understand and interrogate the multilayered influences on marine mammal bycatch in data-limited fisheries, from policy to management:

1. Can we design a management tool that accesses existing knowledge to assess seasonal scenarios of marine mammal bycatch, and visualize the associated risks and data uncertainties? (**Chapter 2**);
2. Are we able to use high-resolution, globally available earth observation data such as sea surface temperature and chlorophyll-a concentration to construct accurate models that describe the ecological processes governing Irrawaddy dolphin habitat selection and predict the seasonal distribution of the species? (**Chapter 3**);
3. Which scientific, socio-political, and economic obstacles have limited the implementation of measures to monitor and mitigate unsustainable rates of small cetacean bycatch in the European Union and United States? (**Chapter 4**)

Thesis Structure

This thesis includes three results sections. First, I introduce the Bycatch Risk Assessment (ByRA) fisheries management tool (**Chapter 2**) as an analytical framework for coastal nations around the world where overfishing and habitat destruction are increasingly serious problems. ByRA documents emerging patterns of interaction between high-risk fishing gears and vulnerable marine mammal species in data-limited situations. Using two species of marine mammals in Malaysia and Vietnam as a test case, ByRA leverages (1) existing field surveys, (2) participatory engagement involving a wide range of stakeholders, and (3) geospatial analysis to provide structured spatially explicit information on risks and vulnerabilities, while accounting for data uncertainty. Map and summary table outputs identify previously unknown overlaps between high-impact fishing activities and suitable marine mammal habitat in three field sites of Southeast Asia. These findings provide a detailed picture of existing and new knowledge about data-limited SSF and can guide future research and action plans for marine mammal species recovery and protection in the region.

Next, an Irrawaddy dolphin distribution paper paints a picture of what is at stake inside a newly designated Important Marine Mammal Area (IMMA) along the active Vietnam-Cambodia maritime border if fishing activities continue to decimate megafauna populations and their habitats (**Chapter 3**). This chapter sets three goals for improving baseline knowledge of a coastal Irrawaddy dolphin (*Orcaella brevirostris*) population inhabiting the waters of the Kep Archipelago, Cambodia: (1) to characterize their spatial distribution; (2) to map variation in seasonal occurrences and habitat preferences; and (3) to estimate the population's ecological niche based on the influence of oceanographic variables (i.e., depth, proximity to shore and river mouths, sea surface temperature, and chlorophyll-a concentration) on predicted probability of distribution. By leveraging globally available earth observation data inside the Kien Giang-Kep Archipelago IMMA, this research aims to inform the spatial management of high conflict areas between small cetaceans and human activities, particularly Illegal, Unreported, and Unregulated (IUU) fishing. As this is the first Irrawaddy dolphin habitat modeling study along the Cambodian-Vietnamese border region, knowledge gained will support the design of transboundary conservation measures and augment the understanding of dolphin habitat selection on a wider scale.

Finally, through regional policy analysis, I bring together the management framework

and available strategies to monitor and mitigate small cetacean bycatch in E.U. and U.S. fisheries (**Chapter 4**). This chapter compares at both the regional and local levels how community-based engagement and research that directly involves fishers enables access to expert knowledge and supports the design and implementation of bycatch monitoring (e.g., at-sea observers, abundance surveys), assessment, and mitigation. Using three case studies with transboundary fishing fleets and high rates of cetacean bycatch in the E.U. and U.S., I analyze how current legal instruments are performing with respect to globally recognized ingredients to effectively reduce unsustainable levels of bycatch. The ingredients, *sensu* Lewison et al., 2011, include community involvement, robust data collection and analyses, and a solid structure of governance. For each case, common dolphins (*Delphinus delphis*) in the Bay of Biscay and harbor porpoises (*Phocoena phocoena*) of the Baltic Proper and U.S. Gulf of Maine, regulations were reviewed alongside existing information about fishing methods and areas and seasons of greatest concern to identify enabling and limiting factors for the management of small cetacean bycatch.

Thesis Contribution

The main contribution of this thesis is to augment understanding of the multiple dimensions that influence marine mammal bycatch. There are spatio-temporal patterns in bycatch occurrence that can be identified, even in data-limited SSF. The ByRA tool combines local expert knowledge with map-based analyses to indicate areas of overlap between high-impact fishing gears and marine mammal species. Notably, the ability to characterize and account for data uncertainty within the tool enables managers to target specific areas and species in need of monitoring and develop clear action plans that can improve the quality of information over time. It performs rapid assessment from the regional to the site scale and can be tailored to new geographies and taxa through discussions with local experts, agency personnel, industry representatives, and scientists. Outputs can be corroborated by and communicated to stakeholders of data-limited fisheries. Through this process, researchers can facilitate robust public engagement to elicit stakeholder knowledge, help political leaders understand the situation, and assist managers in adopting new measures to monitor bycatch. Findings from all three chapters suggest where bycatch monitoring efforts is best refocused to reduce risk and guide research and training in the use of emergent technologies that track the movements of fisheries and threatened marine mammal species.

Recommendations for Management and Policy

This thesis offers two recommendations for marine mammal conservation practices and policies. One is that a science-policy engagement process is often the missing link to advance policy implementation for fisheries bycatch management. Specific to data-limited fisheries, community-driven research involving fishers and other stakeholders is needed to access untapped knowledge and support the design and implementation of locally supported strategies to monitor and mitigate bycatch. This type of engagement involves face-to-face meetings to co-develop assessment methods, iteratively fill knowledge gaps, and galvanize support for more concrete management action. For example, this research's community involvement methods revealed previously unknown patterns in bycatch occurrence in Southeast Asia. They also confirmed the need to expand monitoring to new areas where high-impact fisheries and other human activities operate.

Second, if uncertainty is accurately characterized and accounted for, even low-resolution information can be helpful in marine mammal conservation research. There is a clear need for analytical approaches that ensure data collection in data-scarce situations does not become an obstacle to research. Specific to bycatch management, methods that leverage existing information on animal distributions, fisheries effort, and interaction rates can be applied to characterize bycatch risk and associated data uncertainties. By identifying areas of bycatch concern and accounting for uncertainty, managers can take immediate action regardless of scientific capacity constraints. This enables managers to adopt appropriate technologies for tracking the movements of data-limited fisheries and marine mammals and, importantly, to deploy them in locations that will be informative for management.

The participation of multisectoral stakeholder groups in biodiversity management processes is crucial to conservation success. This message about the importance of community engagement cannot be overstated. Efforts to promote a shared understanding between marine managers, scientists, fishers, and other relevant stakeholders represent a low-cost, transparent, and tractable research approach to augment knowledge about bycatch problems and solutions. The workshops organized in the context of this thesis demonstrate the value of such an approach. By creating an environment for community members to understand the purpose of scientific research and share their knowledge, participants could present their own values, insights, and

concerns more openly. The use of similar participatory processes to manage data-limited fisheries — where marginalized groups are better represented — can lead to bycatch solutions that protect marine biodiversity and maintain fisher livelihoods.

Keywords: marine mammals; fishery-species interactions; Geographic Information System; species distribution, Maxent, biodiversity conservation, fisheries management; data uncertainty

Bibliography

- Alfaro-Shigueto, J., Mangel, J. C., Pajuelo, M., Dutton, P. H., Seminoff, J. A., & Godley, B. J. (2010). Where small can have a large impact: structure and characterization of small-scale fisheries in Peru. *Fisheries Research*, 106(1), 8-17.
- Balint, P. J., Stewart, R. E., Desai, A., & Walters, L. C. (2011). *Wicked environmental problems: managing uncertainty and conflict*. Island Press.
- Barham, E. G., Taguchi, W., & Reilly, S. (1977). Porpoise rescue methods in the yellowfin purse seine fishery and the importance of Medina panel mesh size. *Marine Fisheries Review*, 39(5), 1-10.
- Berkes, F., Mahon, R., McConney, P., Pollnac, R., & Pomeroy, R. (2001). Managing small-scale fisheries. *Information management*, 92, 4-7.
- Bellido, J. M., Santos, M. B., Pennino, M. G., Valeiras, X., & Pierce, G. J. (2011). Fishery discards and bycatch: solutions for an ecosystem approach to fisheries management?. *Hydrobiologia*, 670(1), 317-333.
- Briscoe, D. K., Hiatt, S., Lewison, R., & Hines, E. (2014). Modeling habitat and bycatch risk for dugongs in Sabah, Malaysia. *Endangered Species Research*, 24(3), 237-247.
- Carlén, I., Thomas, L., Carlström, J., Amundin, M., Teilmann, J., Tregenza, N., et al. (2018). Basin-scale distribution of harbour porpoises in the Baltic Sea provides basis for effective conservation actions. *Biological Conservation*, 226, 42-53.
- Carlén, I., Nunny, L., & Simmonds, M. P. (2021). Out of sight, out of mind: how conservation is failing European porpoises. *Frontiers in Marine Science*, 8, 13.
- Chuenpagdee, R., Rocklin, D., Bishop, D., Hynes, M., Greene, R., Lorenzi, M. R., & Devillers, R. (2019). The global information system on small-scale fisheries (ISSF): a crowdsourced knowledge platform. *Marine Policy*, 101, 158-166.
- Coe, J. M. (1984). *Guidelines for reducing porpoise mortality in tuna purse seining (Vol. 13)*. National Oceanic and Atmospheric Administration, National Marine Fisheries Service.
- Costanza, A. B., Guidino, C., Mangel, J. C., Alfaro-Shigueto, J., Verutes, G., Caillat, M., et al. (2021). Participatory Risk Assessment of Humpback Whale (*Megaptera novaeangliae*) and Leatherback Turtle (*Dermochelys coriacea*) Bycatch in Northern Peru. *Frontiers in Marine Science*.
- Dolman, S. J., Evans, P. G. H., Ritter, F., Simmonds, M. P., & Swabe, J. (2021). Implications of new technical measures regulation for cetacean bycatch in European waters. *Marine Policy*, 124, 104320.
- FAO. (2021). *FAO Yearbook. Fishery and Aquaculture Statistics 2019*, Rome. Available at: <https://doi.org/10.4060/cb7874t>
- Grech, A., & Marsh, H. (2007). Prioritising areas for dugong conservation in a marine protected area using a spatially explicit population model. *Applied GIS*, 3, 1-14.
- Gregr, E. J., Baumgartner, M. F., Laidre, K. L., & Palacios, D. M. (2013). Marine mammal habitat models come of age: the emergence of ecological and management relevance. *Endangered Species Research*, 22(3), 205-212.
- Hammond, P. S., Lacey, C., Gilles, A., Viquerat, S., Boerjesson, P., Herr, H., et al. (2017). Estimates of cetacean abundance in European Atlantic waters in summer 2016 from the SCANS-III aerial and

Summary

- shipboard surveys. Wageningen Marine Research.
- Halpern, B. S., Frazier, M., Potapenko, J., Casey, K. S., Koenig, K., et al. (2015). Spatial and temporal changes in cumulative human impacts on the world's ocean. *Nature communications*, 6(1), 1-7.
- Hazen, E. L., Jorgensen, S., Rykaczewski, R. R., Bograd, S. J., Foley, D. G., et al. (2013). Predicted habitat shifts of Pacific top predators in a changing climate. *Nat. Clim. Change* 3, 234–238.
- Hines, E., Ponnampalam, L. S., Junchompoo, C., Peter, C., Vu, L., Huynh, T., et al. (2020). Getting to the bottom of bycatch: a GIS-based toolbox to assess the risk of marine mammal bycatch. *Endangered Species Research*, 42, 37-57.
- ICES. (2020). EU Request on Emergency Measures to Prevent bycatch of Common Dolphin (*Delphinus delphis*) and Baltic Proper Harbour Porpoise (*Phocoena phocoena*) in the Northeast Atlantic. ICES Special Request Advice, 2020, Available online at: https://www.ices.dk/sites/pub/Publication%20Reports/Advice/2020/Special_Requests/eu.2020.04.pdf
- Joseph, J. (1994). The tuna-dolphin controversy in the eastern Pacific Ocean: Biological, economic, and political impacts. *Ocean Development & International Law*, 25(1), 1-30.
- Johnson, A. F., Moreno-Báez, M., Giron-Nava, A., Corominas, J., Erisman, B., Ezcurra, E., & Aburto-Oropeza, O. (2017). A spatial method to calculate small-scale fisheries effort in data poor scenarios. *PLoS One*, 12(4), e0174064.
- Lewison, R. L., Soykan, C. U., Cox, T., Peckham, H., Pilcher, N., LeBoeuf, N., et al. (2011). Ingredients for addressing the challenges of fisheries bycatch. *Bulletin of Marine Science*, 87(2), 235-250.
- Lewison, R. L., Johnson, A. F., & Verutes, G. M. (2018). Embracing complexity and complexity-awareness in marine megafauna conservation and research. *Frontiers in Marine Science*, 5, 207.
- Macher, C., Bertignac, M., Guyader, O., Frangoudes, K., Frésard, M., Le Grand, C., et al. (2018). The role of technical protocols and partnership engagement in developing a decision support framework for fisheries management. *Journal of environmental management*, 223, 503-516.
- McDonald, S. L., Lewison, R. L., & Read, A. J. (2016). Evaluating the efficacy of environmental legislation: A case study from the US marine mammal Take Reduction Planning process. *Global Ecology and Conservation*, 5, 1-11.
- Moore, J. E., Cox, T. M., Lewison, R. L., Read, A. J., Bjorkland, R., McDonald, S. L., et al. (2010). An interview-based approach to assess marine mammal and sea turtle captures in artisanal fisheries. *Biological Conservation*, 143(3), 795-805.
- National Research Council (NRDC). (1992). *Dolphins and the tuna industry*. National Academies Press.
- Pauly, D., & Zeller, D. (2016). Catch reconstructions reveal that global marine fisheries catches are higher than reported and declining. *Nature communications*, 7(1), 1-9.
- Peltier, H., Authier, M., Dabin, W., Dars, C., Demaret, F., Doremus, G., et al. (2020). Can modelling the drift of bycaught dolphin stranded carcasses help identify involved fisheries? An exploratory study. *Global Ecology and Conservation*, 21, e00843.
- Perrin, W. F., Donovan, G. P., & Barlow, J. (1994). *Gillnets and cetaceans*. International Whaling Commission.
- Phillips, S. J., Anderson, R. P., & Schapire, R. E. (2006). Maximum entropy modeling of species geographic distributions. *Ecological modelling*, 190(3-4), 231-259.
- Pilcher, N. J., Adulyanukosol, K., Das, H., Davis, P., Hines, E., Kwan, D., et al. (2017). A low-cost solution for documenting distribution and abundance of endangered marine fauna and impacts from fisheries. *PloS one*, 12(12), e0190021.
- Read, F. L. (2021). *Cost-benefit Analysis for Mitigation Measures in Fisheries with High Bycatch*. ASCOBANS Technical Series No. 2. ASCOBANS Secretariat, Bonn, Germany.
- Redfern, J. V., Ferguson, M. C., Becker, E. A., Hyrenbach, K. D., Good, C., et al. (2006). Techniques for cetacean-habitat modeling. *Marine Ecology Progress Series*, 310, 271-295.
- Reeves, R. R., McClellan, K., & Werner, T. B. (2013). Marine mammal bycatch in gillnet and other entangling net fisheries, 1990 to 2011. *Endangered Species Research*, 20(1), 71-97.
- Rogan, E., Read, A. J., & Berggren, P. (2021). Empty promises: The European Union is failing to protect dolphins and porpoises from fisheries by-catch. *Fish and Fisheries*, 22(4), 865-869.

- SAMBAH. (2016). Final report for LIFE+ project SAMBAH LIFE08 NAT/S/000261 covering the project activities from 01/01/2010 to 30/09/2015. Reporting date 29/02/2016. Available at: <http://www.sambah.org/Nysida-11.htm>
- Shester, G. G., & Micheli, F. (2011). Conservation challenges for small-scale fisheries: Bycatch and habitat impacts of traps and gillnets. *Biological Conservation*, 144(5), 1673-1681.
- Soykan, C. U., Moore, J. E., Zydalis, R., Crowder, L. B., Safina, C., & Lewison, R. L. (2008). Why study bycatch? An introduction to the Theme Section on fisheries bycatch. *Endangered Species Research*, 5(2-3), 91-102.v
- Stewart, K. R., Lewison, R. L., Dunn, D. C., Bjorkland, R. H., Kelez, S., Halpin, P. N., & Crowder, L. B. (2010). Characterizing fishing effort and spatial extent of coastal fisheries. *PloS one*, 5(12), e14451.
- Teh, L. S., Teh, L. C., Hines, E., Junchompoo, C., & Lewison, R. L. (2015). Contextualising the coupled socio-ecological conditions of marine megafauna bycatch. *Ocean & Coastal Management*, 116, 449-465.
- Trimble, M., & Berkes, F. (2013). Participatory research towards co-management: lessons from artisanal fisheries in coastal Uruguay. *Journal of environmental management*, 128, 768-778.
- Verutes, G. M., & Rosenthal, A. (2014). Using simulation games to teach ecosystem service synergies and trade-offs. *Environmental Practice*, 16(3), 194-204.
- Wade, P. R., Long, K. J., Francis, T. B., Punt, A. E., Hammond, P. S., Heinemann, D., et al. (2021). Best Practices for Assessing and Managing Bycatch of Marine Mammals. *Frontiers in Marine Science*.
- World Wild Fund for Nature (WWF). (2009). Factsheet on Bycatch. Available at: https://wwfint.awsassets.panda.org/downloads/bycatch_factsheet.pdf

Summary

Abstract

Bycatch, the incidental capture of non-target species in active fishing gear, is the most significant human threat to coastal marine mammals and a severe conservation problem. Some species face extinction from unsustainable rates of capture and removal by fisheries. Characterizing the effects of bycatch through space and time is similar to finding a needle in a haystack: relatively small populations and limited interactions with dispersed fishing vessels. The behaviors of both parties are unpredictable, and therefore a challenge for researchers to collect data and managers to effectively manage. Bycatch impacts to marine species are difficult to observe and quantify, particularly in small-scale fisheries (SSF) where data on fishing effort and marine mammal abundance and distribution are often limited. Further adding to the problem, a lack of risk frameworks that can integrate and visualize existing datasets has hindered the ability to describe and quantify bycatch risk. This is a knowledge gap worth exploring because ocean data and the systems developed to monitor marine ecosystems are now more sophisticated and cheaper to deploy.

The guiding question of this thesis is: how can we better leverage existing data to characterize the likelihood of bycatch and its consequences to marine mammal populations? When working in developing countries or at local scales these data are often inaccessible, of low quality, or dispersed among multiple sources. Therefore, I investigate how a participatory management tool that combines stakeholder engagement with geospatial analysis can be applied to characterize the distribution of fishing effort, marine mammal species, and their interaction rates (**Chapter 2**). I build temporally stratified models to estimate dolphin distribution and infer seasonal habitat importance (**Chapter 3**). Finally, I conduct three case studies with transboundary fishing fleets and high rates of cetacean bycatch to analyze how well current legal instruments to monitor and protect vulnerable species are performing in the United States and European Union (**Chapter 4**). Overall, I aim to increase data availability and quality in marine mammal conservation research through community involvement, stakeholder review, and revision that turns existing information into action.

I report three interrelated avenues of research in this thesis. First, I describe the design

and application of a new fisheries management tool built specifically to analyze bycatch in data-limited fisheries, the Bycatch Risk Assessment (ByRA). Using marine mammals in Malaysia and Vietnam as test cases, I assess the risks posed to Irrawaddy dolphins (*Orcaella brevirostris*) and dugongs (*Dugong dugon*) by five SSF gear types (hook and line, nets, longlines, pots and traps, and trawls). The evaluation of each species-gear interaction proceeds as three steps: (1) *map* the distribution of fishing activities and marine mammals, often drawing on species distribution models; (2) *score* interaction rates guided by primary and secondary data sources, including field observations, literature review, and expert opinion; and (3) *estimate* bycatch risk, with data inputs and model assumptions communicated.

Second, a more detailed understanding of marine mammal habitat preferences and distribution can aid in the identification of areas to target for monitoring and conservation, which is particularly challenging in data-limited nations of Southeast Asia. Baseline knowledge on dolphin distribution can guide regional conservation efforts considering the seasonality of the species and supporting the design of tailored management strategies that address specific threats. I test the hypothesis that accurate seasonal habitat models, relying on environmental data and species occurrences alone, can be used to describe the ecological processes governing abundance for the resident Irrawaddy dolphin population of the Kep Archipelago, Cambodia.

Finally, fisheries bycatch is an underreported and largely unregulated threat to marine mammals worldwide. In the United States (U.S.) and European Union (E.U.), however, the conservation of small cetaceans is prioritized through regulations, policy directives, and international agreements. A review of the bycatch situation for common dolphins (*Delphinus delphis*) in the Bay of Biscay and harbor porpoises (*Phocoena phocoena*) of the Baltic Proper and U.S. Gulf of Maine highlights management strategies identified to monitor, research, and mitigate bycatch and specific conditions that enable or limit conservation policy implementation.

The methodological approach aims to meet a critical need of fisheries managers: to identify emergent interaction patterns between fishing gears and marine mammals and support the development of management actions that can lead to sustainable fisheries and mitigate bycatch for species of conservation concern. Community-led research involving fishers and other stakeholders can access latent knowledge and support the design and implementation of policies designed to monitor (e.g., onboard observers, abundance surveys), mitigate, and report bycatch required by law. Altogether, I leverage existing knowledge and participatory

engagement to garner new insights about complex species-fishery interactions and systematically screen large areas and data-limited fisheries. Insights from each case serve as a foundation for future bycatch assessments that can address data insufficiencies, guide future monitoring to areas and seasons of greatest concern, and involve key sectors in a policy implementation process that considers marine fisheries and biodiversity conservation objectives.

Keywords: fisheries management; species distribution models; Maxent; seasonality; species-fishery interactions; GIS; bycatch risk assessment; data visualization and uncertainty

Abstract



Chapter 1



USC
UNIVERSIDADE
DE SANTIAGO
DE COMPOSTELA



1 SETTING THE SCENE

“All knowledge is relevant and impactful. It is at the nested scales where we can start to tease out their importance.” -Lynn Scarlett

1.1 INTRODUCTION

Why study marine mammals and the direct effects of their capture in data-limited fisheries? First, the ecological role of marine mammals in coastal-estuarine ecosystems cannot be overstated. They are considered sentinel or flagship species (Hoyt, 2012; Parsons et al., 2015) and help maintain ecosystem structure and function (Nelms et al., 2021). In addition to ecological services, healthy marine mammal populations provide important benefits to people, such as recreation and tourism opportunities for wildlife viewing and cultural heritage (Parnwell, 2013; Cook et al., 2020).

Regular monitoring to assess the conservation status of marine mammals is challenging because they are highly mobile species, difficult to detect from the shore or by boat, and these surveys are expensive and time consuming (Lotze et al. 2011, Davidson et al. 2012; Pilcher et al., 2017). Consequently, some species are classified as Data Deficient on the IUCN Red List and 25% of all marine mammals are listed as threatened (Corrigan et al., 2014; Nelms et al., 2021). Fisheries bycatch, the incidental capture of non-target species in active fishing gear (Lewison et al., 2014), is considered to be the main threat to 11 of 13 Critically Endangered small cetaceans, a marine mammal subgroup that includes dolphins and porpoises (Brownell et al., 2019).

Small-scale fisheries (SSF), also known as artisanal or traditional fisheries, are well-established in coastal zones worldwide and critically important to local economies and livelihoods (Chuenpagdee et al., 2006; Garcia and Rosenberg, 2010). SSF are most active in developing, data-limited nations where less protection and enforcement measures are established

for sensitive species (Berkes et al., 2001). Even in countries with legal protections for marine mammals, fisheries bycatch impacts can be serious (Mangel et al., 2010) and these pressures on vulnerable populations are often driven by a high density of fishing vessels operating in nearshore waters (Pilcher et al., 2017). Despite their documented impacts to marine ecosystems (Jacquet and Pauly, 2008), SSF activities are understudied, compared to commercial, large-scale operations (Berkes et al., 2001). To address this knowledge gap in SSF research, Stewart and colleagues (2010) identified global hotspots of fishing pressure using proxy measures for effort. Designed for data-limited fisheries in the Gulf of California, Johnson et al. (2017) developed a local method to spatially identify where SSF vessels operate and estimate how much they fish.

In 2017, I joined an interdisciplinary team of scientists to investigate SSF in the nations of Malaysia, Thailand, and Vietnam. The primary impetus for this research was the 2016 import provisions of the United States (U.S.) Marine Mammal Protection Act (MMPA) requiring foreign, and often data-limited, fisheries exporting seafood to the U.S. to respect standards for managing marine mammal bycatch (NOAA, 2016). Our primary objective was to gauge the ability of these fisheries to comply with the new MMPA rule and, more specifically, to establish management programs to monitor and report bycatch by 2022, following the maximum five-year grace period (Williams et al., 2016). In visits to Southeast Asian field sites with marine ecologists, veterinarians, fisheries, and social scientists, we found that poor fisheries may struggle to comply with the new rule (Johnson et al., 2017). This conclusion was reached after meetings with local managers and officials who face difficult decisions about how to allocate resources for monitoring fisheries and implementing research programs that estimate bycatch.

How can we fill these knowledge gaps when managers continue to struggle with assembling and to make sense of available data? For example, understanding the timing of overlap between a fishery and a marine mammal population requires localized surveys and models to estimate their distribution. Also, the likelihood of incidental capture is influenced by specific fishing gear characteristics, not visible from the water surface, such as set height or mesh size and length of nets (Read, 2021). Collectively, emerging technologies, participatory engagement, and new approaches for spatial decision-support offer promise to more effectively manage this “wicked” problem of bycatch in data-limited fisheries (Lewison et al., 2018).

1.1.1 Ocean data and monitoring innovations

Since the 1990s, the United Nations and broader international civil community have advanced international conventions on sustainable development and biodiversity protection. The United Nations (UN) Sustainable Development Goals (SDGs; UN, 2015) includes 17 goals to achieve by 2030, the UN Environment Programme (UNEP) Convention on Biological Diversity (CBD) Strategic Plan for Biodiversity 2010-2020 (UNEP, 2010) includes 20 Aichi Biodiversity Targets. Across the SDGs, seven of 17 goals directly address biodiversity, natural capital, or ecosystem services, and 10 of the 20 Aichi Biodiversity Targets require biodiversity metrics (Brooks et al. 2015). Sustainable Development Goal 14 (“Life Below Water”) focuses on policies and management for sustaining ocean and marine resource productivity and, among other foci, it targets greater accountability within global capture fisheries (Atkinson and Cools, 2017). Key Biodiversity Areas and, more recently, Important Marine Mammal Areas (IMMA) delineate where place-based protection and monitoring may represent a cost-effective approach to conservation for this highly diverse and mobile taxonomic group (Corrigan et al., 2014).

Large differences in the quality and availability of ocean data is a fundamental challenge to operationalizing information for fisheries management and the conservation of marine biodiversity around the world. This variability makes it difficult to know the analytical purposes for which data are suited. Also, the accessibility and format of these data – often incongruent with existing analytical workflows – inhibits timely analyses and decision-making. Characterizing the population status of marine mammals is often beyond the capacity of developing countries because this type of research is complex, time-consuming, and costly (Pilcher et al., 2017). Even in the European Union, where range-wide abundance estimates exist (Hammond et al., 2013), surveys are rarely replicated at a frequency necessary to detect population trends (Kaschner et al., 2012).

For identifying potential areas of bycatch concern, it is recommended to start with a review of existing studies on marine mammal distribution and fisheries to understand threatened species, high-risk fishing gears, and where bycatch is most prevalent (Wade et al., 2021). These insights can guide managers in making strategic investments in data collection programs and estimation methods that overcome common resource and technical capacity constraints (Desfosse et al., 2012). In parallel, community-based methods for accessing traditional knowledge and building science expertise, such as workshops and marine mammal strandings

networks, can galvanize action for regular monitoring and assessment (Johnson et al., 2017; Hines et al., 2020; Peltier et al., 2020). For instance, a low-cost, flexible survey tool to document spatial distribution and population trends has been deployed in more than 18 countries to prioritize marine mammal conservation areas (Pilcher et al., 2017).

Monitoring systems designed to track fisheries and bycatch occurrences are no longer just on paper but also stored on Internet servers and accessible to managers, often in real-time. The Global Fishing Watch Program provides data about human activities at sea via the Automatic Identification System (AIS), Vessel Monitoring System (VMS), and machine learning algorithms to detect fishing vessels and gear-type usage (Kroodsma et al. 2018). There are, however, limitations to AIS data transmission coverage and detection algorithms for certain regions (e.g., Southeast Asia), multi-gear fisheries, and smaller vessels (Peltier et al., 2020). In general, information about SSF is scarce as these activities are quite diffuse and, therefore, difficult to track (Chuenpagdee et al., 2006; 2019). With the consent of fishers, GPS trackers installed on fishing equipment or self-reporting via mobile applications facilitate mapping of the extent of artisanal fishing grounds and intensity of use for different gear categories (Hartill and Thompson, 2016; Natsir et al., 2019). For documenting mortality events and obtaining counts of bycaught marine mammals, there are more costly options such as at-sea observer programs and remote electronic monitoring (REM) using fishing activity sensors and closed-circuit television cameras. Case studies of European net fisheries suggest that REM offers cost savings over human observers, depending on the level and type of fishery monitoring required (Course, 2021).

In situations with greater scientific capacity, researchers use underwater acoustic detection or boat and aerial line-transect methods to census marine mammals (e.g., Carlén et al., 2018; Saavedra et al., 2018). This is the customary approach to estimate the distribution and abundance of marine mammals, and track population trends over time (Kaschner et al., 2012). Emerging technologies such as marine environmental DNA show promise in expanding the spatial and temporal coverage of conventional biodiversity monitoring by collecting samples repeatedly from vessels at night and in remote areas (Valsecchi et al., 2021). Ultimately, bycatch research in data-limited fisheries should draw on the best available information from the regional to population level in order to assess environmental drivers of change in marine mammal distribution and, consequently, high-impact fishery interactions (Savoca et al., 2020; Kennelly, 2020).

1.1.2 Marine mammals, fisheries, and their interactions

Fisheries bycatch is considered the leading human cause of mortality in marine mammals (Read et al., 2006; Reeves et al., 2013; Brown et al., 2015). Fisheries can impact marine mammals directly, through incidental injury or mortality, and indirectly by competing for prey (Lewison et al., 2014; Wise et al., 2019). Marine mammal competition with fisheries may reduce local prey stocks and initiate a change in feeding grounds if the population specializes in feeding on a depleted species (Marçalo et al., 2018). For the fishery, interactions with marine species may signal prey nearby and, at the same time, result in damage to nets (Wise et al., 2019). Marine mammals are subject to different levels of bycatch risk, but for some populations, such as those that have frequent interactions with certain types of fishing gear, the risks are high (Alfaro-Shigueto et al., 2010; Wade et al., 2021).

Understanding predator-prey dynamics is key to promoting sustainable captured fisheries (Meynier et al., 2008). Marine mammal diet and distribution are influenced by changes in prey abundance. Trophic models designed to study these interactions are based on the energy needs and energy content of the predator and prey, respectively (Meynier et al., 2008). For example, analysis of stomach contents in short-beaked common dolphins (*Delphinus delphis*) of Portugal confirmed that they specialize in feeding on energy-rich sardines even during periods when stocks are overfished (Marçalo et al., 2018). Small cetaceans, such as common dolphins and harbor porpoises (*Phocoena phocoena*), are generally considered opportunistic feeders, meaning they consume prey based on availability. For example, common dolphins in the Bay of Biscay utilize habitat along the continental shelf and forage for a mixture of most locally abundant species; however, less is known about their diet in the open ocean (Pusineri et al., 2007). These predators have to “develop an adapted foraging strategy shaped by their specific energy requirements” (Spitz et al., 2010, p. 2). As a result, harmful fishery interactions may be unavoidable for species with narrow ranges or during the breeding season (Wise et al., 2019).

Few studies have disentangled this complex relationship between fishing gear usage, bycaught species composition, and their habitats (Shester and Micheli, 2011; García-Godos et al., 2013). In particular, interaction rates between SSF and marine mammals are difficult to characterize because these fisheries are diffuse in effort and not typically documented in official country-level statistics (Chuenpagdee et al., 2006). Further, there are large spatial and temporal gaps in survey coverage of marine mammals globally (Kaschner et al., 2012). Adding to this

challenge is the inter- and intra-annual variability of marine mammal and fisheries distribution, often driven by environmental changes in prey/target species abundance. For example, Orphanides and Palka (2013) observed statistically significant differences in harbor porpoise bycatch rates in relation to the winter North Atlantic Oscillation index value and sea surface temperatures. In Baja California, Mexico, Shester and Micheli (2011) found that bycatch of marine species in SSF traps and gillnets depended less on the size of fishing vessels and more on fishing gear type and habitat characteristics. For species directly interacting with a fishery, data on spatial distribution and timing of overlap with high-risk fishing gears are critical towards identifying and managing complex species-fishery interactions (Goetz et al., 2014; Marçalo et al., 2015; Wise et al., 2018).

1.1.3 Species distribution models

Species Distribution Models (SDMs) play a critical role in biodiversity conservation by characterizing the potential impacts to ecosystems under changing environmental conditions. They enable the evaluation of habitat suitability over a large area by drawing on limited species occurrence and environmental data to build a model for predictions (Franklin, 2010). Inputs may include geophysical variables such as temperature, slope, or precipitation, acquired through earth observation or in-situ field surveys. While SDMs identify areas with similar ecological conditions to where a species occurs, they do not specify where a species is found (Pearson, 2007). Instead, outputs can spatially characterize habitat suitability for a species in the past, present and future using maps and summary statistics. There is no universally correct or accepted SDM methodology. Appropriate techniques should be adapted to the ecological and biogeographical situation to meet the study goals and based on available data (Liu et al., 2009).

Correlative SDMs require only presence information to assist in identifying suitable habitats (Redfern et al., 2006). Even with emerging technologies to characterize short-term changes in environmental conditions and support marine mammal habitat modeling (Gregar et al., 2013), sightings of animal occurrence can be sparse. Marine mammals often dwell in turbid waters, are highly mobile, and difficult to survey. The Global Biodiversity Information Facility (GBIF; <https://gbif.org>) makes available nearly 1.5 billion occurrence records of almost 60% of all named species and can serve as a starting point for marine mammal SDM development. Whether relying on freely available data such as GBIF or expert knowledge to identify hotspots

in species distribution, a typical next step is to home in on specific areas for systematic marine mammal surveys or fisher interviews. To identify key habitat associations and changes in species distribution at the local scale and across seasons, researchers collect marine mammal sightings data from expert interviews and surveys at sea (e.g., Briscoe et al., 2014; Hines et al., 2020; Costanza et al., 2021). These data can then be used to build SDMs with the maximum entropy distribution model (Maxent; https://biodiversityinformatics.amnh.org/open_source/maxent).

1.2 THEORETICAL CANVAS

1.2.1 Embracing complexity in marine mammal conservation research

Marine mammal conservation research and fisheries management is not a one size fits all approach (Read, 2021). Stakeholder involvement helps to capture the human dimension and gives it some definition, no matter how speculative it may be. Many of the questions posed by conservation researchers relate to social science and values; that is, what people care about. For example, in matters of experiential knowledge there are people who are out on fishing boats each day, taking measurements or working with equipment. Direct input from these individuals is more likely to address a specific problem or improve a situation because it invokes the right kind of participation (Trimble and Berkes, 2013). It also asks salient questions to conservation research such as: What values do people care about? What are trade-offs in those value sets? And, most importantly, how do we prioritize those values?

Tapping into available expert knowledge also informs the complex management decisions and practices undertaken by those who are most affected by different conservation interventions. As described by Lewison et al. (2018), “complex systems approaches are not a single type of analyses, rather they are a diverse suite of conceptual, analytical, and computational methodologies that can be applied to ‘wicked’ or unstructured problems (p. 2).” Consequently, traditional complex systems analyses are often information intensive and difficult to implement in data-limited environments. Waiting for better data is also problematic because it may stall ongoing research and management processes. In low-data situations, Lewison and colleagues (2018) suggest a paradigm shift in marine conservation research that first aims to increase complexity awareness (upward movement on the y-axis of **Figure 1**) through an

investment in stakeholder engagement. By accessing local knowledge, researchers can acknowledge non-linear, unpredictable relationships that may only be quantifiable with robust data, and embrace more complex approaches as these data become available.

Best practices for assessing and managing bycatch should focus on understanding the key factors that influence bycatch rates such as marine mammal distribution, population trends, life history, and habitat preferences (Wade et al., 2021). Further, Matthiopoulos et al. (2008) stresses the importance of compiling information on spatial and temporal overlaps between marine mammals and high-impact fisheries. Engagement that utilizes participatory mapping techniques (e.g., Hines et al., 2020; Costanza et al., 2021) can overcome common obstacles to research in data-limited fisheries and species. For example, the use of map-based social simulations were shown to heighten curiosity, promote active participation, and bring diverse voices to the table for discussing tradeoffs between the extraction and conservation of marine resources (Verutes and Rosenthal, 2014). Community involvement also empowers marginalized segments of the population (Chuenpagdee et al., 2006), enhancing participation in research through knowledge co-production and the validation of analytical results (Wiber et al., 2009; Trimble and Berkes, 2013; Rosenthal et al., 2015). It is arguably the process to reduce bycatch that matters more than the data availability. Therefore, policies to effectively manage marine mammal bycatch need to establish clear action plans with quantitative management objectives and reference points.

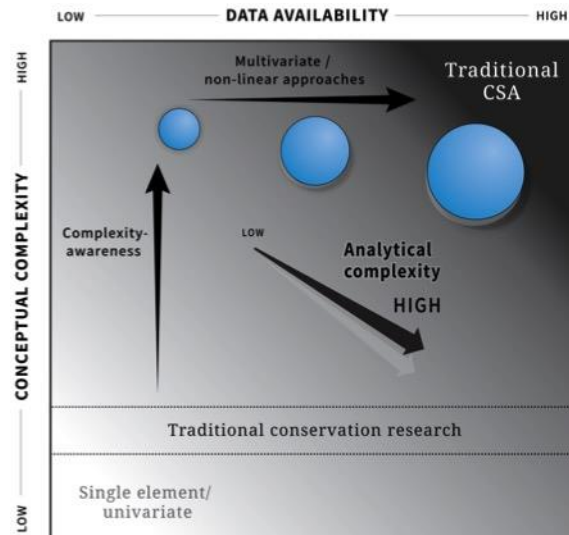


Figure 1. The three dimensional complexity landscape represented by three axes: (A) data availability (x-axis), (B) conceptual complexity (y-axis), (C) analytical complexity (z-axis), where circle size denotes analytical complexity (larger circles represent higher analytical complexity). Traditional Complex System Analyses (CSA) are possible when conceptual complexity, analytical complexity and data availability are high. As conceptual complexity increases, an analysis or application becomes complexity-aware even when data availability or analytical complexity are low (Figure adapted from Lewison et al., 2018).

1.2.2 Advancing policy and practice to manage marine mammal bycatch

According to Desfosse et al. (2012, p. 6), “the lack of objective criteria makes it difficult to direct resources toward improvements in data collection or analytical methodology, and precludes a process for tracking improvements.” However, calculating a biological reference point is just one part of a structured process to assess and reduce marine mammal bycatch. Wade et al. (2021) propose a general framework as: (1) plan the assessment, (2) collect necessary data (e.g., marine mammal abundance and bycatch estimates), (3) analyze bycatch and estimate a biological reference point, and (4) communicate the results. Initially, the aim is to facilitate efficient and effective investment of resources toward developing activities that allow managers to manage more effectively. Even basic information about marine mammal life histories, fishing effort and catch, or bycatch occurrence can be used to overcome barriers to management such as complicated political landscapes or limited scientific capacity (Soykan et al., 2008; Lewison et al., 2011; Teh et al., 2013). Then, regular assessments, as is the case for specific stocks and fisheries in the United States, help scientists and stakeholders identify high-risk species-fishery interactions, improve estimation methods and prioritize funds and resources for monitoring the most problematic areas and seasons (Desfosse et al. 2012).

Few coastal nations assess their fisheries or publish accurate statistics (Pauly and Zeller, 2016), let alone enact policy that lays out a clear procedure for protecting marine mammals from bycatch (McDonald et al., 2016; Dolman et al., 2021). In the European Union (E.U.), anthropogenic removal of marine mammals is covered by fisheries legislation, which provides basic requirements for their protection. Despite legal mandates for E.U. Member States to monitor and mitigate unsustainable levels of bycatch, most efforts to manage fisheries are dominated by short-term economic interests (Hentrich and Salomon, 2006). The result is inadequate implementation and enforcement of policies to reduce the number of bycaught marine mammals in E.U. fisheries (Dolman et al., 2016; Rogan et al., 2021). To determine safe anthropogenic removal limits, managers need reliable, standardized methods for collecting data on population abundance and bycatch rates (Saavedra et al., 2018; Wade et al., 2021). Therefore, it is not surprising that Member States struggle to report on the conservation status for listed marine mammal species because obtaining these estimates is resource-intensive, requiring long-term information and international cooperation.

On the other side of the Atlantic Ocean, the United States (U.S.) demonstrates for

specific populations and situations that a well-defined marine mammal conservation strategy can lead to significant reductions in bycatch (McDonald et al., 2016). The U.S. MMPA prohibits anthropogenic removal of marine mammals (NOAA, 2016). Successful efforts to monitor and mitigate bycatch in U.S. waters has been traced to several factors. First, Potential Biological Removal (PBR) is a unique approach in the MMPA for estimating the maximum allowable number of animals that can be removed from a population (Wade, 1998). If bycatch exceeds PBR, the marine mammal stock is considered “strategic,” and a multisectoral body called a Take Reduction Team (TRT), is formed. TRTs are composed of representatives from fishery management councils, scientists, federal and state agencies, and environmental organizations (Orphanides and Palka, 2013). Altogether, certain stocks are prioritized and regularly monitored when there is a bycatch problem. Nevertheless, Take Reduction planning has varied in its effectiveness across regions and species (McDonald et al., 2016), perhaps because strategies are focused primarily on commercial fishing vessels. Complementary approaches for data-limited fisheries and species are needed to acquire data on marine mammal abundance and estimate bycatch rates (Wade et al., 2021).

With origins in the U.S. and Australia for measuring risk to important fishery species and managing marine resources (Patrick et al., 2010, Williams et al., 2011), assessment tools are now available to map risk to species from human activities using open source geospatial software (Arkema et al., 2014). For mapping bycatch risk, this translates into identifying drivers of exposure over space and time, such as the likelihood of capture from different fishing gears or the timing of overlap based on habitat suitability estimates from SDMs (Briscoe et al., 2014). Bycatch risk assessment also aims to make better use of existing data. In the absence of robust information on bycatch occurrence, the overlap between risky fisheries and vulnerable marine mammal species is a valuable starting point (Wade et al., 2021). Participatory mapping techniques and spatially explicit risk assessment were used to evaluate seasonal scenarios of bycatch risk inside an Important Marine Mammal Area of Southeast Asia (Hines et al., 2020) and in Latin America (Costanza et al., 2021). Findings from these risk assessments guided monitoring to areas and seasons of greatest concern by involving industry and community stakeholders in a dialogue that considered fisheries and biodiversity conservation objectives.

1.3 AIM AND RESEARCH QUESTIONS

How can we address the global problem of marine mammal bycatch in data-limited fisheries? It is the guiding question that structures this thesis. Without contesting the importance of small-scale fishing activities — to provide nutritional sustenance and support community livelihoods — I explore how the combination of engagement, participatory mapping, and interdisciplinary research can assist in implementation of international conservation policies and locally-supported management strategies to reduce fisheries bycatch. I believe this is a topic worth exploring because SSF support the well-being of more than half a billion people worldwide (FAO, 2012). Moreover, these activities contribute to marine mammal bycatch (Reeves et al., 2013; Brown et al., 2015) and are typically data-limited (Stewart et al., 2010). While the harmful effects of bycatch on marine biodiversity are well-known, research on how to more effectively monitor these activities and assess their impacts, especially in data-scarce environments, is still emerging. To this end, I investigate four interrelated research questions using examples from Southeast Asia, the E.U. and the U.S.:

1. How can a spatially explicit fisheries management tool, relying on existing data only, support monitoring and mitigation of bycatch risks in developing countries? (**Chapter 2**);
2. How do presence-only species distribution models perform when using remotely sensed data as proxies for the complex ecological processes governing dolphin habitat and prey abundance? (**Chapter 3**);
3. What are the enabling and limiting conditions for implementing small cetacean conservation policies, and how do they differ between the E.U. and U.S.? (**Chapter 4**);
4. What are the lessons for conservation policy and practice based on analyses of marine mammal bycatch challenges and opportunities in different regions of the world? (**Chapters 2, 3, and 4**).

1.4 METHODOLOGICAL APPROACH

I acquired all data utilized in this research through partnerships with marine mammal researchers, government agencies, and non-governmental organizations. Specifically, they conducted boat and aerial surveys to track marine mammals and fisheries of the Southeast Asian field sites and understand their distribution and interaction rates (**Chapters 2 and 3**). Data

collection also relied on qualitative methods. Social science colleagues in Vietnam and Malaysia conducted semi-structured interviews with fishers, vendors, tourism operators, and marine managers to spatially characterize fishing grounds, fish landings and market locations, gear type usage, and opportunities for alternative livelihoods (**Chapter 2**). Community research and outreach techniques were also crucial in developing this thesis. I organized, prepared, and delivered multiple meetings with participation from local government officials, experts, and knowledge holders who either use, manage, or conduct research in the field sites (**Chapters 2 and 3**). Notably, the workshops to present preliminary findings enabled our team to communicate how these peoples' data would be used in the ByRA tool and how we could work together to improve data quality and availability over time. In summary, data collected using these methods ranged from quantitative data, mainly boat surveys, to qualitative information such as map annotations from interviews with fishers and during workshop exercises.

To analyze these data, I used machine-learning algorithms available in the Maxent correlative SDM software, geospatial mapping, the InVEST species risk assessment model, and interpretation of descriptive statistics (**Chapters 2 and 3**). The stakeholder workshops in Vietnam, Thailand, and Malaysia elicited expert opinion and, along with a literature review, were used to score species-fishery interaction rates and characterize data input uncertainty. For the latter, weighted average calculations accounted for differences in data quality across field sites and stated (relative) importance of exposure and consequence criteria scores in the risk assessment. Qualitative data from semi-structured interviews were used to fill gaps in coverage of the aerial and boat surveys of fishing distribution and gear-type density (**Chapter 2**). High-resolution earth observation products for sea-surface temperature and chlorophyll-a concentration were corrected and processed with assistance from the Plymouth Marine Laboratory (**Chapter 3**). Finally, and to round out the thesis, I reviewed the literature, scientific reports from intergovernmental bodies, and existing policies designed to protect small cetacean populations in the E.U. and U.S. (**Chapter 4**). Overall, I applied a mixed-methods approach to acquire, integrate, and analyze qualitative and quantitative data and evaluate the ability of international policies and local management strategies to reduce marine mammal bycatch.

1.5 REFERENCES

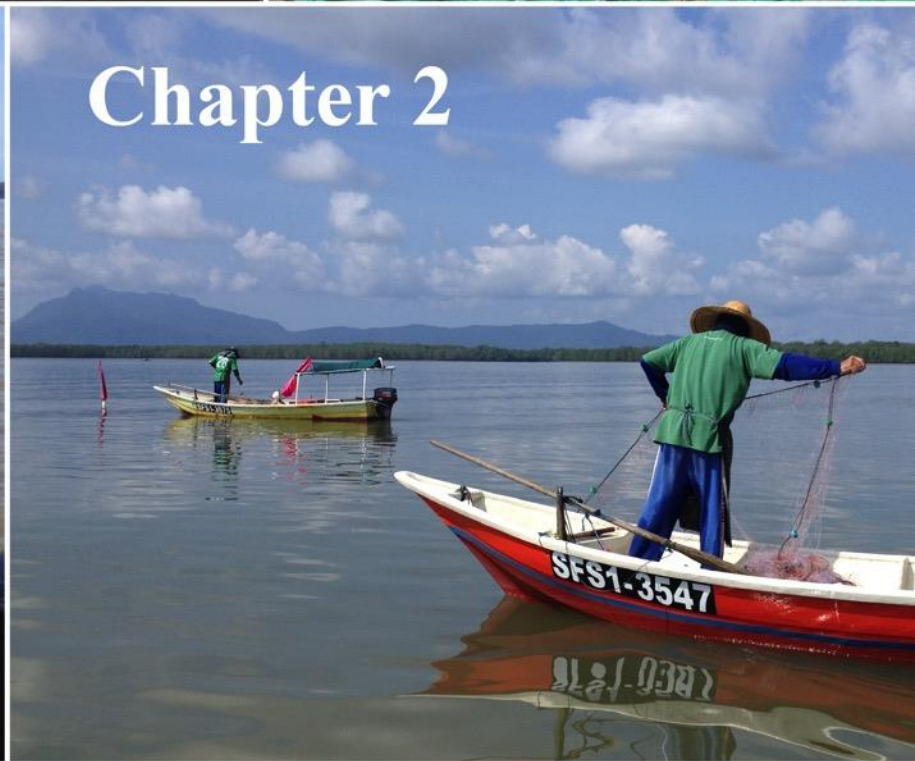
Alfaro-Shigueto, J., Mangel, J. C., Pajuelo, M., Dutton, P. H., Seminoff, J. A., & Godley, B. J. (2010). Where

- small can have a large impact: structure and characterization of small-scale fisheries in Peru. *Fisheries Research*, 106(1), 8-17.
- Arkema, K. K., Verutes, G., Bernhardt, J. R., Clarke, C., Rosado, S., Canto, M., et al. (2014). Assessing habitat risk from human activities to inform coastal and marine spatial planning: a demonstration in Belize. *Environmental Research Letters*, 9(11), 114016.
- Berkes, F., Mahon, R., McConney, P., Pollnac, R., & Pomeroy, R. (2001). Managing small-scale fisheries. *Information management*, 92, 4-7.
- Briscoe, D. K., Hiatt, S., Lewison, R., & Hines, E. (2014). Modeling habitat and bycatch risk for dugongs in Sabah, Malaysia. *Endangered Species Research*, 24(3), 237-247.
- Brooks, T. M., Butchart, S. H., Cox, N. A., Heath, M., Hilton-Taylor, C., Hoffmann, M., et al. (2015). Harnessing biodiversity and conservation knowledge products to track the Aichi Targets and Sustainable Development Goals. *Biodiversity*, 16(2-3), 157-174.
- Brown, S.L., Reid, D. and Rogan, E. (2015). Spatial and temporal assessment of potential risk to cetaceans from static fishing gears. *Marine Policy*, 51: 267-280.
- Brownell, R. L., Reeves, R. R., Read, A. J., Smith, B. D., Thomas, P. O., Ralls, K., et al. (2019). Bycatch in gillnet fisheries threatens Critically Endangered small cetaceans and other aquatic megafauna. *Endangered Species Research*, 40, 285-296.
- Carlén, I., Thomas, L., Carlström, J., Amundin, M., Teilmann, J., Tregenza, N., et al. (2018). Basin-scale distribution of harbour porpoises in the Baltic Sea provides basis for effective conservation actions. *Biological Conservation*, 226, 42-53.
- Chuenpagdee, R., Liguori, L., Palomares, M. L., & Pauly, D. (2006). Bottom-up, global estimates of small-scale marine fisheries catches.
- Chuenpagdee, R., Rocklin, D., Bishop, D., Hynes, M., Greene, R., Lorenzi, M. R., & Devillers, R. (2019). The global information system on small-scale fisheries (ISSF): a crowdsourced knowledge platform. *Marine Policy*, 101, 158-166.
- Cook, D., Malinauskaitė, L., Davíðsdóttir, B., & Ögmundardóttir, H. (2020). A contingent valuation approach to estimating the recreational value of commercial whale watching—the case study of Faxaflói Bay, Iceland. *Tourism management perspectives*, 36, 100754.
- Corrigan, C. M., Ardron, J. A., Comeros-Raynal, M. T., Hoyt, E., Notarbartolo Di Sciara, G., & Carpenter, K. E. (2014). Developing important marine mammal area criteria: learning from ecologically or biologically significant areas and key biodiversity areas. *Aquatic Conservation: marine and freshwater ecosystems*, 24(S2), 166-183.
- Course, G.P. (2021). Monitoring Cetacean Bycatch: An Analysis of Different Methods Aboard Commercial Fishing Vessels. ASCOBANS Secretariat, Bonn, Germany. ASCOBANS Technical Series No.1. Available at: https://www.ascobans.org/sites/default/files/document/ascobans_ac26_inf2.5b_bycatch-monitoring-methods-analysis.pdf
- Costanza, A., Bruce, C. G., Mangel, J. C., Alfaro-Shigueto, J., Verutes, G., et al. (2021). Participatory Risk Assessment of Humpback Whale (*Megaptera novaeangliae*) and Leatherback Turtle (*Dermochelys coriacea*) Bycatch in Northern Peru. *Frontiers in Marine Science*, 1792.
- Davidson, A. D., Boyer, A. G., Kim, H., Pompa-Mansilla, S., Hamilton, M. J., Costa, D. P., et al. (2012). Drivers and hotspots of extinction risk in marine mammals. *Proceedings of the National Academy of Sciences*, 109(9), 3395-3400.
- Desfosse, L. L., Karp, W. A., & Brooke, S. G. (2012). Evaluating the quality of bycatch data and bycatch estimates among disparate fisheries. *Marine Fisheries Review*, 74(3), 6-13.
- Dolman, S., Baulch, S., Evans, P. G., Read, F., & Ritter, F. (2016). Towards an EU action plan on cetacean bycatch. *Marine Policy*, 72, 67-75.
- Dolman, S. J., Evans, P. G. H., Ritter, F., Simmonds, M. P., & Swabe, J. (2021). Implications of new technical measures regulation for cetacean bycatch in European waters. *Marine Policy*, 124, 104320.
- FAO. Fishing People. FAO Fisheries and Aquaculture Department, FAO, Rome. 2012. Available at: <http://www.fao.org/fishery/topic/13827/en>
- Franklin, J. (2010). Mapping species distributions: spatial inference and prediction. Cambridge University Press.
- Garcia, S. M., & Rosenberg, A. A. (2010). Food security and marine capture fisheries: characteristics, trends,

- drivers and future perspectives. *Philosophical Transactions of the Royal Society B: Biological Sciences*, 365(1554), 2869-2880.
- García-Godos, I., Van Waerebeek, K., Alfaro-Shigueto, J., & Mangel, J. C. (2013). Entanglements of large cetaceans in Peru: few records but high risk. *Pacific Science*, 67(4), 523-532.
- Goetz, S., Read, F. L., Santos, M. B., Pita, C., & Pierce, G. J. (2014). Cetacean–fishery interactions in Galicia (NW Spain): results and management implications of a face-to-face interview survey of local fishers. *ICES Journal of marine Science*, 71(3), 604-617.
- Gregr, E. J., Baumgartner, M. F., Laidre, K. L., & Palacios, D. M. (2013). Marine mammal habitat models come of age: the emergence of ecological and management relevance. *Endangered Species Research*, 22(3), 205-212.
- Hammond, P. S., Macleod, K., Berggren, P., Borchers, D. L., Burt, L., Cañadas, A., et al. (2013). Cetacean abundance and distribution in European Atlantic shelf waters to inform conservation and management. *Biological Conservation*, 164, 107-122.
- Hartill, B., & Thompson, F. (2016). Review of self-reporting tools for recreational fishers. *New Zealand Fisheries Assessment Report*, 6, 35.
- Hentrich, S., & Salomon, M. (2006). Flexible management of fishing rights and a sustainable fisheries industry in Europe. *Marine Policy*, 30(6), 712-720.
- Hines, E., Ponnampalam, L. S., Junchompoo, C., Peter, C., Vu, L., Huynh, T., et al. (2020). Getting to the bottom of bycatch: a GIS-based toolbox to assess the risk of marine mammal bycatch. *Endangered Species Research*, 42, 37-57.
- Hoyt, E. (2012). *Marine protected areas for whales, dolphins and porpoises: a world handbook for cetacean habitat conservation and planning*. Routledge.
- Jacquet, J., & Pauly, D. (2008). Funding priorities: big barriers to small-scale fisheries. *Conservation biology*, 22(4), 832-835.
- Johnson, A. F., Caillat, M., Verutes, G. M., Peter, C., Junchompoo, C., Long, V., et al. (2017). Poor fisheries struggle with US import rule. *Science*, 355(6329), 1031-1032.
- Johnson, A. F., Moreno-Báez, M., Giron-Nava, A., Corominas, J., Erisman, B., Ezcurra, E., & Aburto-Oropeza, O. (2017). A spatial method to calculate small-scale fisheries effort in data poor scenarios. *PLoS One*, 12(4), e0174064.
- Kaschner, K., Quick, N. J., Jewell, R., Williams, R., & Harris, C. M. (2012). Global coverage of cetacean line-transect surveys: status quo, data gaps and future challenges.
- Kennelly, S. J. (2020). Bycatch Beknown: Methodology for jurisdictional reporting of fisheries discards—Using Australia as a case study. *Fish and Fisheries*, 21(5), 1046-1066.
- Kroodsma, D. A., Mayorga, J., Hochberg, T., Miller, N. A., Boerder, K., Ferretti, F., et al. (2018). Tracking the global footprint of fisheries. *Science*, 359(6378), 904-908
- Lewison, R. L., Soykan, C. U., Cox, T., Peckham, H., Pilcher, N., LeBoeuf, N., et al. (2011). Ingredients for addressing the challenges of fisheries bycatch. *Bulletin of Marine Science*, 87(2), 235-250.
- Lewison, R. L., Crowder, L. B., Wallace, B. P., Moore, J. E., Cox, T., Zydalis, R., et al. (2014). Global patterns of marine mammal, seabird, and sea turtle bycatch reveal taxa-specific and cumulative megafauna hotspots. *Proceedings of the National Academy of Sciences*, 111(14), 5271-5276.
- Lewison, R. L., Johnson, A. F., & Verutes, G. M. (2018). Embracing complexity and complexity-awareness in marine megafauna conservation and research. *Frontiers in Marine Science*, 5, 207.
- Liu, C., White, M., and Newell, G. (2009). “Measuring the accuracy of species distribution models: a review,” in *Proceedings of the 18th World IMACs/MODSIM Congress*, Cairns, 4241,4247
- Lotze, H. K., Coll, M., Magera, A. M., Ward-Paige, C., & Airoldi, L. (2011). Recovery of marine animal populations and ecosystems. *Trends in ecology & evolution*, 26(11), 595-605.
- Mangel, J. C., Alfaro-Shigueto, J., Van Waerebeek, K., Cáceres, C., Bearhop, S., Witt, M. J., & Godley, B. J. (2010). Small cetacean captures in Peruvian artisanal fisheries: high despite protective legislation. *Biological Conservation*, 143(1), 136-143.
- Marçalo, A., Katara, I., Feijó, D., Araújo, H., Oliveira, I., Santos, J., et al. (2015). Quantification of interactions between the Portuguese sardine purse-seine fishery and cetaceans. *ICES Journal of Marine Science*, 72(8), 2438-2449.
- Marçalo, A., Nicolau, L., Giménez, J., Ferreira, M., Santos, J., Araújo, H., et al. (2018). Feeding ecology of the

- common dolphin (*Delphinus delphis*) in Western Iberian waters: has the decline in sardine (*Sardina pilchardus*) affected dolphin diet?. *Marine Biology*, 165(3), 1-16.
- Matthiopoulos, J., Smout, S., Winship, A. J., Thompson, D., Boyd, I. L., & Harwood, J. (2008). Getting beneath the surface of marine mammal–fisheries competition. *Mammal Review*, 38(2-3), 167-188.
- McDonald, S. L., Lewison R. L., & Read A. J. (2016). Evaluating the efficacy of environmental legislation: A case study from the US marine mammal Take Reduction Planning process. *Global Ecology and Conservation*, 5, 1-11.
- Meynier, L., Pusineri, C., Spitz, J., Santos, M. B., Pierce, G. J., & Ridoux, V. (2008). Intraspecific dietary variation in the short-beaked common dolphin *Delphinus delphis* in the Bay of Biscay: importance of fat fish. *Marine Ecology Progress Series*, 354, 277-287.
- National Oceanic and Atmospheric Administration (NOAA). (2016). Fed. Regist. 81 (157), 54390.
- Natsir, M., Ruchimat, T., Agustina, S., & Yulianto, I. (2019). Application of global positioning system tracker to detect the fishing ground location and effective effort in artisanal fishery. *Sensors and Materials*, 31(3), 803-814.
- Nelms, S. E., Alfaro-Shigueto, J., Arnould, J. P., Avila, I. C., Nash, S. B., et al. (2021). Marine mammal conservation: over the horizon. *Endangered Species Research*, 44, 291-325.
- Orphanides, C. D., & Palka, D. L. (2013). Analysis of harbor porpoise gillnet bycatch, compliance, and enforcement trends in the US northwestern Atlantic, January 1999 to May 2010. *Endangered Species Research*, 20(3), 251-269.
- Parnwell, M. J. (2013). Whale Worship and Tourism Development in the Hòi An–DaNang Corridor, Việt Nam. *South East Asia Research*, 21(3), 475-496.
- Parsons, E. C. M., Baulch, S., Bechshoft, T., Bellazzi, G., Bouchet, P., Cosentino, A. M., et al. (2015). Key research questions of global importance for cetacean conservation. *Endangered Species Research*, 27(2), 113-118.
- Patrick, W. S., Spencer, P., Link, J., Cope, J., Field, J., Kobayashi, D., et al. (2010). Using productivity and susceptibility indices to assess the vulnerability of United States fish stocks to overfishing. *Fishery Bulletin*, 108(3), 305-322.
- Pauly, D., & Zeller, D. (2016). Catch reconstructions reveal that global marine fisheries catches are higher than reported and declining. *Nature communications*, 7(1), 1-9.
- Pearson, R. G. (2007). Species' distribution modeling for conservation educators and practitioners. *Synthesis*. American Museum of Natural History, 50, 54-89.
- Peltier, H., Authier, M., Dabin, W., Dars, C., Demaret, F., Doremus, G. et al. (2020). Can modelling the drift of bycaught dolphin stranded carcasses help identify involved fisheries? An exploratory study. *Global Ecology and Conservation*, 21, e00843.
- Pilcher, N. J., Adulyanukosol, K., Das, H., Davis, P., Hines, E., Kwan, D., et al. (2017). A low-cost solution for documenting distribution and abundance of endangered marine fauna and impacts from fisheries. *PloS one*, 12(12), e0190021.
- Pusineri, C., Magnin, V., Meynier, L., Spitz, J., Hassani, S., & Ridoux, V. (2007). Food and feeding ecology of the common dolphin (*Delphinus delphis*) in the oceanic Northeast Atlantic and comparison with its diet in neritic areas. *Marine Mammal Science*, 23(1), 30-47.
- Read, A. J., Drinker, P., & Northridge, S. (2006). Bycatch of marine mammals in US and global fisheries. *Conservation biology*, 20(1), 163-169.
- Read, A. J. (2013). Development of conservation strategies to mitigate the bycatch of harbor porpoises in the Gulf of Maine. *Endangered Species Research*, 20(3), 235-250.
- Read, F. L. (2021). Cost-benefit Analysis for Mitigation Measures in Fisheries with High Bycatch. ASCOBANS Technical Series No. 2. ASCOBANS Secretariat, Bonn, Germany.
- Redfern, J. V., Ferguson, M. C., Becker, E. A., Hyrenbach, K. D., Good, C., Barlow, J., et al. (2006). Techniques for cetacean–habitat modeling. *Marine Ecology Progress Series*, 310, 271-295.
- Reeves, R. R., McClellan, K., & Werner, T. B. (2013). Marine mammal bycatch in gillnet and other entangling net fisheries, 1990 to 2011. *Endangered Species Research*, 20(1), 71-97.
- Rogan, E., Read, A. J., & Berggren, P. (2021). Empty promises: The European Union is failing to protect dolphins and porpoises from fisheries by-catch. *Fish and Fisheries*, 22(4), 865-869.
- Rosenthal, A., Verutes, G., McKenzie, E., Arkema, K. K., Bhagabati, N., Bremer, L. L., et al. (2015). Process

- matters: a framework for conducting decision-relevant assessments of ecosystem services. *International Journal of Biodiversity Science, Ecosystem Services & Management*, 11(3), 190-204.
- Saavedra C, Gerrodette T, Louzao M, Valeiras J, Garcia S, Cervino S, et al. (2018). Assessing the environmental status of the short-beaked common dolphin (*Delphinus delphis*) in North-western Spanish waters using abundance trends and safe removal limits. *Progress in Ocean*, 166, 66-75.
- Samhouri, J. F., & Levin, P. S. (2012). Linking land-and sea-based activities to risk in coastal ecosystems. *Biological Conservation*, 145(1), 118-129.
- Santos, M. B., German, I., Correia, D., Read, F. L., Cedeira, J. M., Caldas, M., et al. (2013). Long-term variation in common dolphin diet in relation to prey abundance. *Marine Ecology Progress Series*, 481, 249-268.
- Savoca, M. S., Brodie, S., Welch, H., Hoover, A., Benaka, L. R., Bograd, S. J., & Hazen, E. L. (2020). Comprehensive bycatch assessment in US fisheries for prioritizing management. *Nature Sustainability*, 3(6), 472-480.
- Shester, G. G., & Micheli, F. (2011). Conservation challenges for small-scale fisheries: Bycatch and habitat impacts of traps and gillnets. *Biological Conservation*, 144(5), 1673-1681.
- Soykan, C. U., Moore, J. E., Zydalis, R., Crowder, L. B., Safina, C., & Lewison, R. L. (2008). Why study bycatch? An introduction to the Theme Section on fisheries bycatch. *Endangered Species Research*, 5(2-3), 91-102.v
- Spitz, J., Mourocq, E., Leauté, J. P., Quéro, J. C., & Ridoux, V. (2010). Prey selection by the common dolphin: fulfilling high energy requirements with high quality food. *Journal of experimental Marine Biology and ecology*, 390(2), 73-77.
- Stewart, K. R., Lewison, R. L., Dunn, D. C., Bjorkland, R. H., Kelez, S., Halpin, P. N., & Crowder, L. B. (2010). Characterizing fishing effort and spatial extent of coastal fisheries. *PloS one*, 5(12), e14451.
- Trimble, M., & Berkes, F. (2013). Participatory research towards co-management: lessons from artisanal fisheries in coastal Uruguay. *Journal of environmental management*, 128, 768-778.
- United National Environment Programme (UNEP). (2010). *UNEP/CBD/COP/DEC/X/2 The Strategic Plan for Biodiversity 2011-2020 and the Aichi Biodiversity Targets*. Nagoya, Japan.
- United Nations (UN). (2015). Resolution A/RES/70/1 of 25 September 2015. Available at: http://www.un.org/en/development/desa/population/migration/generalassembly/docs/globalcompact/A_RES_70_1_E.pdf [accessed 2018-3-28].
- Valsecchi, E., Arcangeli, A., Lombardi, R., Boyse, E., Carr, I. M., Galli, P., & Goodman, S. J. (2021). Ferries and environmental DNA: underway sampling from commercial vessels provides new opportunities for systematic genetic surveys of marine biodiversity. *bioRxiv*.
- Verutes, G. M., & Rosenthal, A. (2014). Using simulation games to teach ecosystem service synergies and trade-offs. *Environmental Practice*, 16(3), 194-204.
- Wade, P. R. (1998). Calculating limits to the allowable human-caused mortality of cetaceans and pinnipeds. *Marine Mammal Science*, 14(1), 1-37.
- Wade, P. R., Long, K. J., Francis, T. B., Punt, A. E., Hammond, P. S., Heinemann, D., et al. (2021) Best Practices for Assessing and Managing Bycatch of Marine Mammals. *Frontiers in Marine Science*, 8:757330.
- Wiber, M., Charles, A., Kearney, J., & Berkes, F. (2009). Enhancing community empowerment through participatory fisheries research. *Marine policy*, 33(1), 172-179.
- Williams, A., Dowdney, J., Smith, A. D. M., Hobday, A. J., & Fuller, M. (2011). Evaluating impacts of fishing on benthic habitats: a risk assessment framework applied to Australian fisheries. *Fisheries Research*, 112(3), 154-167.
- Williams, R., Burgess, M. G., Ashe, E., Gaines, S. D., & Reeves, R. R. (2016). US seafood import restriction presents opportunity and risk. *Science*, 354(6318), 1372-1374.
- Wise, L., Galego, C., Katara, I., Marçalo, A., Meirinho, A., Monteiro, S. S., et al. (2019). Portuguese purse seine fishery spatial and resource overlap with top predators. *Marine Ecology Progress Series*, 617, 183-198.
- Zeller, D., Palomares, M. D., Tavakolie, A., Ang, M., Belhabib, D., Cheung, W. W., et al. (2016). Still catching attention: Sea Around Us reconstructed global catch data, their spatial expression and public accessibility. *Marine Policy*, 70, 145-152.



Chapter 2



USC
UNIVERSIDADE
DE SANTIAGO
DE COMPOSTELA



2 USING GIS AND STAKEHOLDER INVOLVEMENT TO INNOVATE MARINE MAMMAL BYCATCH RISK ASSESSMENT IN DATA-LIMITED FISHERIES¹

2.1 INTRODUCTION

Small-scale fisheries (SSF) are a critical means of subsistence and livelihood in many regions of the world. They provide needed sources of protein, food security, and poverty alleviation (Allison and Ellis, 2001; Garcia and Rosenberg, 2010), and support the well-being of more than half a billion people worldwide (FAO, 2012). Despite their importance globally, SSF struggle with sustainability when local communities do not have access to the social capital necessary to participate in resource management (Berkes, 2001; Kosamu, 2015; Teh et al., 2015). As a result, information and data about SSF is often limited as compared to large-scale, industrial fishing operations (Salas et al., 2007; Stewart et al., 2010; Chuenpagdee et al., 2017). Furthermore, some SSF have been identified as a threat to marine ecosystems and species (Chuenpagdee et al., 2006; Laneri et al., 2010; Wallace et al., 2010). Given the tenuous status of many coastal-marine species and the socioeconomic importance of SSF, robust frameworks are needed to support sustainable fisheries and species conservation in SSFs (Merino et al., 2012; Williams et al., 2016; Johnson et al., 2017).

SSF, like other fisheries sectors, incurs fisheries bycatch. Bycatch refers to the



¹ This chapter previously appeared as an article in the PLOS ONE journal. The original citation is as follows: Verutes, G. M., Johnson, A. F., Caillat, M., Ponnampalam, L. S., Peter, C., Vu, L., et al. (2020). Using GIS and stakeholder involvement to innovate marine mammal bycatch risk assessment in data-limited fisheries. *PloS one*, 15(8), e0237835. doi: 10.1371/journal.pone.0237835

unintended capture of non-target species (Kappel, 2005; Lewison et al., 2014), and it has been identified as the largest threat to marine mammals globally (Read, 2008; Reeves et al., 2013). For depleted marine mammal populations, even a few entanglements per year can pose a significant threat (Minton et al., 2011), especially when combined with cumulative impacts from other anthropogenic threats (Van Waerebeek and Reyes, 1994; Jaaman et al., 2008; Halpern et al., 2015). Bycatch risk is particularly challenging to analyze and calculate in SSF because of data gaps on fishing effort and marine mammal distribution and ranges (Moore et al., 2010; Reeves et al., 2013; Chuenpagdee et al., 2017). Species conservation research developed in close collaboration with local stakeholders, agency personnel, and scientists can be used to overcome these obstacles by characterizing the relationship between SSF and the distribution of threatened marine mammals (Soykan et al., 2008; Bellido et al., 2011; Hines et al., 2015).

Recent innovations in geospatial technology have demonstrated success in supporting sustainable fisheries and marine mammal conservation. Global positioning systems coupled with unmanned aerial and marine drones equipped with laser, thermal, and acoustic sensors now enable scientists and conservation practitioners to track marine megafauna movements (Baird et al., 2013; Hodgson et al., 2013; Christiansen et al., 2017) and SSF fishing effort (Natale et al., 2015), map species distribution and habitat preferences (Tobeña et al., 2016; Kuit et al., 2019) and estimate taxa-specific impacts from human activities (Shester and Micheli, 2011; Mannocci et al., 2017; Hazen et al., 2018). In addition, community involvement and local expertise can be integrated with remote sensing and spatial analyses to fill data gaps, characterize uncertainty of existing information, and produce actionable information to address sustainability challenges (Berkes, 2007; Ruckelshaus et al., 2015). Given the growing availability of tools to manage SSF, including those that draw on local knowledge and geographic information systems (GIS), we aim to integrate and visualize existing data on SSF interactions with marine mammals to increase the efficacy of fisheries management research and reduce uncertainty.

A risk assessment evaluates the likelihood, or probability, of an event happening and the magnitude of the consequences if the event happens (Hobday et al., 2011; Gibbs and Browman, 2015). Species risk assessment is one approach to support sustainable resource use and conservation by evaluating the risk-reduction potential of different fisheries management options in marine fish stocks, habitats, and ecosystems (Patrick et al., 2010; Williams et al., 2011; Samhoury and Levin, 2012). With a similar goal in mind, geographers and spatial ecologists have

developed tools to map and measure the probability of exposure, and resulting vulnerabilities to marine species, from offshore wind farm impacts and vessel noise to fisheries bycatch (Bradbury et al., 2014; Cominelli et al., 2019; Baerum et al., 2019). Studies that use GIS to evaluate risk of these incidental interactions can help address the marine mammal bycatch problem because they present frameworks for the analysis of biodiversity and its susceptibility to one or more threats. Further, spatially explicit marine species risk assessments (e.g., Samhoury and Levin, 2012; Arkema et al., 2014; Briscoe et al., 2014) draw on participatory mapping, spatial analysis and data visualization techniques, which are particularly important in data-limited contexts (Ruckelshaus et al., 2015; Rosenthal et al., 2015), to engage stakeholders, establish trust, and access local knowledge (Wiber et al., 2004; Trimble and Berkes, 2013).

Despite advances in GIS technology for data collection, spatial analysis, and risk assessment, there remains a need for tools that incorporate the spatio-temporal dimension of SSF and include both bycatch exposure and its consequences to resident marine mammal populations. For this reason, we developed the Bycatch Risk Assessment (ByRA), a tool for spatially explicit risk assessment tailored specifically for marine mammal bycatch in data-limited fisheries. ByRA combines existing SSF and marine mammal data within an open source GIS-based framework. Most importantly, outputs from the ByRA, which include bycatch risk maps and plots describing species-gear interactions during different seasons and scenarios, are produced in accessible interactive web visualization and summary table formats. These products can therefore easily be communicated to non-expert stakeholders and vetted by experts for iterative improvement that augments the understanding of local fisheries, identifies and fills knowledge gaps, and can be used for designing strategies to meet sustainability objectives (Soykan et al., 2008; Alfaro-Shigueto et al., 2010; FAO, 2018).

Here, we present the results from an application of ByRA in Southeast Asia, specifically Malaysia and Vietnam. In these countries, fish are a major source of nutrition and livelihoods (Needham and Funge-Smith, 2015; Ahmad et al., 2016) and managers strive to assemble reliable, accurate, and spatially explicit information about SSF bycatch (Soykan et al., 2008; Reeves et al., 2013). The ByRA has two important characteristics that make it useful for understanding the distribution of fishing activities, marine mammals, and their interaction rates over space and time: (1) it is designed for rapid spatial assessment at the site scale, with SSF data inputs and assumptions communicated in a transparent manner; and (2) it is developed in close

collaboration with local stakeholders, agency personnel, and scientists, which is critical for actionable evaluation of different bycatch management interventions and strategies. ByRA facilitates stakeholder engagement, identifies areas of bycatch concern, and co-creates knowledge. We describe how ByRA can be used to leverage existing data on animal distributions and fisheries effort, integrate participatory mapping and local expert knowledge within an open source GIS framework.

2.2 METHODS

To develop the ByRA tool, we used three case study sites in Southeast Asia and the bycatch of two species of marine mammals. The sites were Kien Giang Biosphere Reserve (Vietnam), Kuching Bay and the Mersing Archipelago (Malaysia) (**Figure 2**). The first two experience bycatch of Irrawaddy dolphins (*Orcaella brevirostris*), and the latter has a significant dugong (*Dugong dugon*) population. At each of the field sites, we had the support of and worked collaboratively with local researchers and resource management agencies to undertake this work and use their data on marine mammal and small-scale fisheries vessel occurrence.

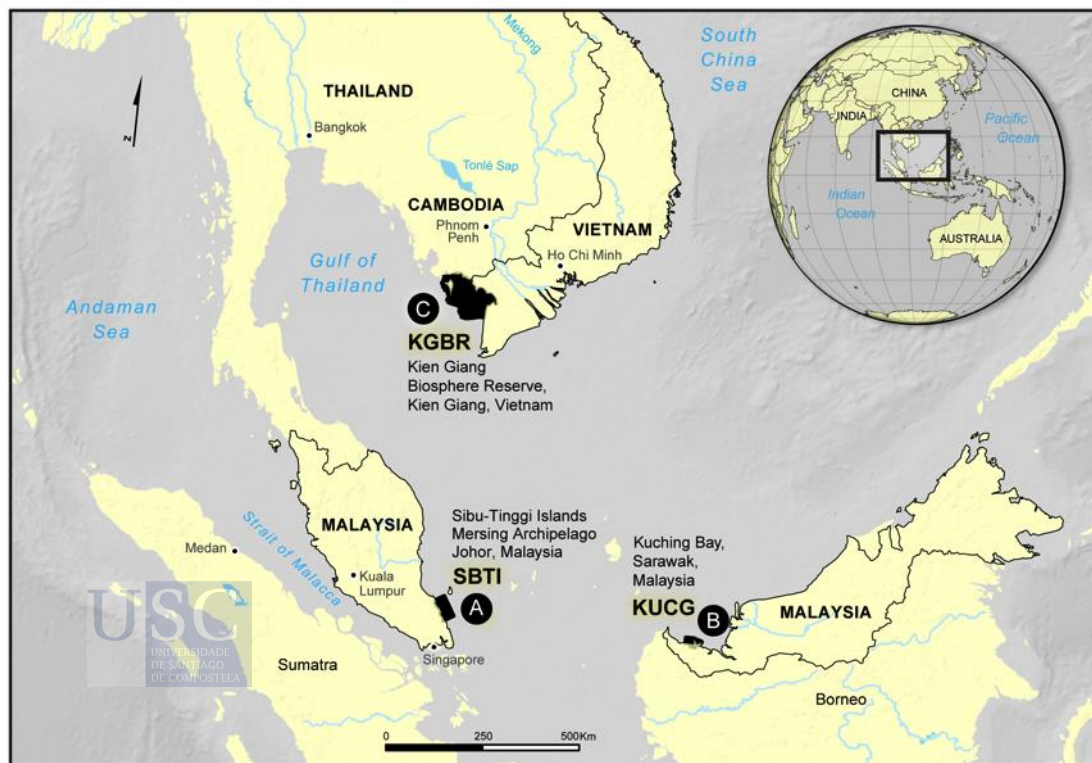


Figure 2. Three field sites selected in Southeast Asia. Areas of bycatch concern shown in black.

Bycatch risk was assessed from existing GIS data on marine mammal occurrence and fishing activities. These were mapped as habitat suitability and kernel density estimations, respectively. Fishing data were organized into five general gear categories (hook and line, nets, longlines, pots and traps, and trawls). Drivers of bycatch risk included environmental and sociopolitical factors, specifically seasonal weather (monsoonal) patterns and the current status of fisheries management that influence the distribution of marine mammal populations and SSFs. In Kuching Bay, Malaysia we assessed three scenarios (post monsoon, dry, and pre monsoon) to capture seasonal drivers known to change fishing patterns and Irrawaddy dolphin occurrence over time and, therefore, vary their exposure to bycatch risk, including encounter rates and timing of overlap with different gears in space. In all sites we identified consequences (impacts) of such interactions, including life history stages affected by gear-specific threats and local conservation status of the species. The following sections describe three key steps we took to leverage existing data with the ByRA tool: (i) engage stakeholders and acquire existing knowledge, (ii) build bycatch scenarios, and (iii) analyze and visualize bycatch risk and data uncertainty.

2.2.1 Engage stakeholders and acquire existing knowledge

Our methodological approach emphasized transparency and building collaborative relationships prior to acquiring data, including representatives from provincial governments, non-governmental organizations (NGOs), and scientists from local universities (**Table 1**). When requesting information, we described our intended use and respected constraints on sharing data based on local management hierarchy, and how it would be reported. For example, we received sensitive information (e.g., animal occurrence) in part because data holders were involved in the project from its inception, understood how the knowledge would be used, and knew their participation would be anonymized through the tool.

The following questions posed during the data acquisition phase yielded the most useful information to perform the ByRA: (i) What kinds of surveys and technology do you use to track marine mammals and fishing vessels? (ii) Which fisheries are present and what fishing gears are used? (iii) Which spatial data are available/exist for your field site to help understand risk of bycatch (e.g., sightings of marine mammals, bathymetric soundings from nautical charts, fisheries management guidelines)? (iv) Does the area have an existing fisheries observer

program, stranding network or other indications of work related to marine mammals and, if so, in which season(s) is monitoring conducted?

Table 1. Summary of each field site, including focal species, situational context, and partner(s).

Abbreviated and full name	Focal species	Situational context	Partner(s) and publications
A) SBTI: Sibu-Tinggi Islands, Mersing Archipelago, Johor, Malaysia	Dugongs (<i>Dugong dugon</i>)	The Mersing Archipelago lies along the southeast coast of Peninsular Malaysia; partners have been studying dugongs and the social science of dugong conservation since 2014	The MareCet Research Organization, Malaysia (Ponnampalam et al., 2015)
B) KUCG: Kuching Bay, Sarawak, Malaysia	Irrawaddy dolphins (<i>Orcaella brevirostris</i>)	Expansive estuarine system near the city of Kuching; partners have been studying cetaceans in Kuching Bay since 2008	Sarawak Dolphin Project; Institute of Biodiversity and Environmental Conservation, Universiti Malaysia Sarawak (Minton et al., 2011; Peter et al., 2016)
C) KGBR: Kien Giang Biosphere Reserve, Vietnam	Irrawaddy dolphins (<i>Orcaella brevirostris</i>)	A Biosphere Reserve designated by UNESCO in 2007; the area experiences one of the highest levels of fishing in the country; the Vietnam Marine Megafauna Network regularly monitors the waters of KGBR	Kien Giang Biosphere Reserve, Vietnam; Southern Institute of Ecology (Vietnam Academy of Science and Technology); Vietnam Marine Megafauna Network (Center for Biodiversity Conservation and Endangered Species) (Vu et al., 2017)

2.2.1.1 Areas of interest and subregions

Based on the spatial coverage of existing marine mammal and fisheries surveys, we structured the risk assessment by delineating areas of interest (AOI) that extended 10 km beyond locations with high SSF and marine mammal occurrence. This minimized edge effects in the geospatial calculations and focused on known areas of bycatch concern. To summarize and compare ByRA findings within each site, we defined between 4 and 8 subregions (**Figure 3**) that differed by ecological, environmental, and/or governance factors. The AOI for Sibu-Tinggi Islands (SBTI) spanned the existing Sultan Iskandar Marine Park and surrounding waters covering the extent over which the MareCet Research Organization conducts aerial distributional line transect surveys of dugongs and fishing activities (Ponnampalam et al., 2015). We divided the Kuching Bay site (KUCG) into four subregions as in Peter et al. (2016) to capture two ecologically distinct coastal and two hydrologically connected inland areas of Kuching's expansive riverine system. The AOI for Kien Giang Biosphere Reserve (KGBR) is the entire biosphere reserve,

which was subdivided following the survey strata used by the Vietnam Marine Megafauna Network (Vu et al., 2017).

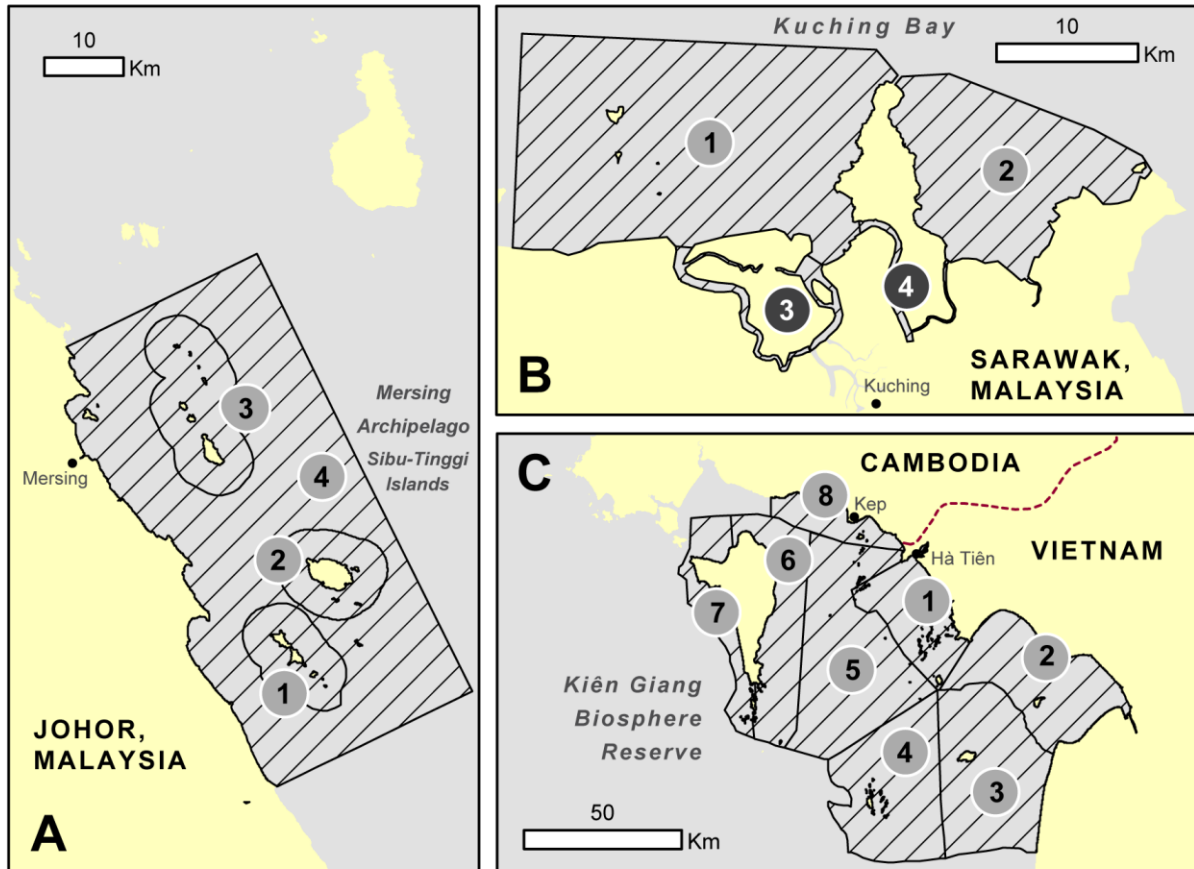


Figure 3. Subregions based on management, conservation, geopolitical and ecological similarities across the three SE Asian field sites. A) SBTI: Zones 1-3 delineate the 2 nautical mile boundaries of the existing Sultan Iskandar Marine Park. Zone 4 covers the remaining core dugong ranging areas as monitored by The MareCet Research Organization in Johor, Malaysia; (B) KUCG: 1) Santubong-Salak Bay, 2) Bako-Buntal Bay, 3) Salak Telaga Air Rivers, 4) Santubong-Buntal Rivers as in Peter et al. (2016). Darkest gray circles indicate the river network and estuaries of Kuching Bay; (C) KGBR: Zones 1-7 based on survey strata of the Vietnam Marine Megafauna Network.

2.2.1.2 Fishing activities and gear usage

We acquired information about fishing gears known to entangle, cause strandings or mortality of the two coastal marine mammals of interest. All fishing methods were organized into five broad but distinct categories: (1) nets, (2) trawls, (3) pots and traps, (4) longlines, and (5) hook and line (Table 2). Combining diverse fishing methods into five general gear categories streamlined the data acquisition process by helping local partners identify the most common fishing techniques in each site. For instance, we initially identified more than 20 different gears used by fishers

inside KGBR, Vietnam and neighboring Cambodian waters (Vu et al., 2017). These five groups of fishing activities known to encounter marine mammals served to elucidate gear-specific impacts during the expert judgement stage.

Table 2. Fishing methods and corresponding gear categories identified in each SEA field site.

Gear category	A) SBTI	B) KUCG	C) KGBR	
Nets	drift net purse seine gillnet	gillnet (“pukat / ranto”) set net - nylon drift net (“tangsi”) trammel net (“pukat 3 lapis / jaring”)	anchovy purse seine mackerel purse seine purse seine with light bottom gillnet surface gillnet shrimp gillnet	small size trammel net sardine gillnet crab gillnet crab trammel net mosquito net set net
Trawls	trawl net	trawl net	single (“normal”) trawl pair trawl electric trawl	
Pots and traps	trap	pots and traps	crab trap cuttlefish trap octopus trap rat tail	
Longlines	bottom line	longline - high: (“rawai timbul”) longline - low (“rawai tenggelam”)	fish hooks and lines	
Hook and line	line fishing	rod line (“pancing”)	squid hooks and lines	

2.2.1.3 Environmental and marine mammal sightings data

We began by compiling globally-available GIS layers (e.g., continental land mass and islands, major rivers, bathymetry) to characterize the coastal-marine environment in the study areas. Three online sources, in particular, (1) Natural Earth (naturalearthdata.com), (2) GADM (gadm.org) and (3) GPS Nautical Charts (fishing-app.gpsnauticalcharts.com) offered free reference layers and viewers to identify available nautical charts for purchase. Monitoring efforts by local partners documented sightings of animals and SSF during aerial and boat-based surveys between 2008 and 2016. These data included GPS location (latitude/longitude), individuals observed (number) or gear type (name), and time of year (season) for each recorded sighting (**Figure 4; Table S1.1**). Drawings of fishing grounds by fishers and government officers were also acquired for the SBTI and KGBR sites.

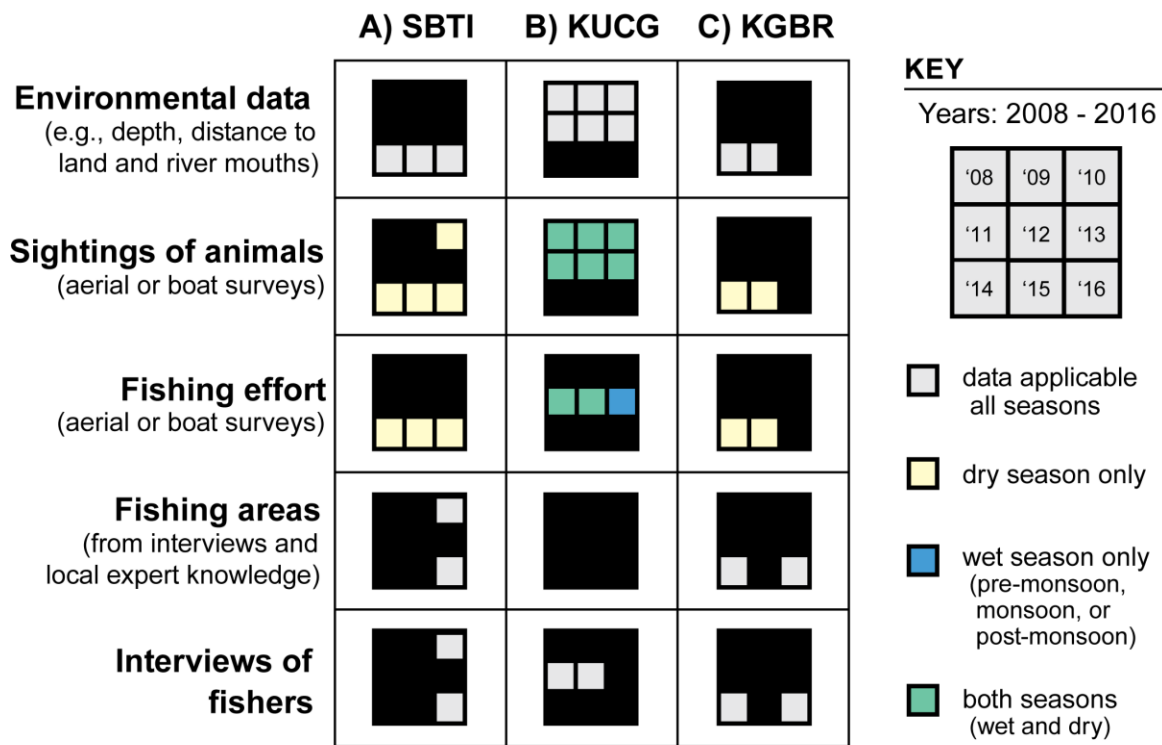


Figure 4. Inventory of environmental, biological, and fisheries data summarized by site, year, and season for each field site. Detailed metadata is available in Table S2.1 of the supporting information.

To prepare these layers for input to ByRA, we leveraged several spatial data processing routines in QGIS, an open source GIS software platform (QGIS Development Team, 2018). This included georeferencing and digitizing depth soundings from nautical charts, cost distance analysis, and inverse distance weighting for calculating distance to land and river mouths and producing bathymetric interpolation surfaces. Sightings of marine mammals coupled with environmental data were used in habitat suitability models to estimate their distribution and relative abundance in two Malaysian field sites.

2.2.2 Build bycatch scenarios

Scenarios are simplified descriptions of the present and possible futures (Henrichs et al., 2010). In this application of ByRA, we used scenario layers assembled in GIS to highlight suitable habitat areas for marine mammals and the current distribution and intensity of fishing activities by gear type. The scenarios included environmental and socio-political factors such as seasonal monsoons and fishing regulations, e.g., gear restrictions and sensitive habitat zones that can

influence the behaviors of fishers and marine mammals. The resulting scenario layers captured emergent patterns of species-gear interactions and were subsequently evaluated in three separate bycatch risk assessments (see Section 2.2.3: ‘Assess and visualize bycatch risk and data uncertainty’).

2.2.2.1 Habitat suitability

Habitat models are important tools to link marine mammal observations to environmental variables and identifying critical habitat (Redfern et al., 2006; Gregr et al., 2013). To estimate the distribution and relative abundance of dugongs and Irrawaddy dolphins in geographical space, we used species distribution models suitable for small sample sizes (Pearson et al., 2007; Elith et al., 2011; Briscoe et al., 2014), or a rule-based GIS approach for habitat suitability designed for data-limited situations. Depth, distance to land, and distance to river mouths have been shown by numerous researchers to be commonly important measures of habitat suitability for dugongs and coastal cetaceans, including Irrawaddy dolphins (see Minton et al., 2011; Briscoe et al., 2014; Jackson-Ricketts et al., 2020). The selection of the appropriate habitat model, to identify the most important areas within the distribution of a species, is site and dataset-specific (Valavanis et al., 2008) and good predictive ability has been achieved with parsimonious models (Pearson, 2007).

When marine mammal sightings were available, we applied the Maxent modeling software (biodiversityinformatics.amnh.org/open_source/maxent) to map suitable environmental conditions. Maxent needs 30 or more sightings for reasonable statistical power (Pearson et al., 2007; Tobeña et al., 2016) and this quantity of occurrence data existed for both Malaysian field sites. Presence-only data of Irrawaddy dolphins and dugongs occurrence were used to quantify the statistical relationship between predictor environmental covariates at locations where a species had been observed versus background locations in which no observation was done (Phillips et al., 2006). The Maxent algorithm inferred species distribution as a function of relevant environmental covariates (Dudík et al., 2007), which in the SBTI and KUCG sites were water depth (m), seafloor slope (degrees), and/or distance to land and river mouths (km). Next, we converted Maxent outputs from continuous to categorical data in order to match rating scores for each species-gear interaction (see Section: 2.2.3.2. ‘Spatially explicit criteria’). Habitat suitability layers were reclassified 1 to 3 (lowest to highest suitability) based on the omission rate

threshold of 10% (10% of the training occurrence data classified in non-suitable habitats) and the maximum relative occurrence rate (maximum probability for a species to be in a suitable habitat). Maxent variable selection, model testing, performance evaluation and validation is described in the Supporting Information (2.7.1.2 ‘Spatial data on species for the spatial overlap criterion’; **Tables S1.2 and S1.4; Figures S1.7-S1.10**).

There were insufficient observations of Irrawaddy dolphins ($n = 2$) for a correlative model in Vietnam. Instead, we employed a ‘low-data’ approach to map suitable habitat areas for Irrawaddy dolphins in KGBR based on Briscoe et al. (2014), which used a rule-based GIS analysis to designate areas of marine mammal habitat in an area with limited sightings data. The Union tool in QGIS was used to map the overlap between bathymetry and cost distance layers for depicting levels of habitat use in KGBR, specifically: (i) depth range (0–15 m), (ii) proximity to major river mouths (<25 km) and (iii) proximity to land (<10 km) based on previous Irrawaddy dolphin research (Parra et al., 2006; Minton et al., 2011; Jackson-Ricketts et al., 2020) (**Table S1.3; Figure S1.4**).

2.2.2.3 Seasonality

To account for changes in fishing activity and Irrawaddy dolphin habitat use throughout the year, we defined seasonal scenarios in KUCG and analyzed species-gear interactions over three distinct periods of time—i.e., post-monsoon (March to May), dry season (May to September), and pre-monsoon (September to December). In SBTI, aerial surveys to monitor dugongs and SSF around the Sibutinggi Islands were conducted during the dry season only, typically from November to February, to avoid the northeast monsoon (Suhaila et al., 2010). Fishing activity is less intense during the wet season (Lee S.F., personal communication, January 25, 2017) and so we focused on estimating dugong bycatch risk between March and November. In KGBR, an annual composite was used to identify spatial patterns of bycatch risk, as SSF activities remain relatively constant throughout the year in Kien Giang, Vietnam.

2.2.2.4 Fishing extent and intensity

To map fishing intensity by gear type, we used kernel density estimation (KDE), an interpolation technique available in QGIS for mapping hotspots that estimates location, spatial extent, and intensity of fishing activity (Shahrabi and Pelot, 2009). This non-parametric kernel method uses

the probability density function of a random variable (in this case, fishing gear incidence) and fits a smoothly tapered surface to each point (Kelsall and Diggle, 1995). A limited search distance parameter (1 or 2 km) was applied based on the distance between each boat or aerial line transect to create a continuous surface that represented the relative magnitude of fishing intensity by gear type over the entire area of interest (**Figure S1.11**). KDE was applied in two Malaysian field sites to analyze the gear occurrence data, collected as individual point locations. In KGBR, we compiled map layers representing fishing grounds based on areas previously identified during fisher interviews and by provincial government staff. Due to limited sightings of fishing activities in southern Vietnam, the ‘intensity of gear use’ exposure criterion was omitted from the risk equation.

2.2.3 Assess and visualize bycatch risk and data uncertainty

To assess risk of bycatch in each site, we combined geospatial layers of (1) species distribution, based on habitat suitability, and (2) fisheries presence, organized by gear type, distribution, and intensity of use (**Figure 5A**). The core functionality of the ByRA tool – to draw on assembled scores of interaction rates and assess bycatch risk (**Figure 5B-C**) – is executed through the user interface of InVEST, a freely downloadable software suite (Sharp et al., 2019; naturalcapitalproject.stanford.edu/software/invest). Here, we adapted the exposure-consequence criteria for habitat risk assessment (Arkema et al., 2014; Wyatt et al., 2017), where risk of fisheries bycatch is calculated as a function of the likelihood of exposure (interaction between the marine mammal and the fishery), and its consequence, which is the gear-specific impact to a species. For two additional exposure criteria unique to bycatch risk, we defined: (1) likelihood of interaction, as the probability that the animal will encounter a fishing gear if spatial overlap was detected, and (2) catchability, as the likelihood of animal capture by a gear type when this overlap occurs. *Sensu* Samhuri and Levin (2012), species-only consequence attributes were defined as: (a) the resilience of a species to a stressor (based on age of maturity, reproductive strategy, population connectivity, local status of species) and (b) its sensitivity (mortality and life stages affected by gear).



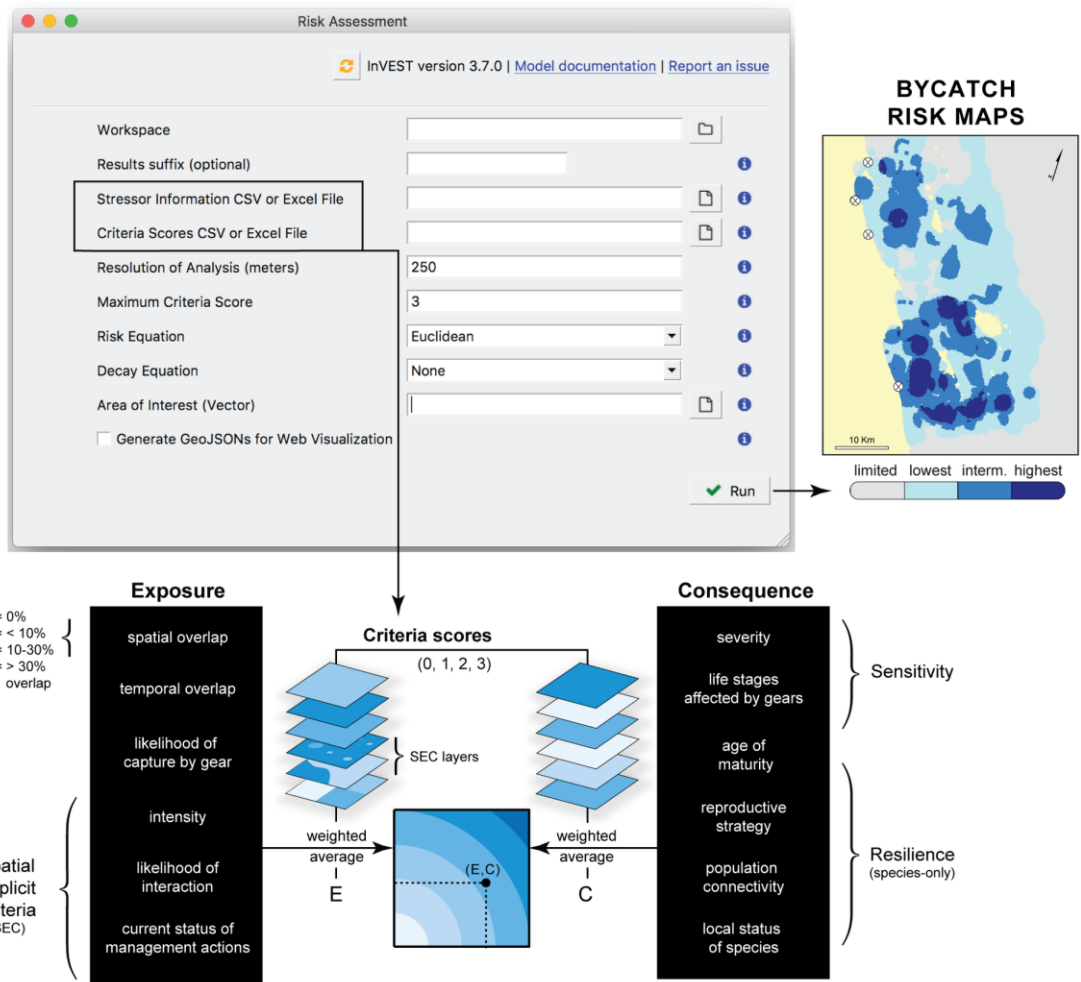
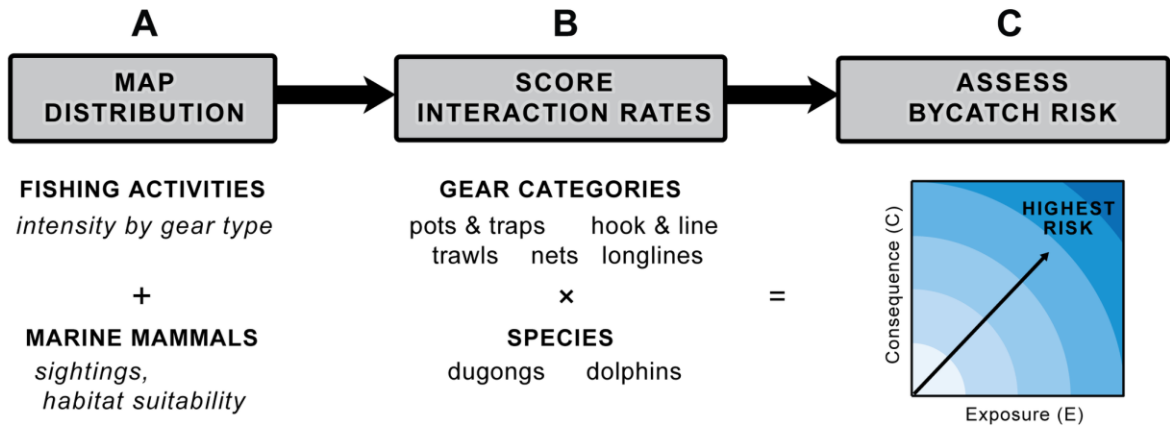


Figure 5. Bycatch risk assessment conceptual model and tool process diagram. Top panel depicts how layers and rating scores are assembled and combined. Bottom panel shows the tool interface and steps to estimate risk for each grid cell within an area of interest. Colored bands in the risk plot are numerically determined and based on the range of exposure and consequence scores (0, 1, 2 and 3 in this assessment).

2.2.3.1 Expert evaluation

Species-gear interactions for a total of twelve bycatch exposure and consequence criteria were scored as guided by field observations, literature review, and, subsequently, expert opinion (**Table 3**). In August 2017, researchers and agency personnel specializing in marine biology, fisheries ecology, marine veterinary medicine, biogeography, and social sciences participated in a judgment process to score interactions (1 to 3, low to high contribution to risk) along with their confidence in each opinion. Representatives from each field site, with working knowledge of marine mammals and SSF activities, set the final rating scores. The supplementary information lists individual exposure (E) and consequence (C) criteria, along with justifications for the interaction ratings, data quality and attribute weights (**Tables S1.5-S1.6**).

2.2.3.2 Spatially explicit criteria

When available GIS data could be used to characterize species-gear interaction rates, spatially explicit criteria (SEC) layers were created to differentiate rating scores over space (1 to 3, lowest to highest exposure or consequence; **Figure 5**). For this application of ByRA we mapped and scored interaction rates for three exposure criteria: (i) intensity of gear use, (ii) current status of management, and (iii) likelihood of interaction between the gear and species (**Table 3**; **Figures S1.11-S1.13**). A geospatial workflow was coded as a plugin for QGIS (available at mmbycatchtoolbox.org) to automate the necessary GIS operations (i.e. unions and definition queries) for preparing ByRA SEC input layers. Each output was reclassified (1 to 3; low to high) using a Jenks natural breaks algorithm to minimize the variation within each class. Encounter rates, or ‘likelihood of interaction’, were calculated as the sum of overlapping layers for habitat suitability (1–3) and gear intensity (1–3), where a sum total of 6 or 5 = high, 4 = medium, and 3 or 2 = low likelihood of interaction between gear and species. Current status of management was scored as “1” if implemented and “2” if identified for a given area. Areas where no management or regulation was identified were scored “3”, which was the maximum score (highest contribution to exposure) for this criterion.



Table 3. Definitions and scoring bins for the exposure, consequence, and Spatially Explicit Criteria (SEC).

Exposure criteria	High risk (3)	Medium risk (2)	Low risk (1)	Description
Spatial overlap	>30% of species overlaps with gear	10-30% of species overlaps with gear	<10% of species overlaps with gear	The overlap by grid cell between the distribution in space of each species and gear is calculated by the toolbox
Temporal overlap	all year (12 months)	most of year (4-11 months)	occasional (1-3 months)	The duration of time that the species and gear overlap in space
Intensity of gear use	high intensity	medium intensity	low intensity	Overlap between gear-type density and species distribution (SEC)
Likelihood of interaction between gear and species	high likelihood	medium likelihood	low likelihood	The overlap between habitat suitability and intensity of gear use. The resulting encounter rates are ranked low to high (SEC)
Likelihood of capture by gear	high likelihood	medium likelihood	low likelihood	The “catchability” of species by gear includes behavior of animals during interaction, for example, dugong may roll around nets
Current status of management	no strategies identified / implemented	management strategies identified, not implemented	management strategies identified & implemented	Management strategies can limit the use of certain gears in certain areas, thereby mitigating negative impacts to species (SEC)

2 Management tool: Bycatch risk assessment

Consequence criteria	High risk (3)	Medium risk (2)	Low risk (1)	Description
Sensitivity				
Mortality	lethal	sub-lethal	negligible	The severity (direct effect) of gear on mortality rate of a species
Life stages affected by gear	adults only	mixed	juveniles only	If a gear strands a species before they have the opportunity to reproduce, recovery is likely to be inhibited
Resilience				
Age of maturity	> 4 years	2 - 4 years	< 2 years	Greater age at maturity corresponds to lower productivity
Reproductive strategy	long calving interval / high parental invest	medium calving interval / high parental invest	short calving interval / med parental invest	The extent to which a species protects and nourishes its offspring
Population connectivity (DPS = distinct population segment; ESU = evolutionary significant unit)	negligible exchange between the focal regional population and other populations	occasional movement/ exchange between the focal regional population and other populations	regular movement/ exchange between the focal regional population and other populations	The realized exchange with other populations based on spatial patchiness of distribution, degree of isolation, and potential dispersal capability; based on monitoring surveys or direct tracking estimates; 3 = DPS or ESU and 1 = not a DPS or ESU
Local status of the species	endangered	threatened or of concern	low concern	The conservation status of the species in the country

2.2.3.3 Measuring bycatch risk

Two common methods for measuring environmental risk based on expert opinion are Euclidean distance and multiplicative functions. Cumulative impact mapping studies tend to use a multiplicative approach (Halpern et al., 2008; Ban et al., 2010), whereas species risk assessments typically estimate risk as the Euclidean (straight-line) distance for each species-threat combination in risk plots (Samhuri and Levin, 2012; Arkema et al., 2014), which leads to a more precautionary scoring and higher risk (Patrick et al., 2010; Hobday et al., 2011). A recent evaluation of qualitative risk assessment frameworks suggests better model performance using a Euclidean distance measure (Hordyk and Carruthers, 2018). Therefore, we selected Euclidean distance, from the origin (minimum score) to the average of criteria scores for exposure (E) and consequence (C), to quantify bycatch risk (**Eq. 1**). If a stressor and species did not overlap, the tool assumed that $E = 0$, $C = 0$, and therefore Risk (R_{ij}) = 0 for the grid cell being evaluated.

$$R_{ij} = \sqrt{(E - 1)^2 + (C - 1)^2} \quad (\text{Eq. 1})$$

2.2.3.4 Characterizing uncertainty of data sources

We applied a variable weighting structure and data quality scores – i.e., a weighted-average where d_i = data quality weight and w_i = attribute weight – to account for data uncertainty and substantiate the species-gear interaction ratings for each site (**Eq. 2; Table S1.7**). To characterize data input uncertainty for stakeholder outreach, we designed a simple tri-color matrix (**Table 4**). ByRA outputs coupled with a visualization of data quality were shared with managers to convey how existing information in data-limited sites could be used to further improve the quality of risk estimates over time.

$$E = \frac{\sum_{i=1}^n \frac{e_i}{d_i \cdot w_i}}{\sum_{i=1}^n \frac{1}{d_i \cdot w_i}}$$

$$C = \frac{\sum_{i=1}^n \frac{c_i}{d_i \cdot w_i}}{\sum_{i=1}^n \frac{1}{d_i \cdot w_i}} \quad (\text{Eq. 2})$$



Table 4. Diagnostic to characterize data uncertainty based on where existing information fits along a spectrum of green-yellow-red (highest to lowest data quality, respectively).

Data type	Green	Yellow	Red
Animal sightings distribution	Data collected during line transect survey. Data could be used to estimate relative abundance with robust methodologies and measurements of uncertainties.	Sightings/photo id collected during opportunistic surveys. Relative abundance estimation might be possible.	Very few sightings were collected during line transect or opportunistic survey, no formal abundance estimation possible.
Habitat suitability	Estimated from modeling, quantification of uncertainty available from modeling, collection of environmental variables.	Estimated using non-modeled distribution methodology, minimal environmental variables were collected.	Information from other regions used to estimate animal distribution.
Fishing effort / gear type densities	Data available such as fishing effort per unit of distance or time possible using modeling, uncertainty measurements possible.	Spatial distribution of fishing gears, relative (to time or space) fishing effort or fishing gears, based on interviews or expert opinion.	Sparse or incomplete data, no geospatial or precise localization of the fishing effort/gear distribution.
Bycatch / stranding data	Robust data about bycatch is available from interview data / observers on boat or stranding data. Estimation of bycatch rate possible with measurement of uncertainties.	Relative estimation of bycatch from interviews or stranding data.	No estimation of bycatch or strandings available.

2.3 RESULTS

ByRA generated accessible, non-technical maps for visualizing bycatch risk estimates. Map outputs captured spatial trends in species distribution and fishing effort to highlight fishing areas likely to have high interaction rates as well as seasonal changes in bycatch risk. The uncertainty of data inputs was characterized and outputs were error checked and improved by local experts and stakeholders.

2.3.1 Visualizing bycatch risk

We found that risk estimates in ByRA were driven primarily by the fishing method (gear type) and the density of fishing activities that were found to overlap suitable marine mammal habitat areas ('intensity of use' and 'likelihood of interaction' exposure criteria, respectively). Areas

with high marine mammal occurrence and fisheries activity were predicted as the highest risk of SSF bycatch. Specific to the three field sites, areas where nets and trawls were used (gears rated as highest likelihood and impact on a number of exposure and consequence attributes by local experts and the literature, **Tables S1.5-S1.6**) were identified by the tool to pose substantial risk to both Irrawaddy dolphins and dugongs. By season and scenario, a range of bycatch risk maps were produced—classified as lowest, intermediate and highest risk—the latter of which served to pinpoint areas of greatest bycatch concern (**Figure 6**).

Visualization of risk outputs also identified drivers of risk by gear type and subregion (**Figure 7**). Nets and trawls were scored by local experts to have a considerably higher likelihood (exposure) and impact (consequence) to both marine mammal species where they co-occurred, while pots and traps were more benign, especially for dugongs. The top-right corner of ByRA risk plots (darkest blue color bands in **Figure 7**) indicated which gears were the strongest drivers of bycatch risk, when each species-gear interaction occurred. This included nets for dugongs in SBTI, nets and pots and traps for Irrawaddy dolphins in KUCG, and additionally trawls for Irrawaddy dolphins in KGBR. If these interactions were to occur in areas of highest suitability for marine mammals, the estimated risk increased further (rightward movement along the x-axis) due to a greater likelihood of species-gear interaction and, therefore, higher average exposure score. Variation in bycatch exposure over space and time was captured as gear-specific exposure ratings, and then reflected as a subset of spatially explicit criteria input layers (**Figure 7; Figures S1.11-S1.13**). Separately, we shared SEC layers in a simple visual format (maps and tables) with marine mammal scientists and managers to facilitate discussions about data uncertainty and validate preliminary findings.

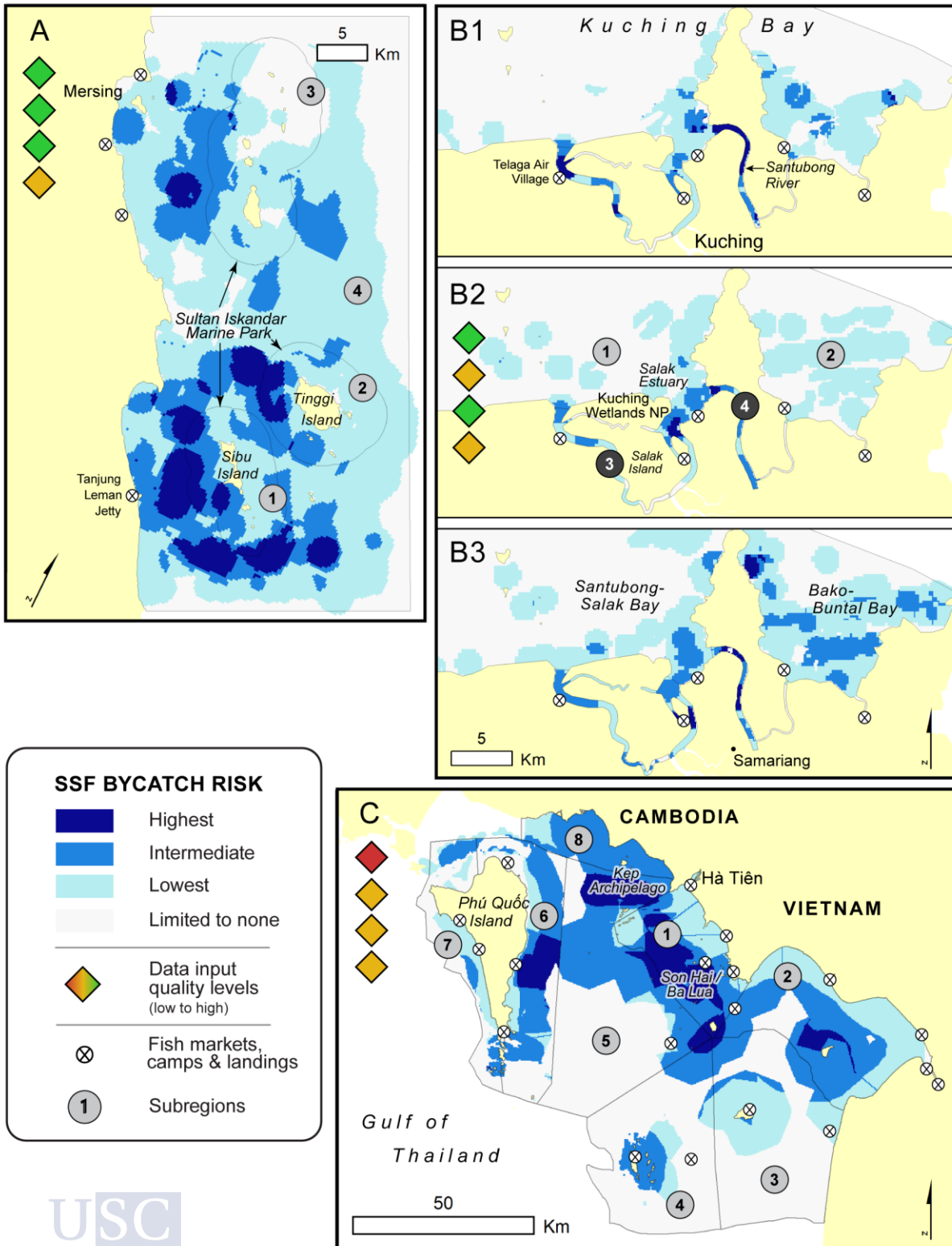


Figure 6. Estimated bycatch risk in three field sites (A-C). (A) Sibutinggi Islands, Johor, Malaysia (SBTI) for dugongs, (B) Kuching Bay, Malaysia (KUCG) during the dry season, pre-monsoon and post-monsoon, B1-3 respectively, and (C) Kien Giang Biosphere Reserve, Vietnam (KGBR) for Irrawaddy dolphins. Data quality levels of four categories of ByRA inputs from Tables 4 and 5 are displayed as colored diamonds.

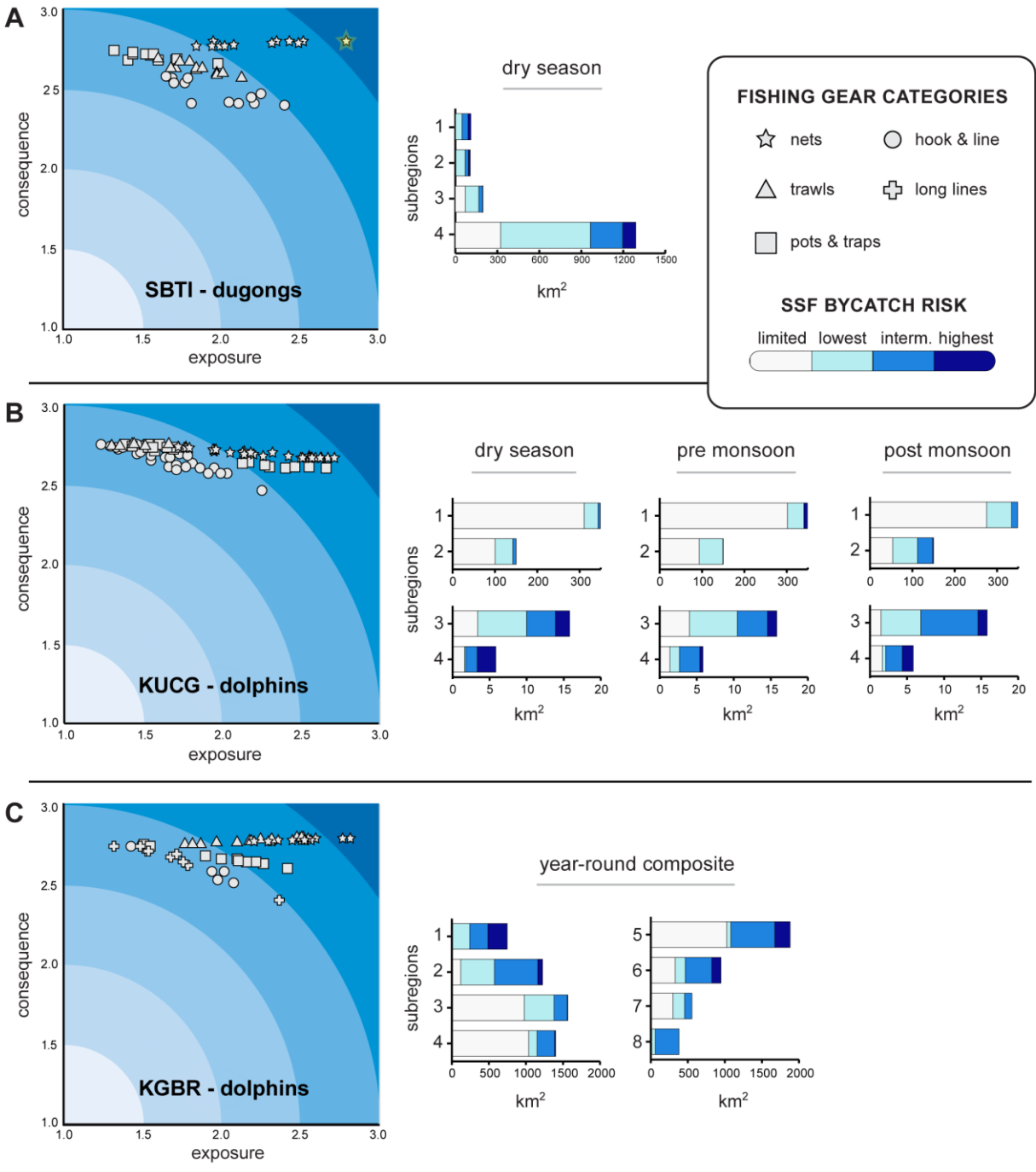


Figure 7. Plots and bar charts summarizing drivers and emergent patterns of bycatch risk. Coordinates (gray symbols) are mapped as the weighted average of exposure and consequence criteria scores. They explain the contribution to risk of each gear category by subregion, habitat suitability type, and scenario. ByRA calculates risk based on distance from the origin (exposure = 1.0, consequence = 1.0) to each coordinate on a cell-by-cell basis where darker blue indicates higher risk. Star symbol with a yellow halo at the top-right indicates conditions of highest risk. Bar charts show total area at risk (x-axis) by risk level (blue color palette) and subregion (y-axis) for each field site (A-C) and scenario. Note the two x-axes for the KUCG site in panel B.

2.3.2 Capturing expert knowledge

ByRA's map input layers and species-gear interaction scores were iteratively improved through expert review and feedback using interactive maps and discourse in a participatory GIS framework. A combination of regional meetings, workshops, and expert interviews served to refine the approach and confirm early results. A transparent and flexible approach to stakeholder involvement and risk assessment was cited as key by our collaborators to build trust in the process and elicit local knowledge often buried in reports and on the data hard drives of representatives from provincial governments and other institutions. For example, colleagues based in Vietnam, who were not able to attend a meeting with our team, later provided key data layers on the location of river mouths for modeling Irrawaddy dolphin habitat suitability and common gears observed by government officials in fishing areas where GPS use was prohibited.

Two site visits in 2017 served to build a shared understanding of the ByRA approach among the project team and how ByRA could be further standardized to accommodate varying quantities and qualities of data and fill critical information gaps. The second site visit was a ByRA learning exchange workshop with our in-country collaborators to demonstrate how they could apply the tool in their home countries. We found that including these face-to-face meetings in our project budget was a necessary step to galvanize action across the region in support of research efforts, specifically, to make better use of existing data from animal and SSF observation records, expert knowledge, government reports, and the literature. These connections also made subsequent engagement and remote support for applying the ByRA in new geographies easier because many scientific and technological hurdles (e.g., capacity strengthening, understanding the methodological approach, user interface and data uncertainty) had been overcome.

2.3.3 Characterizing uncertainty

In-person meetings with stakeholders in August 2017 yielded a diagnostic for data uncertainty, showing a gradient of data input quality across the three field sites (**Table 5**). This was used by our team to identify and discuss commonalities across locations and taxa, prioritize new techniques to undertake such as local surveys of environmental data, animal occurrence, fisheries effort, and acknowledge uncertainty as part of outreach. We found that by visualizing uncertainty of data inputs qualitatively (using green, yellow and red colors of a globally-recognized traffic

light signal), scientists and managers had a clearer set of priorities for future acquisition and integration of existing information; with an emphasis on filling data gaps, reducing data uncertainty in areas of highest bycatch concern identified by the tool, and restarting monitoring activities that had stalled due to funding limitations.

Table 5. Classification of data input uncertainty in three SEA field sites. Green = substantial data available, yellow = limited data available, and red = data are either incomplete or severely limited.

Data type	Field sites		
	SIBU	KUCG	KGBR
Animal sightings distribution	Systematic transect aerial survey	Systematic transect boat survey	Systematic line transect boat survey; not enough sightings to characterize distribution
Habitat suitability	Seagrass data and mammal acoustics; limited environmental data collected during survey	Environmental data collected with the transect survey	Environmental data partially collected
Fishing effort / gear type densities	Collected during line transect surveys and from interviews		From interviews only
Bycatch / stranding data	From interviews and some records of stranded animals due to interactions with fisheries		Presence absence of bycatch from interviews only

ByRA map outputs were also error checked by in-country collaborators with certain areas flagged as potential over- or underestimates of fishing activity and habitat suitability, two important drivers of bycatch risk in the tool. We could only characterize data uncertainty and validate outputs because local experts were present to corroborate bycatch risk estimates based on information previously provided by researchers and knowledge holders. The visualization of uncertainty across a range of data inputs and field sites assisted researchers in Malaysia, Vietnam, and Cambodia to chart a path forward by concentrating limited resources in areas with substantial information gaps and consider monitoring protocols and technologies that had already yielded substantial returns in neighboring regions (see Vu et al., 2017 for KGBR, Vietnam example).

2.3.4 Emergent patterns and findings

For all three SEA field sites, ByRA outputs identified emergent spatial trends of interactions between SSF and marine mammals; specifically, fishing gears and locations that are likely to



have high bycatch rates and damaging effects on marine mammal population viability. For instance, coastal areas with the highest level of bycatch risk to dugongs (darkest blue bars in **Figure 7A**) were well distributed across the four subregions of SBTI (between 13–44 km²) despite subregion 4 being the most expansive (68% of combined total area of subregions 1–3), closest to the main fishing village (Mersing), and least protected (no fisheries management identified). ByRA revealed this and other non-obvious patterns that would be difficult to uncover without a spatio-temporally explicit risk assessment framework. For instance, risk coordinates plotted for each species-gear interaction and range of habitat suitability highlighted that nets deployed in some areas of SBTI posed an intermediate level of bycatch risk, similar to other SSF gears. On the other hand, risk from nets was highest inside subregion 3 (**Figure 6A** and **Figure 7A**). Furthermore, area summaries of bycatch risk levels as bar charts (**Figure 7**) displayed how risk shrinks and expands over space and time, including seasonal changes in total area of estuarine and coastal waters at greatest SSF bycatch risk.

As illustrated in the Kuching Bay (KUCG) field site, seasonal snapshots depicted how bycatch risk is likely to change during the year and within subregions (**Figure 6B**). For the dry season (May to September) the greatest proportion of intermediate-highest risk, relative to total area, was inside the river system of subregions 3 and 4 (37 and 70%, respectively) compared to just 2 and 5% in coastal subregions. After the wet season, additional risk hotspots emerged in coastal areas of subregions 1 and 2 (**Figure 7B**) because SSF activities increased and Irrawaddy dolphin occurrence was high in these areas. Distance to land was identified by Maxent to be the most important environmental variable for Irrawaddy dolphins post-monsoon (50% overall contribution; **Table S1.4**). As a result, bycatch risk estimates shifted to their highest levels in these coastal areas of KUCG until the dry season, specifically where there was high SSF occurrence and no fisheries management strategies identified.

The most data-scarce of the three SEA sites, KGBR Vietnam represents a template for ByRA users applying the tool in places where existing data are severely limited (red to yellow uncertainty levels in **Table 4**). Despite relying entirely on data collected by others who used indirect measures of SSF activity and marine mammal distribution (i.e. fisher interviews, participatory mapping, and environmental overlays such as distance to land, depth and other optimal habitat variable ranges), we found three distinct areas within subregions 1, 5 and 6 that accounted for almost all (88%) of the highest level of bycatch risk across the KGBR site.

Therefore, it was still possible to identify specific locations in southern Vietnam – i.e. greatest likelihood of interaction between dolphins and high-impact gears (nets and trawls, in this case) – as priority candidates for further monitoring and data collection.

2.4 DISCUSSION

In this study, we present spatially explicit estimates of bycatch risk in three SE Asian field sites. A total of 10,810 km² of estuarine and coastal waters were systematically screened to home in on 805 km² (approximately 7.5% of the total area of interest) identified as the highest level of bycatch risk to dugongs and dolphins. For these areas of concern, nets and trawls were the gear types associated with the highest bycatch risks, in large part, due to greater exposure (distribution and intensity relative to other SSF gears) and consequences (mortality) if these fisheries were to encounter marine mammals. The spatially and temporally explicit scenarios in Kuching Bay showed patterns of risk that shifted to and from the estuarine and coastal waters across seasons. By integrating information from fisher interviews and line-transect surveys, we mapped the likelihood of species-gear interactions over space and time and at local scales. In parallel, geospatial analysis techniques such as participatory mapping with local scientists and agency experts were used to build habitat suitability layers by site and season. Finally, SSF gear and species interaction rates were scored to assess and map bycatch risk and data uncertainty. These ByRA outputs demonstrated the potential of a new tool to co-create knowledge and garner insights about bycatch exposure in data-limited small-scale fisheries.

Characterizing the effects of marine mammal bycatch through space and time can be compared to finding a needle in a haystack—as bycatch is difficult to observe and quantify (Read, 2008; Lewison et al., 2018). However, the results from ByRA are encouraging. Despite the challenges to sustainability that small-scale fisheries face, ByRA demonstrates the ability to make use of limited data as a means of addressing some of these challenges, e.g., pinpointing fishing areas where and when to concentrate efforts (monitoring, education, and outreach) and, conversely, identifying low risk areas where additional effort is not warranted, saving time and resources. This kind of information is urgently needed in Southeast Asia, and many parts of the developing world, where resources and capacity to conserve marine biodiversity and mitigate bycatch are scarce (Soykan et al., 2008; Teh et al., 2015). This can also help fisheries in developing countries comply with new import regulations from provisions within the Marine

Mammal Protection Act (Williams et al., 2016; Johnson et al., 2017).

Against a backdrop of the importance of SSF as nutrition source and livelihood for coastal communities (Béné et al., 2007; FAO, 2012), effective bycatch mitigation depends first on identifying emergent patterns of exposure, which is driven by myriad factors including prey abundance, seasonality, and gear preferences (Stobutzki et al., 2001; Shester and Micheli, 2011; Alfaro-Shigueto, 2018). Nevertheless, outputs from ByRA identified patterns in bycatch occurrence (e.g., particular species, fishing gears, and locations) that had high interaction rates. For instance, in subregion 3 of SBTI, interactions between nets and dugongs were numerically determined to be the highest risk level (2.79 for exposure and 2.80 for consequence; max score of 3.00) of all species-gear interactions evaluated. Interestingly, the bycatch exposure score was highest for dolphins in KUCG with nets deployed during the pre-monsoon in subregion 4 (2.71 out of 3.00), which aligns with evidence that gillnets are an acute threat causing direct mortalities to marine mammals in significant numbers worldwide (Read, 2008; Reeves et al., 2013). By disentangling this and other drivers of exposure, we found patterns of highest bycatch risk under conditions of (1) high species-fishery encounter rates, (2) high-impact gears in use (especially nets and trawls) (3) no management identified, and (4) suitable marine mammal habitat.

2.4.1 Limitations and simplifications

An obvious information gap in our study was bycatch data from onboard observers, a common requirement in US fisheries policy (NOAA, 2016), and a monitoring technique in SEA that is not commonly utilized. To date, efforts to characterize bycatch and map risk in Southeast Asia have relied almost entirely on fisher interviews to map the extent of fisheries operating in the region (Briscoe et al., 2014; Pilcher et al., 2017). Without technology to comprehensively monitor use of the marine environment by fishers, we were unable to capture activities or interactions that occur at night or with discarded or unattended gear. The use of onboard observers, remote electronic monitoring, and other rapid, low-cost technologies (Pilcher et al., 2017), would greatly enhance the ability of ByRA to identify high-risk, under-surveyed areas. However, one of the strengths of the ByRA approach is the ability to accurately describe and account for data uncertainty, a clear demonstration of how even low-resolution information can be applied to more effectively investigate risk and guide future bycatch monitoring and management (Hoffman and Hammonds, 1994; Lewison et al., 2018). For example, areas of highest bycatch risk in the

SBTI field site provide more evidence that supports recent calls for designation of a dugong sanctuary inside the Mersing Archipelago (Ponnampalam et al., 2015). Likewise, despite a paucity of data in KGBR, habitat suitability maps derived entirely from GIS overlays showed strong agreement with Irrawaddy dolphin sightings acquired independently of the ByRA analysis (**Figure S1.4**; Vu et al, 2017; Tubbs et al., 2019). Although these analyses provide more information and insight on bycatch risk areas and management interventions that are likely to reduce risk, additional research is needed to compare modeled outputs to other modeled empirical data on bycatch rates, or strandings (Hamel et al., 2009; Peltier et al., 2012).

Another consideration for future research is the need to account for antagonistic or synergistic effects that may better reflect the total risk of bycatch to the species (Hordyk and Carruthers, 2018). While ByRA's default calculation of cumulative risk is additive (sum of individual risk scores for all gear types evaluated), intermediate outputs can be reanalyzed and combined as appropriate in each decision context. There is also a need for better data on the interaction rates of species with SSF gears such as gillnets and traps that also have ecological impacts to habitats and ecosystems (Shester and Micheli, 2011; Alfaro-Shigueto et al., 2018). We took a precautionary approach of maximum risk based on expert opinion (as in Stobutzki et al., 2001; Patrick et al., 2010; Hobday et al., 2011), due to the strong evidence that associates SSF gear with marine mammals stranding and mortality (Van Waerebeek and Reyes, 1994; Jaaman et al., 2008). Data uncertainty with fishing locations is also an important consideration. Our kernel density estimates were limited by a survey line artifact (circular horseshoe pattern) that when reclassified into three levels of exposure gave the effect of discontinuity in the fishing effort and gear-type intensity maps (**Figures S1.11 and S1.13**). Data uncertainty levels yellow and red (adequate to limited data quality) served to flag this and other areas for improvement (**Table 5**).

2.4.2 Future directions

Marine mammal scientists and conservation groups in the SEA region continue to collect data on environmental habitat variables to understand seasonality, cetacean behaviors, and enhance the effectiveness of protection and management measures (Ponnampalam et al., 2015; Kuit et al., 2019). This information is critical, especially to reduce bycatch risk. These data will inform habitat model selection (Tobeña et al., 2016; Peter et al., 2016; Tubbs et al., 2020) and increase ByRA's analytical complexity (Lewison et al., 2018) in support of more dynamic ocean

management (Hazen et al., 2018). For example, marine megafauna networks in Vietnam and Cambodia aim to fill information gaps over the next few years, e.g., additional sighting records of Irrawaddy dolphins for correlative habitat models such as Maxent, while integrating local knowledge and strengthening capacity to generate actionable information for communicating with government officials and policy makers over the longer term (Vu et al., 2017). These efforts may be more feasible in areas identified by the tool as highest relative risk (e.g., subregions 1–2 and 5–6 in KGBR) and where there is likely to be interest in the conservation of important marine mammals for tourism and alternative livelihoods (Berkes, 2001; Béné et al., 2007; Kosamu, 2015). Deployment of other technologies such as passive acoustic monitoring and telemetry can also aid in these efforts.

Species-gear interactions and their impacts vary widely by location and across small-scale fisheries (Soykan et al., 2008; Shester and Micheli, 2011; Alfaro-Shigueto et al., 2018), which underscores the importance of ByRA as a tool to integrate existing knowledge, characterize bycatch likelihood and identify areas where bycatch risk is high. We found that a substantial investment in the process of scoring species-gear interactions (exposure and consequence criteria) based on available field data, literature, and expert knowledge was essential to capture salient effects associated with small-scale fisheries gears and other local fishing methods. In the SEA case studies, consequence criteria scores had a limited range because only one species was evaluated in each site. Still, variation in the final weighted average of exposure criteria scores highlight how much risk estimates posed by one gear can vary over space and time (e.g., 1.71 to 2.81 range of exposure scores for nets within SBTI). Spatial planners and managers can benefit from this insight by mapping fishing gears and at-risk marine species (Marçalo et al., 2015; Cominelli et al., 2019; Jackson-Ricketts et al., 2020) and then applying ByRA to identify bycatch hotspots where mitigation is needed to reduce bycatch risk.

There are also opportunities to apply ByRA for multispecies assessment, which can illuminate high risk gears across species by season or scenario. This may include comparing risk between fishing areas, how different gears contribute to risk, or evaluating alternative management strategies under consideration (Samhuri and Levin, 2012; Arkema et al., 2014; Duggan et al., 2015). Through leveraging global systems and regional seafood ratings programs that compile small-scale fisheries knowledge (Chuenpagdee et al., 2017; SFW, 2020), multi-species risk assessment can be applied to disentangle the human dimension of fisheries bycatch

and integrate locally-relevant criteria, such as set height or mesh strength of nets, that embrace the conceptual complexity of marine megafauna conservation research (Lewison et al., 2018). After risk baselines have been developed (Hodgson et al., 2019; Tulloch et al., 2020), it is possible to compare feasible management and policy interventions. Finally, GIS-based scenarios that capture inter-annual variability and modifications of fishing gears (Alfaro-Shigueto et al., 2010) could be incorporated into ByRA to examine how the location and timing of risk is likely to change in the future, and anticipate at-risk areas in need of further monitoring and evaluation.

2.5 CONCLUSION

We created a spatially explicit management tool (ByRA) to better understand and characterize risk of bycatch posed by common fishing gears in data-limited small-scale fisheries. Three unique field sites, where substantial marine mammal bycatch has been reported, were systematically screened using existing data and a powerful form of visualization to map areas and seasons of concern in a region where distinct spatio-temporal patterns of bycatch risk had not been identified. ByRA employed a range of geospatial and participatory engagement techniques—including specific methods tailored for data scarce areas—to compile and analyze existing information about small-scale fisheries and better plan further research, bycatch mitigation, and species recovery and protection. This information enables managers to establish baselines, deliberate with stakeholders on the next steps for data acquisition, and identify interventions that are likely to mitigate bycatch risk in small-scale fisheries. It may also help these fisheries comply with European Commission and U.S. regulations (NOAA, 2016; European Commission, 2016) that require efforts to reduce the acute threat of marine mammal bycatch to sustainable levels.

2.6 REFERENCES

- Ahmad, N. I., Wan Mahiyuddin, W. R., Tengku Mohamad, T. R., Ling, C. Y., Daud, S. F., Hussein, N. C., et al. (2016). Fish consumption pattern among adults of different ethnics in Peninsular Malaysia. *Food & nutrition research*, 60(1), 32697.
- Alfaro-Shigueto, J., Mangel, J. C., Darquea, J., Donoso, M., Baquero, A., Doherty, P. D., & Godley, B. J. (2018). Untangling the impacts of nets in the southeastern Pacific: Rapid assessment of marine turtle bycatch to set conservation priorities in small-scale fisheries. *Fisheries research*, 206, 185-192.
- Alfaro-Shigueto, J., Mangel, J. C., Pajuelo, M., Dutton, P. H., Seminoff, J. A., & Godley, B. J. (2010). Where small can have a large impact: structure and characterization of small-scale fisheries in Peru. *Fisheries Research*, 106(1), 8-17.
- Allison, E. H., & Ellis, F. (2001). *The livelihoods approach and management of small-scale fisheries*.

- Marine policy, 25(5), 377-388.
- Arkema, K. K., Verutes, G., Bernhardt, J. R., Clarke, C., Rosado, S., Canto, M., et al. (2014). Assessing habitat risk from human activities to inform coastal and marine spatial planning: a demonstration in Belize. *Environmental Research Letters*, 9(11), 114016.
- Bærum, K. M., Anker-Nilssen, T., Christensen-Dalsgaard, S., Fangel, K., Williams, T., & Vølstad, J. H. (2019). Spatial and temporal variations in seabird bycatch: Incidental bycatch in the Norwegian coastal gillnet-fishery. *PloS one*, 14(3), e0212786.
- Baird, R. W., Webster, D. L., Aschettino, J. M., Schorr, G. S., & McSweeney, D. J. (2013). Odontocete cetaceans around the main Hawaiian Islands: Habitat use and relative abundance from small-boat sighting surveys. *Aquatic Mammals*, 39(3).
- Ban, N. C., Alidina, H. M., & Ardron, J. A. (2010). Cumulative impact mapping: advances, relevance and limitations to marine management and conservation, using Canada's Pacific waters as a case study. *Marine Policy*, 34(5), 876-886.
- Bellido, J. M., Santos, M. B., Pennino, M. G., Valeiras, X., & Pierce, G. J. (2011). Fishery discards and bycatch: solutions for an ecosystem approach to fisheries management?. *Hydrobiologia*, 670(1), 317-333.
- Béné, C., Macfadyen, G., & Allison, E. H. (2007). Increasing the contribution of small-scale fisheries to poverty alleviation and food security (No. 481). Food & Agriculture Org..
- Berkes, F. (2007). Community-based conservation in a globalized world. *Proceedings of the National academy of sciences*, 104(39), 15188-15193.
- Berkes, F. (2001). Managing small-scale fisheries: alternative directions and methods. IDRC.
- Bradbury, G., Trinder, M., Furness, B., Banks, A. N., Caldow, R. W., & Hume, D. (2014). Mapping seabird sensitivity to offshore wind farms. *PloS one*, 9(9), e106366.
- Briscoe, D. K., Hiatt, S., Lewison, R., & Hines, E. (2014). Modeling habitat and bycatch risk for dugongs in Sabah, Malaysia. *Endangered Species Research*, 24(3), 237-247.
- Christiansen, F., Esteban, N., Mortimer, J. A., Dujon, A. M., & Hays, G. C. (2017). Diel and seasonal patterns in activity and home range size of green turtles on their foraging grounds revealed by extended Fastloc-GPS tracking. *Marine biology*, 164(1), 1-11.
- Chuenpagdee, R., Liguori, L., Palomares, M. L., & Pauly, D. (2006). Bottom-up, global estimates of small-scale marine fisheries catches. *Fish. Centre Res. Report*, 14(8).
- Chuenpagdee, R., Rocklin, D., Bishop, D., Hynes, M., Greene, R., Lorenzi, M. R., & Devillers, R. (2019). The global information system on small-scale fisheries (ISSF): a crowdsourced knowledge platform. *Marine Policy*, 101, 158-166.
- Cominelli, S., Leahy, M., Devillers, R., & Hall, G. B. (2019). Geovisualization tools to inform the management of vessel noise in support of species' conservation. *Ocean & coastal management*, 169, 113-128.
- Dudík, M., Phillips, S. J., & Schapire, R. E. (2007). Maximum entropy density estimation with generalized regularization and an application to species distribution modeling. *Journal of Machine Learning Research*, 8(6), 1217-1260.
- Duggan, J. M., Eichelberger, B. A., Ma, S., Lawler, J. J., & Ziv, G. (2015). Informing management of rare species with an approach combining scenario modeling and spatially explicit risk assessment. *Ecosystem Health and Sustainability*, 1(6), 1-18.
- Elith, J., Phillips, S. J., Hastie, T., Dudík, M., Chee, Y. E., & Yates, C. J. (2011). A statistical explanation of MaxEnt for ecologists. *Diversity and distributions*, 17(1), 43-57.
- European Commission. (2016). Commission Implementing Decision (EU) 2016/1251 of 12 July 2016 adopting a multiannual Union programme for the collection, management and use of data in the fisheries and aquaculture sectors for the period 2017–2019. *Official Journal of the European Union*, 59(L 207), 113-177. Available from: http://data.europa.eu/eli/dec_impl/2016/1251/oj
- FAO. (2012). *Fishing People*. FAO Fisheries and Aquaculture Department, FAO, Rome. Available from: <http://www.fao.org/fishery/topic/13827/en>
- FAO. (2018). *The State of World Fisheries and Aquaculture 2018—Meeting the sustainable development*

- goals, Rome, Italy. Available from: <http://www.fao.org/fishery/sofia/en>
- Garcia, S. M., & Rosenberg, A. A. (2010). Food security and marine capture fisheries: characteristics, trends, drivers and future perspectives. *Philosophical Transactions of the Royal Society B: Biological Sciences*, 365(1554), 2869-2880.
- Gibbs, M. T., & Browman, H. I. (2015). Risk assessment and risk management: a primer for marine scientists. *ICES Journal of Marine Science*, 72(3), 992-996.
- Gregg, E. J., Baumgartner, M. F., Laidre, K. L., & Palacios, D. M. (2013). Marine mammal habitat models come of age: the emergence of ecological and management relevance. *Endangered Species Research*, 22(3), 205-212.
- Halpern, B. S., Frazier, M., Potapenko, J., Casey, K. S., Koenig, K., Longo, C., et al. (2015). Spatial and temporal changes in cumulative human impacts on the world's ocean. *Nature communications*, 6(1), 1-7.
- Halpern, B. S., Walbridge, S., Selkoe, K. A., Kappel, C. V., Micheli, F., D'Agrosa, C., et al. (2008). A global map of human impact on marine ecosystems. *science*, 319(5865), 948-952.
- Hamel, N. J., Burger, A. E., Charleton, K., Davidson, P., Lee, S., Bertram, D. F., & Parrish, J. K. (2009). Symposium Paper: Bycatch and beached birds: assessing mortality impacts in coastal net fisheries using marine bird strandings. *Marine Ornithology*, 37, 41-60.
- Hazen, E. L., Scales, K. L., Maxwell, S. M., Briscoe, D. K., Welch, H., Bograd, S. J., et al. (2018). A dynamic ocean management tool to reduce bycatch and support sustainable fisheries. *Science advances*, 4(5), eaar3001.
- Henrichs, T., Zurek, M., Eickhout, B., Kok, K., Raudsepp-Hearne, C., Ribeiro, T., et al. (2010). Scenario development and analysis for forward-looking ecosystem assessments. *Ecosystems and human well-being: A manual for assessment practitioners*, 10, 151–219.
- Hines, E., Strindberg, S., Junchompoo, C., Ponnampalam, L. S., Ilangakoon, A. D., Jackson-Ricketts, J., & Mananunsap, S. (2015). Line transect estimates of Irrawaddy dolphin abundance along the eastern Gulf Coast of Thailand. *Frontiers in Marine Science*, 2, 63.
- Hobday, A. J., Smith, A. D. M., Stobutzki, I. C., Bulman, C., Daley, R., Dambacher, J. M., ... & Zhou, S. (2011). Ecological risk assessment for the effects of fishing. *Fisheries Research*, 108(2-3), 372-384.
- Hodgson, A., Kelly, N., & Peel, D. (2013). Unmanned aerial vehicles (UAVs) for surveying marine fauna: a dugong case study. *PloS one*, 8(11), e79556.
- Hodgson, E. E., Essington, T. E., Samhuri, J. F., Allison, E. H., Bennett, N. J., Bostrom, A., et al. (2019). Integrated risk assessment for the blue economy. *Frontiers in Marine Science*, 6, 609.
- Hoffman, F. O., & Hammonds, J. S. (1994). Propagation of uncertainty in risk assessments: the need to distinguish between uncertainty due to lack of knowledge and uncertainty due to variability. *Risk analysis*, 14(5), 707-712.
- Hordyk, A. R., & Carruthers, T. R. (2018). A quantitative evaluation of a qualitative risk assessment framework: Examining the assumptions and predictions of the Productivity Susceptibility Analysis (PSA). *PloS one*, 13(6), e0198298.
- Jaaman, S. A., Lah-Anyi, Y. U., & Pierce, G. J. (2008). Directed fisheries for dolphins and dugongs in Sabah, East Malaysia: past and present. *Borneo Science*, 23(2008), 1-20.
- Jackson-Ricketts, J., Junchompoo, C., Hines, E. M., Hazen, E. L., Ponnampalam, L. S., Ilangakoon, A., & Monanunsap, S. (2020). Habitat modeling of Irrawaddy dolphins (*Orcaella brevirostris*) in the Eastern Gulf of Thailand. *Ecology and evolution*, 10(6), 2778-2792.
- Johnson, A. F., Caillat, M., Verutes, G. M., Peter, C., Junchompoo, C., Long, V., et al. (2017). Poor fisheries struggle with US import rule. *Science*, 355(6329), 1031-1032.
- Kappel, C. V. (2005). Losing pieces of the puzzle: threats to marine, estuarine, and diadromous species. *Frontiers in Ecology and the Environment*, 3(5), 275-282.
- Kelsall, J. E., & Diggle, P. J. (1995). Non-parametric estimation of spatial variation in relative risk. *Statistics in medicine*, 14(21-22), 2335-2342.
- Kosamu, I. B. (2015). Conditions for sustainability of small-scale fisheries in developing countries. *Fisheries Research*, 161, 365-373.

- Kuit, S. H., Ponnampalam, L. S., Ng, J. E., Chong, V. C., & Then, A. Y. H. (2019). Distribution and habitat characteristics of three sympatric cetacean species in the coastal waters of Matang, Perak, Peninsular Malaysia. *Aquatic Conservation: Marine and Freshwater Ecosystems*.
- Laneri, K., Louzao, M., Martínez-Abraín, A., Arcos, J. M., Belda, E. J., Guallart, J., et al. (2010). Trawling regime influences longline seabird bycatch in the Mediterranean: new insights from a small-scale fishery. *Marine Ecology Progress Series*, 420, 241-252.
- Lewison, R. L., Crowder, L. B., Read, A. J., & Freeman, S. A. (2004). Understanding impacts of fisheries bycatch on marine megafauna. *Trends in ecology & evolution*, 19(11), 598-604.
- Lewison, R. L., Johnson, A. F., & Verutes, G. M. (2018). Embracing complexity and complexity-awareness in marine megafauna conservation and research. *Frontiers in Marine Science*, 5, 207.
- Mannocci, L., Roberts, J. J., Miller, D. L., & Halpin, P. N. (2017). Extrapolating cetacean densities to quantitatively assess human impacts on populations in the high seas. *Conservation Biology*, 31(3), 601-614.
- Marçalo, A., Katara, I., Feijó, D., Araújo, H., Oliveira, I., Santos, J., et al. (2015). Quantification of interactions between the Portuguese sardine purse-seine fishery and cetaceans. *ICES Journal of Marine Science*, 72(8), 2438-2449.
- Merino, G., Barange, M., Blanchard, J. L., Harle, J., Holmes, R., Allen, I., et al. (2012). Can marine fisheries and aquaculture meet fish demand from a growing human population in a changing climate?. *Global Environmental Change*, 22(4), 795-806.
- Minton, G., Peter, C., & Tuen, A. A. (2011). Distribution of small cetaceans in the nearshore water of Sarawak, East Malaysia. *Raffles Bulletin of Zoology*, 59(1).
- Moore, J. E., Cox, T. M., Lewison, R. L., Read, A. J., Bjorkland, R., McDonald, S. L., et al. (2010). An interview-based approach to assess marine mammal and sea turtle captures in artisanal fisheries. *Biological Conservation*, 143(3), 795-805.
- Natale, F., Carvalho, N., & Paulrud, A. (2015). Defining small-scale fisheries in the EU on the basis of their operational range of activity The Swedish fleet as a case study. *Fisheries Research*, 164, 286-292.
- Needham, S., & Funge-Smith, S. J. (2015). The consumption of fish and fish products in the Asia-Pacific region based on household surveys. *RAP publication*, 12, 87.
- National Oceanic and Atmospheric Administration (NOAA). (2016). *Federal Register*. 81(157), 54390.
- J. Parra, G., Schick, R., & J. Corkeron, P. (2006). Spatial distribution and environmental correlates of Australian snubfin and Indo-Pacific humpback dolphins. *Ecography*, 29(3), 396-406.
- Patrick, W. S., Spencer, P., Link, J., Cope, J., Field, J., Kobayashi, D., et al. (2010). Using productivity and susceptibility indices to assess the vulnerability of United States fish stocks to overfishing. *Fishery Bulletin*, 108(3), 305-322.
- Pearson, R. G., Raxworthy, C. J., Nakamura, M., & Townsend Peterson, A. (2007). Predicting species distributions from small numbers of occurrence records: a test case using cryptic geckos in Madagascar. *Journal of biogeography*, 34(1), 102-117.
- Pearson, R. G. (2007). Species' distribution modeling for conservation educators and practitioners. *Synthesis*. American Museum of Natural History, 50, 54-89.
- Peltier, H., Dabin, W., Daniel, P., Van Canneyt, O., Dorémus, G., Huon, M., & Ridoux, V. (2012). The significance of stranding data as indicators of cetacean populations at sea: modelling the drift of cetacean carcasses. *Ecological Indicators*, 18, 278-290.
- Peter C., Poh A. N. Z., Ngeian J., Tuen A. A., Minton G. (2016). Identifying Habitat Characteristics and Critical Areas for Irrawaddy Dolphin, *Orcaella brevirostris*: Implications for Conservation. In: Das I., Tuen A. (eds) *Naturalists, Explorers and Field Scientists in South-East Asia and Australasia. Topics in Biodiversity and Conservation*, Springer, 15, 225-238.
- Phillips, S. J., Anderson, R. P., & Schapire, R. E. (2006). Maximum entropy modeling of species geographic distributions. *Ecological modelling*, 190(3-4), 231-259.
- Pilcher, N. J., Adulyanukosol, K., Das, H., Davis, P., Hines, E., Kwan, D., et al. (2017). A low-cost solution for documenting distribution and abundance of endangered marine fauna and impacts from

- fisheries. *PloS one*, 12(12), e0190021.
- Ponnampalam, L. S., Izmal, J. F., Adulyanukosol, K., Ooi, J. L., & Reynolds, J. E. (2015). Aligning conservation and research priorities for proactive species and habitat management: the case of dugongs *Dugong dugon* in Johor, Malaysia. *Oryx*, 49(4), 743-749.
- QGIS Development Team. (2018). QGIS Geographic Information System. Open Source Geospatial Foundation Project. Available from: <http://qgis.osgeo.org>
- Read, A. J. (2008). The looming crisis: interactions between marine mammals and fisheries. *Journal of Mammalogy*, 89(3), 541-548.
- Redfern, J. V., Ferguson, M. C., Becker, E. A., Hyrenbach, K. D., Good, C., Barlow, J., et al. (2006). Techniques for cetacean-habitat modeling. *Marine Ecology Progress Series*, 310, 271-295.
- Reeves, R. R., McClellan, K., & Werner, T. B. (2013). Marine mammal bycatch in gillnet and other entangling net fisheries, 1990 to 2011. *Endangered Species Research*, 20(1), 71-97.
- Rosenthal, A., Verutes, G., McKenzie, E., Arkema, K. K., Bhagabati, N., Bremer, L. L., et al. (2015). Process matters: a framework for conducting decision-relevant assessments of ecosystem services. *International Journal of Biodiversity Science, Ecosystem Services & Management*, 11(3), 190-204.
- Ruckelshaus, M., McKenzie, E., Tallis, H., Guerry, A., Daily, G., Kareiva, P., et al. (2015). Notes from the field: lessons learned from using ecosystem service approaches to inform real-world decisions. *Ecological Economics*, 115, 11-21.
- Salas, S., Chuenpagdee, R., Seijo, J. C., & Charles, A. (2007). Challenges in the assessment and management of small-scale fisheries in Latin America and the Caribbean. *Fisheries research*, 87(1), 5-16.
- Samhuri, J. F., & Levin, P. S. (2012). Linking land-and sea-based activities to risk in coastal ecosystems. *Biological Conservation*, 145(1), 118-129.
- Seafood Watch (SFW). (2020). Seafood Watch Fisheries Standards v4. Available at: <https://www.seafoodwatch.org/globalassets/sfw/pdf/standards/fisheries/seafood-watch-fisheries-standard-version-f4.pdf>
- Shahrabi, J., & Pelot, R. (2009). Kernel Density Analysis of maritime fishing traffic and incidents in Canadian Atlantic waters. *Journal of Applied Sciences*, 9(3), 415-426.
- Sharp R, et al. (2019). InVEST 3.7.0 user guide. Collaborative publication by The Natural Capital Project, Stanford University, the University of Minnesota, The Nature Conservancy, and the World Wildlife Fund. Stanford, CA: Stanford University. Available from: <http://releases.naturalcapitalproject.org/invest-userguide/latest/>
- Shester, G. G., & Micheli, F. (2011). Conservation challenges for small-scale fisheries: Bycatch and habitat impacts of traps and gillnets. *Biological Conservation*, 144(5), 1673-1681.
- Soykan, C. U., Moore, J. E., Zydalis, R., Crowder, L. B., Safina, C., & Lewison, R. L. (2008). Why study bycatch? An introduction to the Theme Section on fisheries bycatch. *Endangered Species Research*, 5(2-3), 91-102.
- Stewart, K. R., Lewison, R. L., Dunn, D. C., Bjorkland, R. H., Kelez, S., Halpin, P. N., & Crowder, L. B. (2010). Characterizing fishing effort and spatial extent of coastal fisheries. *PloS one*, 5(12), e14451.
- Stobutzki, I., Miller, M., & Brewer, D. (2001). Sustainability of fishery bycatch: a process for assessing highly diverse and numerous bycatch. *Environmental Conservation*, 28(2), 167-181.
- Suhaila, J., Deni, S. M., Zin, W. W., & Jemain, A. A. (2010). Trends in peninsular Malaysia rainfall data during the southwest monsoon and northeast monsoon seasons: 1975-2004. *Sains Malaysiana*, 39(4), 533-542.
- Teh, L. S., Teh, L. C., Hines, E., Junchompoo, C., & Lewison, R. L. (2015). Contextualising the coupled socio-ecological conditions of marine megafauna bycatch. *Ocean & Coastal Management*, 116, 449-465.
- Tobeña, M., Prieto, R., Machete, M., & Silva, M. A. (2016). Modeling the potential distribution and richness of cetaceans in the Azores from fisheries observer program data. *Frontiers in Marine Science*, 3, 202.
- Trimble, M., & Berkes, F. (2013). Participatory research towards co-management: lessons from artisanal

- fisheries in coastal Uruguay. *Journal of environmental management*, 128, 768-778.
- Tubbs, S. E., Baç, A. A., Côté, G., Jones, A. L., & Notman, G. (2019). Sighting and stranding reports of Irrawaddy dolphins (*Orcaella brevirostris*) and Dugongs (*Dugong dugon*) in Kep and Kampot, Cambodia. *Aquatic Mammals*, 45(5), 563-568.
- Tubbs, S. E., Keen, E., Jones, A., & Thap, R. (2020). On the distribution, behaviour and seasonal variation of Irrawaddy Dolphins (*Orcaella brevirostris*) in the Kep Archipelago, Cambodia. *Raffles Bulletin of Zoology*, 68, 137-149.
- Tulloch, V., Pirotta, V., Grech, A., Crocetti, S., Double, M., How, J., et al. (2020). Long-term trends and a risk analysis of cetacean entanglements and bycatch in fisheries gear in Australian waters. *Biodiversity and Conservation*, 29(1), 251-282.
- Valavanis, V. D., Pierce, G. J., Zuur, A. F., Palialexis, A., Saveliev, A., Katara, I., & Wang, J. (2008). Modelling of essential fish habitat based on remote sensing, spatial analysis and GIS. *Essential fish habitat mapping in the Mediterranean*, 5-20.
- Van Waerebeek, K., & Reyes, J. C. (1994). Interactions between small cetaceans and Peruvian fisheries in 1988/89 and analysis of trends. *Report of the International Whaling Commission*, 15, 495-502.
- Vu L, Tho TA, Hung NN, Duy L. (2017). Conservation of cetaceans in Kien Giang Biosphere Reserve, Vietnam. *Conservation Leadership Program*, 3234115.
- Wallace, B. P., Lewison, R. L., McDonald, S. L., McDonald, R. K., Kot, C. Y., Kelez, S., et al. (2010). Global patterns of marine turtle bycatch. *Conservation letters*, 3(3), 131-142.
- Wiber, M., Berkes, F., Charles, A., & Kearney, J. (2004). Participatory research supporting community-based fishery management. *Marine Policy*, 28(6), 459-468.
- Williams, A., Dowdney, J., Smith, A. D. M., Hobday, A. J., & Fuller, M. (2011). Evaluating impacts of fishing on benthic habitats: a risk assessment framework applied to Australian fisheries. *Fisheries Research*, 112(3), 154-167.
- Williams, R., Burgess, M. G., Ashe, E., Gaines, S. D., & Reeves, R. R. (2016). US seafood import restriction presents opportunity and risk. *Science*, 354(6318), 1372-1374.
- Wyatt, K. H., Griffin, R., Guerry, A. D., Ruckelshaus, M., Fogarty, M., & Arkema, K. K. (2017). Habitat risk assessment for regional ocean planning in the US Northeast and Mid-Atlantic. *PloS one*, 12(12), e0188776.xxx

2.7 SUPPORTING INFORMATION

2.7.1 Methodology and Scoring Scheme

2.7.1.1 Methods and tool for risk assessment

A Bycatch Risk Assessment (ByRA) was applied to estimate risk of bycatch based on the spatial and temporal coincidence of ranked probabilities of overlap between species and fishing occurrences. This methodology was adapted from previous species risk assessment approaches and tools (Samhoury and Levin, 2012; Arkema et al., 2014) and expands on the productivity-susceptibility analyses developed specifically for important fish species in the United States and Australia (Patrick et al., 2010; Hobday et al., 2011). By combining distribution maps of species and fishing activities, and rating each species-gear interaction in space and time, ByRA produced a series of GIS layers, showing risk scores for each site or region, and a map layer for each focal species classified by the relative amount of risk (high/medium/low) in three Southeast Asian field sites (SBTI, KUCG, and KGBR).

Risk of bycatch was calculated as *exposure*, or the degree a species experiences stress due to gear-specific threat (spatial/temporal overlap, threat intensity, likelihood of interaction, catchability, and current status of management strategies) and its *consequence*, defined as the resilience of a species to a stressor (age of maturity, reproductive strategy, population connectivity, local status of species) and its sensitivity (mortality and life stages affected by gear). Using information from primary and secondary sources along with an extensive review of the literature, we scored the interactions between two species (dugongs and Irrawaddy dolphins) and up to five categories of fishing gears present at each site. For some ratings, based on their ecological relevance and available information to score a given species-gear interaction, we either omitted or weighted (up/down) their importance in the average scores for exposure and consequence criteria. Finally, a Euclidean (straight-line) distance function from the origin (minimum score) to the average exposure and consequence scores was applied to estimate individual and cumulative bycatch risk on a cell-by-cell basis.

2.7.1.2 Spatial data on species for the spatial overlap criterion

To predict habitat suitability in two of three field sites, the modeling software Maxent (version 3.4.1) was used (Phillips et al., 2020). Maxent has been widely applied to build Ecological Niche Models (ENMs) and Species Distribution Models (SDMs). We used presence only data to quantify the statistical relationship between predictor environmental covariates at locations where a species had been observed versus ‘background’ locations in which no species had been observed within the study region. By doing so, we could identify habitat suitability levels within the study region; specifically, to calculate the relative occurrence rate (ROR) of dugongs (*Dugong dugon*) and Irrawaddy dolphins (*Orcaella brevirostris*) and estimate suitable habitat. Ultimately, Maxent outputs served as inputs to ByRA, specifically to calculate two exposure criteria: spatial overlap (between the distributions of species and gear) and encounter rates (likelihood of interaction between species and gear).

To identify the best parameters within Maxent and avoid overfitting, we used the R tool package ENMeval, designed for data partitioning and model execution (Muscarella et al., 2014; R Core

Team, 2017). ENMeval automatically executes Maxent several times to aid in identifying settings that balance model fit and predictive ability. For each Malaysian site, Maxent runs with different parameters and combinations of environmental data were tested to fit each model and evaluate their performance (Rhoden et al., 2017). With each model, an AICc value, and different measurements related to the Area Under the Curve (AUC) were calculated (Warren et al., 2010; Muscarella et al., 2014).

We applied ENMeval with different sets of environmental variables. For each variable, regularization factors ranging from 0.5 to 4 (with a step of 0.5) were tested in ENMeval. A model with the lowest delta AICc value was considered the best performing model. After the appropriate parameters were identified by comparing AICc and AUC values for the test data (Warren et al., 2010), those parameters were used to run a cross-validation model in Maxent. We used the *k*-fold cross-validation option with 10-folds (Muscarella et al., 2014). The method estimates errors around fitted functions and predictive performance on held-out data (Elith et al., 2011). A jackknife test was conducted for each selected model to identify the importance of the different environmental variables within the model. Here, each of *n* occurrence localities was used for testing once. If after analyzing ENMeval outputs it was not possible to identify one best set of parameters, all the best models identified were run in Maxent and the resulting outputs compared.

Model selection and outputs. To identify the best model, we analyzed the different Maxent outputs. There is a lack of consensus regarding which validation statistic(s) are appropriate to identify the model that best predicts the data (Muscarella et al., 2014) and how to determine the appropriate threshold value which will divide the study area into suitable and not suitable habitat (Liu et al., 2005; Pearson et al., 2007; Warren and Seifert, 2011). Given our goal to identify different level of habitat suitability within the study area and map marine mammal interaction with fishing activity within these areas, we computed three different evaluation metrics, two of which quantified model overfitting (OR_{MTP} and OR₁₀), and also a visual inspection of the Maxent output maps:

1. Test AUC values (AUC_{TEST}) - the area under the curve of the receiver operating characteristic plot based on the test data provides an indication of the model's goodness of fit. Higher values indicate a better ability to discriminate between conditions at withheld versus background data.
2. Minimum training presence omission rate (OR_{MTP}) - the proportion of test (withheld) data with Maxent output values lower than that corresponding to the training data with the lowest ranking value (referred to as the 0% training omission). Lower omission rates indicate less overfitting of the model.
3. 10% training omission rate (OR₁₀) - the omission rate of test data, excluding the 10% of training data with the lowest predicted suitability (referred to as 10% training omission).
4. Visual inspection of Maxent output maps with the threshold between suitable and not suitable habitat corresponding to a 0% and 10% omission rate.

For the first three metrics, a t-test was run between models to detect if the difference observed across the 10 *k*-fold of those values was significant or not. If there was no significant difference, visual inspection of the Maxent output maps were conducted to select the appropriate model.

Maxent outputs included: 1) a curve illustrating the relationship between omission rates (proportion of occurrence present in not suitable habitat) and cumulative threshold, 2) a measure of the AUC validation statistics, 3) a table that summarizes the omission rate corresponding to a relative occurrence rate (ROR) threshold used to transform the probability map to a habitat suitability layer, 4) a prediction surface map, and 5) an analysis of the environmental variables relationship with these data and their overall contribution to the model.

Three levels of habitat suitability. To use Maxent outputs as species distribution inputs to the ByRA, we split continuous estimates of habitat suitability into classification levels. Once a threshold (either 0% or 10% OR) value was selected to transform probability into suitable versus unsuitable habitat, we produced maps of three levels of habitat suitability (low, medium and high). All grid cells with an ROR below the threshold value were classified as unsuitable habitat. The first category, *low suitability*, ranged from the omission rate threshold value to 50% of the maximum ROR of each species. The second category, *medium suitability*, ranged from 50% of the maximum ROR to 75% of the maximum ROR of each species. The final category, *high suitability*, ranged from 75% of the maximum ROR to the maximum ROR of each species.

2.7.1.2.1 Dugongs

In SBTI field site, the first aerial survey was conducted in 2010 over an eight-day period during the dry season. Then, from 2014 to 2016 additional surveys were commissioned over a 6-day period. Given the timing of dugong occurrence data available, it was not possible to split the data by seasonal weather (monsoonal) patterns, as in the KUCG field site. A total of 1360 dugong sightings were recorded with group sizes ranging from one to 43 individuals (**Table S2.1**).

Environmental covariates. The environmental parameter, bathymetric slope, was calculated using a digital bathymetry layer created in GIS for the SBTI field site (as in Briscoe et al., 2014). Independent of the bathymetric slope variable being included, the Maxent models with the lowest AICc were always the ones with the LQHPT features and a regularization parameter of 3.5 (**Table S2.2**). No significant difference ($p > 0.05$) was detected between these two models. A small difference in the medium level of habitat suitability could be observed, but this was unlikely to be significant (**Figures S2.1, S2.2, and S2.3**). A corridor of highly suitable habitat was visible between Sibutinggi Islands and the mainland (**Figure S2.1**). The highest habitat suitability areas for dugongs were found mainly around the islands known to have extensive seagrass meadows. For both models, the environmental variables that contributed the most were distance to river mouths (40%) and then distance to land (35%). Both models correctly identified the test occurrence data as suitable habitat 88% of the time (**Table S2.2**).

2.7.1.2.2 Irrawaddy dolphins

In KUCG, between one and 8 consecutive days of boat surveys were conducted before and after the monsoon season each year from 2008 to 2013. This regular survey interval offered the possibility to predict habitat usage of Irrawaddy dolphins by season, i.e., post-monsoon (March to May), at the heart of the dry season (June to August) and pre-monsoon (September to November) (**Table S2.1**). A data merge of all seasons included 882 dolphin occurrences recorded in groups ranging from one to 45 individuals in size. While some dolphin sightings were recorded during the monsoon season (December to February), these data were not used because of the small sample size ($n=20$) and recurring challenges associated with difficult

weather conditions and poor visibility, resulting in surveyors missing dolphins present in the area.

In KGBR, the boat surveys by Vu et al. (2017) were the first ever conducted for the area. The team in Vietnam conducted three surveys over several days and months of the year 2014. In 2015, one survey over nine days was also completed. However, only two sightings of Irrawaddy dolphin were recorded over this two-year period. Maxent needs a minimum of five occurrences (Pearson et al., 2007). Habitat suitability for dolphins in KGBR was estimated using habitat preference parameters identified by Minton and colleagues (2011) and also in Thailand, the closest available data with a complete analysis of habitat suitability, by Jackson-Ricketts, 2017 (**Table S2.3; Figure S2.4**).

Environmental covariates. Environmental data known to influence the distribution of the Irrawaddy dolphins in their marine habitat such as sea surface temperature, pH, and salinity (Peter et al., 2016; Vu et al., 2017) were collected each time a dolphin was sighted in both the KUCG and KGBR sites. However, no environmental data outside these sighting points were available with high enough resolution to be spatially interpolated and used as covariates in Maxent. Consequently, only fixed physical environmental variables that could be mapped in a GIS were used; specifically, distance to river mouth, distance to land, and ocean depth (**Table S2.1**). For depth information, we lacked a detailed bathymetric chart for Kuching Bay. This made it necessary to interpolate depth data collected by a boat-based fish finder during cetacean surveys. The acquired depth values followed boat transect lines and values between these lines were interpolated. The resulting bathymetry layer had linear artifacts for depth values and we chose not to use bathymetric slope as an environmental covariate in Maxent. Only one set of environmental parameters (not including slope) were tested for KUCG. Maxent runs were evaluated with all occurrence data together (“All_Data_”) and with these occurrence data split by season (**Table S2.4**).

All sightings data. When all dolphin occurrences were pooled together, two models had the same AIC scores, one with LQHP features and one with LQHPT features, and both using a regularization parameter of 1.0. The model (“All_Data_1”) with LQHPT features had a significantly ($p < 0.05$) better AUC of 90.58%, but the 10% and 0% omission rates were not significantly different (**Table S2.4**). The environmental variable contribution rates to the model were also different between these two models. For the LQHP model, distance to land was the variable that contributed most to the model, whereas for the LQHPT model, both distance to river mouths and distance to land contributed the same amount (no significant difference of the contribution rate between these two variable based on t-test; $p > 0.05$).

Visual observation of the Maxent output maps showed some important differences (**Figure S2.5**). Generally, both models predicted the most suitable habitat to be within the rivers and near river mouths. However, the medium habitat suitability range differed substantially, as this intermediate suitability level covered a smaller area in the LQHPT model. In addition, the edges of low suitability areas extended further offshore in LQHP as compared to the LQHPT model.

Sightings data by season. When Irrawaddy dolphin occurrence data were split by season in KUCG, several models with different combination of Maxent features and regularization values

had similar AICc values. For each of three seasons, two models with similar AICc (a difference of less than two points) were identified by the ENMeval function (**Figures S2.6-S2.10**). The model with the lowest delta AICc value was considered the best model. For the post-monsoon and dry season, the models with the Threshold feature (“PoM_2” and “Dry_2”, respectively) had significantly higher mean AUC values ($p < 0.05$) than models without this feature class. For the dry season and pre-monsoon in KUCG, we selected models where distance to river mouths had the highest variable importance (55% and 49%, respectively) and there was strong discrimination on held out data (cross-validated AUCs of 94.02 and 87.48).

In terms of model overfitting, no significant differences were detected between the 10% training presence omission rates (**Table S2.4**). Finally, a visual inspection of predicted suitability levels served to identify which habitat suitability map would be used as input to the ByRA. Overall, Maxent models that included the threshold features had a more patchy distribution of the medium level of habitat suitability and linear artifacts at the edge of the medium suitability level, which was a consequence of the depth covariate layer.

Across seasons in KUCG, the environmental covariates we tested did not contribute in the same way to model predictions. For the dry and pre-monsoon season, distance to river mouths provided the strongest contribution. During the post-monsoon season, however, it was the distance to land variable that contributed the most (**Table S2.4**). The distribution of three habitat suitability levels also differed substantially across the three seasons. The entire spatial extent of suitable dolphin habitat went furthest offshore prior to the monsoon season and then moved closer to land during the dry season. The extent of highest habitat suitability level followed the same pattern; that is, it was centered in the river network or just outside major river mouths during the dry season and then extended further offshore before and after the monsoon (**Figure S2.6**).

2.7.1.3 Rankings for resilience criteria

Resilience attributes were used in ByRA to describe the consequences (impact) to species by evaluating how a species population will respond and recover from impact. The literature on resiliency of dugongs and Irrawaddy dolphins was reviewed to compile rating scores for the consequence criteria related to age of maturity, reproductive strategy, population connectivity, and local status of species (**Table S2.5**).

2.7.1.3.1 Dugongs

Age of maturity. Given their inconspicuous behavior, information about the life cycle of dugongs was sparse. According to research in Australia, the age of maturity of dugongs varies in space and time, between sexes, populations, and environmental conditions (Marsh et al., 1984; Kwan, 2002). For females, a minimum age of maturity of six years was observed at Mabuiag Island (Kwan, 2002). In Marnington Island, the age of maturity ranged from 14.5 to 17.5 years for females and 15 to 16 years for males (Marsh et al., 1984). In Mabuiag Island, it was 6 to 7 years for females and 4 to 13 years for males (Kwan, 2002). Literature suggests an age of maturity greater than four years for both male and female dugongs.

Reproductive strategy. Calving interval is typically estimated using the length of gestation period and ratio of the number of mature females to the number of pregnant females. Similar to age of

sexual maturity, the calving interval of dugongs varies considerably (Kwan, 2002) and is relatively long (Mann, 2009). Based on observations of different populations, we estimated a calving interval between 3 and 7 years (Marsh et al., 1984; Marsh, 1995; Kwan, 2002]. Maternal investment – time and energy spent beginning at conception (Hayssen, 1993) – is also high. Female dugongs can simultaneously be pregnant and nurse a calf (Marsh, 1995). While the gestation period of dugongs is well understood, information is sparse about the lactation period.

Population connectivity. Dugongs have been observed to undertake micro-scale commuting between seagrass beds (<15 km) and large-scale (>15 km) movements. Some individuals undertook movements ranging from several hundreds of kilometers up to 1000km, driven by warmer waters or available seagrass meadows (Sheppard et al., 2006; Hobbs et al., 2007). Large-scale movement, in which individuals did not stop at a feeding area, could be driven by spatial memory of foraging path or by social cues (Sheppard et al., 2006). Furthermore, dugongs can migrate long distances in response to habitat degradation (Preen and Marsh, 1995).

Local status of species. At the international level, dugongs have been categorized as ‘Vulnerable’ by the IUCN Red List (Marsh and Sobotzick, 2015). In Peninsular Malaysia, the Fisheries Act 2985 and the Fisheries Regulations 1999 (Control of Endangered Species of Fish) aim to protect dugongs (Briscoe et al., 2014; Ponnampalam et al., 2015). The Department of Fisheries Malaysia implemented a National Plan of Action for Dugongs in 2011 to protect, conserve and manage dugongs and their habitats (DOFM, 2011a; Ponnampalam et al., 2015).

2.7.1.3.2 Irrawaddy dolphins

The literature on resiliency of Irrawaddy dolphins when recovering from a threat, particularly in Malaysia and Vietnam, was limited. To rank resilience criteria for this species, we reviewed studies from Trat Bay, Thailand (Junchompoo et al., 2014; Hines et al., 2015; Jackson-Ricketts, 2017), which neighbors Cambodia to the north along the Gulf of Thailand. A genetic diversity study by Caballero et al. (2018) suggests connectivity between populations in India, Thailand and Cambodia, but less is known about dolphins using the coastal waters of the KGBR and KUCG sites. Regional studies of Irrawaddy suggest that adult length is achieved between 4 and 6 years old (Stacey and Arnold, 1999) and age at reproductive maturity for both females and males is between 3 to 6 years (Stacey and Leatherwood, 1997). Irrawaddy dolphins are not fully weaned until 2 years of age, with an average weaning age of about 24 months. From birth to about six months, calf nutrition comes entirely from the mother, who invests heavily in her young (Stacey and Leatherwood, 1997). The IUCN classifies this species as ‘Endangered’ or a decreasing population trend (Minton et al., 2017) due in part to incidental capture in fishing nets.

2.7.1.4 Literature review for scoring the remaining exposure and consequence criteria

Existing aerial surveys in SBTI and boat surveys in KUCG were used to map the distribution and intensity of fishing gear use (Ponnampalam et al., 2015; Peter et al., 2016). The MareCet Research Organization also conducted in-depth interviews of fishers in SBTI during 2010 and 2016 as part of social science research for dugong conservation. Surveyors asked respondents to draw approximate fishing grounds around Sibut-Tinggi and neighboring islands. This qualitative information was later merged into the kernel density maps by gear type, assuming the lowest intensity score for gear-specific fishing areas not identified by aerial surveys (**Figure S2.11**). In KGBR, the Vietnam Marine Megafauna Network interviewed fishers opportunistically in 2014

and again in 2016 to characterize fishing activities by gear type. However, it was not possible to combine these interview data with boat-based observations of fisheries in the KGBR study area because their data sheets noted only the number of flags displayed at the water surface (**Table S2.1**). Flags attached to gears allow for a qualitative estimate of the distribution of fishing activities within an area but do not provide specifics about the gear itself. Consequently, this criterion (intensity of gear use) was omitted as an exposure attribute in KGBR (**Table S2.6**).

The peer-review and grey literature on exposure and consequence-sensitivity of dugongs and Irrawaddy dolphins to five categories of fishing gears was reviewed to compile ratings for the remaining risk criteria (**Tables S2.5-2.6**) that characterize extent to which a population was exposed to a stressor. Specifically, these criteria described the overlap between a species' distribution and the extent of fishing activity in space and time. Also accounted for was the relative likelihood of capture by gear "catchability" and the degree to which current management had been identified and/or implemented with respect to the fishing gear in question. Lastly, we scored two criteria related to the consequence-sensitivity of a species population – i.e., how it will respond and recover from the impact (mortality/severity and life stages affected by gear).

2.7.1.4.1 Exposure

Temporal overlap. Irrawaddy dolphins use the coastal, estuarine and riverine waters of Kuching Bay (Minton et al., 2011). Scientific surveys conducted in KUCG along with interviews of fishers indicated that dolphins are generally present year-round (C. Peter, personal communication, August 4, 2017). Nets were reported to be used all year within these areas (Table 27 in DOFM, 2011b). Less is known about Irrawaddy dolphins in the waters around KGBR and Cambodia.

Likelihood of capture. The scientific community has identified gillnets as a serious threat to dugongs and dolphins but this has been largely unquantified (Read, 2008; Lewison et al., 2009; Reeves et al., 2013). There were limited reports in Southeast Asia of dugong bycatch from nets due to a long tradition of hunting the animal for their body parts and meat, and consequently the challenges associated with identifying cause of death. The research by Jaaman et al. (2009) in East Malaysia suggested that bycatch rates, particularly in gillnets, may be unsustainably high. Even if a dugong encounters a net with weak mesh, the animal may scare and roll around the net or ropes after impact (A. Ilangakoon, personal communication, March 8, 2018). For dugongs, incidental catch in push net trawlers has been reported (Hines et al., 2005). In Thailand, dolphins were observed following trawlers and sometimes swam too close to the nets, causing mass drownings with multiple dolphins found stranded together (W. Laovechprasit, personal communication, August 4, 2017). While the marine megafauna monitoring network in Trat Bay, Thailand found part of a trap around a dolphin (Junchompoo et al., 2014), there were no reports of pots and traps entangling dolphins in KUCG.

Current status of management. Dugongs are among the species protected under the Malaysia Fisheries Act (DOFM, 1985) and Fisheries Regulations. The Malaysian government committed to protecting 10% of the marine environment by 2020 (Ponnampalam et al., 2015). The Sultan Iskandar Marine Park, inside the SBTI field site, extends 2 nautical miles from low tide mark of the islands (**Figure S2.12**). The marine park, gazetted in 1994, is a no-take zone for fishing. Most of the bycatch threats to dugongs and other megafauna occur in the areas beyond the

boundaries of the park. Additional areas around Sibutu-Tinggi Islands (cross-hatching in **Figure S2.12**) have been proposed for fisheries management (Ponnampalam et al., 2015). The current status of management in KUCG and KGBR was mapped in GIS based on identified conservation areas (**Figure S2.12**) (Minton et al., 2011; Peter et al., 2016; Vu et al., 2017).

2.7.1.4.2 Consequence-sensitivity

Mortality. The diving time of dugongs is usually less than 12 minutes (Chilvers et al., 2004; Sheppard et al., 2006). If the animal is entangled by fishing gear and not retrieved within their lung capacity, it will drown. The scientific community considers the severity of dugongs caught in nets to be lethal and interactions with nets are known to be a significant cause of dugong mortality (Marsh, 2000; Dolar et al., 2005). To our knowledge, there have been no studies conducted to quantify the severity of encounters between dugongs and other types of fishing gears (trawls, hook and line, etc.). Based on the biology and behavior of dugongs and how different gears function in the water, we estimated the impact from hook and line as negligible, while trawls and pots and traps to be sublethal (Adulyanukosol and Poovachiranon, 2006; Briscoe et al., 2014). Similar severity ratings were used for Irrawaddy dolphin, except trawls were scored as lethal instead of sublethal (Junchompoo et al. 2014; Hines et al., 2015).

Life stages affected by gear. Along the Mersing Archipelago, many dugongs have been lost in the past three years as a result of bycatch in and around the SBTI field site. They were mainly juveniles and young adults. For each dugong with reproductive potential lost in SBTI, it is estimated to take 15 years to replace another one in the population (L. Ponnampalam, personal communication, August 4, 2017). For Irrawaddy dolphins (KUCG and KGBR sites), we zeroed out the rating score for this attribute due to lack of information and ecological relevance.

2.7.2 Limitations and simplifications

Despite an extensive literature review, it was not possible to justify exposure and consequence criteria ratings for all interactions between two species and five fishing gears in three field sites of Southeast Asia. Two expert working groups were organized, one in California (July 2017) and the other in Thailand (August 2017) to systematically review criteria descriptions and reach a consensus on ratings when references were not available. This convening of partners served to define the scoring bins (1-3) for each criterion and parameterize ByRA's variable weighting structure for data quality and criteria importance scores (**Tables S2.5-S2.7**).

Maxent enables users to tune numerous settings for creating complex models with many parameters (Elith et al., 2011). However, it is subject to several challenges related to model specifications (Phillips and Dudík, 2008; Muscarella et al., 2014) and interpretation of outputs (Warren et al., 2010; Rhoden et al., 2017). One issue is the lack of controls for over-parameterization and sampling bias. Here, the choice of the best available model depended on the model's ability to predict independent test data only, and not the model complexity. Consequently, Maxent is known to overfit the data (Warren et al., 2010; Warren and Seifert, 2011; Muscarella et al., 2014). Given the paucity of available environmental data for the SBTI and KUCG field sites, we constrained our environmental predictors to a maximum of four variables (**Table S2.1**). It is possible that some of the selected models were overfit based on a limited set of environmental variables for a potentially larger number of Maxent parameters.

2.7.3 Supplementary References

- Adulyanukosol, K., & Poovachiranon, S. (2006). Dugong (*Dugong dugon*) and seagrass in Thailand: present status and future challenges. In: Proceedings of the 3rd international symposium on SEASTAR2000 and Asian bio-logging science (The 7th SEASTAR2000 workshop), Graduate school of Informatics, Kyoto University, 41-50.
- Arkema, K. K., Verutes, G., Bernhardt, J. R., Clarke, C., Rosado, S., Canto, M., et al. (2014). Assessing habitat risk from human activities to inform coastal and marine spatial planning: a demonstration in Belize. *Environmental Research Letters*, 9(11), 114016.
- Briscoe, D. K., Hiatt, S., Lewison, R., & Hines, E. (2014). Modeling habitat and bycatch risk for dugongs in Sabah, Malaysia. *Endangered Species Research*, 24(3), 237-247.
- Caballero, S., Dove, V., Jackson-Ricketts, J., Junchompoo, C., Cohen, S., & Hines, E. (2018). Mitochondrial DNA diversity and population structure in the Irrawaddy dolphin (*Orcaella brevirostris*) from the Gulf of Thailand and the Mekong River. *Marine Mammal Science*, 35(1), 300-310.
- Chilvers, B. L., Delean, S., Gales, N. J., Holley, D. K., Lawler, I. R., Marsh, H., & Preen, A. R. (2004). Diving behaviour of dugongs, *Dugong dugon*. *Journal of Experimental Marine Biology and Ecology*, 304(2), 203-224.
- Department of Fisheries Malaysia (DOFM) (1985). Fisheries Act of 1985. Available from: [http://www.dof.gov.my/dof2/resources/user_1/UploadFile/AKTA_PERATURAN/Akta_A1413\(BM\)_-_Akta_Perikanan_\(Pindaan\)_2012.pdf](http://www.dof.gov.my/dof2/resources/user_1/UploadFile/AKTA_PERATURAN/Akta_A1413(BM)_-_Akta_Perikanan_(Pindaan)_2012.pdf).
- Department of Fisheries Malaysia (DOFM) (2011a). National Plan of Action for Dugongs 2011 Putrajaya, Malaysia. [In Bahasa Malaysia].
- Department of Fisheries Malaysia (DOFM) (2011b). Perangkaan Tahunan Perikanan 2011 (Annual Fisheries Statistics 2011).
- Dolar, M. L. L., Jefferson, T. A., Marsh, H., Wang, J. Y., & Estacion, J. (2005). Report of the Second Workshop on The Biology and Conservation of Small Cetaceans and Dugongs of South East Asia. W. F. Perrin, & R. R. Reeves (Eds.). UNEP-CMS.
- Elith, J., Phillips, S. J., Hastie, T., Dudík, M., Chee, Y. E., & Yates, C. J. (2011). A statistical explanation of MaxEnt for ecologists. *Diversity and distributions*, 17(1), 43-57.
- Hayssen, V. (1993). Empirical and theoretical constraints on the evolution of lactation. *Journal of Dairy Science*, 76(10), 3213-3233.
- Hines, E., Adulyanukosol, K., Duffus, D., & Dearden, P. (2005). Community perspectives and conservation needs for dugongs (*Dugong dugon*) along the Andaman coast of Thailand. *Environmental Management*, 36(5), 654-664.
- Hines, E., Strindberg, S., Junchompoo, C., Ponnampalam, L. S., Ilangakoon, A. D., Jackson-Ricketts, J., & Mananunsap, S. (2015). Line transect estimates of Irrawaddy dolphin abundance along the eastern Gulf Coast of Thailand. *Frontiers in Marine Science*, 2, 63.
- Hobbs, J. P. A., Frisch, A. J., Hender, J., & Gilligan, J. J. (2007). Long-distance oceanic movement of a solitary dugong (*Dugong dugon*) to the Cocos (Keeling) Islands. *Aquatic Mammals*, 33, 175-178.
- Hobday, A. J., Smith, A. D. M., Stobutzki, I. C., Bulman, C., Daley, R., Dambacher, J. M., et al. (2011). Ecological risk assessment for the effects of fishing. *Fisheries Research*, 108(2-3), 372-384.
- Jaaman, S. A., Lah-Anyi, Y. U., & Pierce, G. J. (2009). The magnitude and sustainability of marine mammal by-catch in fisheries in East Malaysia. *Journal of the Marine Biological Association of the United Kingdom*, 89(5), 907-920.
- Jackson-Ricketts, J. (2017). Diet, life history, habitat, and conservation of Irrawaddy dolphins (*Orcaella brevirostris*) in the Gulf of Thailand. Doctoral dissertation, University of California, Santa Cruz.
- Junchompoo, C., Monanunsap, S., & Penpein, C. (2014). Population and Conservation Status of Irrawaddy Dolphins (*Orcaella brevirostris*) in Trat Bay, Trat Province, Thailand. In: Proceedings of the Design Symposium on Conservation of Ecosystem (The 13th SEASTAR2000 workshop), Kyoto University Design School, 2, 2-38.

- Kwan, D. (2002). Towards a sustainable indigenous fishery for dugongs in Torres Strait: a contribution of empirical data analysis and process. Doctoral dissertation, James Cook University.
- Lewison, R. L., Soykan, C. U., & Franklin, J. (2009). Mapping the bycatch seascape: multispecies and multi-scale spatial patterns of fisheries bycatch. *Ecological Applications*, 19(4), 920-930.
- Liu, C., Berry, P. M., Dawson, T. P., & Pearson, R. G. (2005). Selecting thresholds of occurrence in the prediction of species distributions. *Ecography*, 28(3), 385-393.
- Mann, J. (2009). Parental behavior. *Encyclopedia of marine mammals*, Academic Press, 830-836.
- Marsh, H., Heinsohn, G. E., & Marsh, L. M. (1984). Breeding Cycle, Life History and Population Dynamics of the Dugong, *Dugong dugon* (Sirenia: Dugongidae). *Australian Journal of Zoology*, 32(6), 767-788.
- Marsh, H., & Sobtzick, S. (2015). *Dugong dugon*. The IUCN Red List of Threatened Species 2015: e.T6909A43792211.
- Marsh, H. (2000). Evaluating management initiatives aimed at reducing the mortality of dugongs in gill and mesh nets in the Great Barrier Reef World Heritage Area. *Marine Mammal Science*, 16, 684-694.
- Marsh, H. (1995). The life history, pattern of breeding, and population dynamics of the dugong. Information and technology report, 1, 75-83.
- Minton, G., Peter, C., Tuen, A. A. (2011). Distribution of small cetaceans in the nearshore water of Sarawak, East Malaysia. *Raffles Bulletin of Zoology*, 59(1).
- Minton, G., Smith, B. D., Braulik, G. T., Krebs, D., Sutaria, D., & Reeves, R. (2017). *Orcaella brevirostris*. The IUCN Red List of Threatened Species, 2017-3.
- Muscarella, R., Galante, P. J., Soley-Guardia, M., Boria, R. A., Kass, J. M., Uriarte, M., & Anderson, R. P. (2014). ENM eval: An R package for conducting spatially independent evaluations and estimating optimal model complexity for Maxent ecological niche models. *Methods in ecology and evolution*, 5(11), 1198-1205.
- Patrick, W. S., Spencer, P., Link, J., Cope, J., Field, J., Kobayashi, D., et al. (2010). Using productivity and susceptibility indices to assess the vulnerability of United States fish stocks to overfishing. *Fishery Bulletin*, 108(3), 305-322.
- Pearson, R. G., Raxworthy, C. J., Nakamura, M., & Townsend Peterson, A. (2007). Predicting species distributions from small numbers of occurrence records: a test case using cryptic geckos in Madagascar. *Journal of biogeography*, 34(1), 102-117.
- Peter C., Poh A. N. Z., Ngeian J., Tuen A. A., Minton G. (2016). Identifying Habitat Characteristics and Critical Areas for Irrawaddy Dolphin, *Orcaella brevirostris*: Implications for Conservation. In: Das I., Tuen A. (eds) *Naturalists, Explorers and Field Scientists in South-East Asia and Australasia*. Topics in Biodiversity and Conservation, Springer, 15, 225-238.
- Phillips SJ, Dudík M, Schapire RE. Maxent software for modeling species niches and distributions (Version 3.4.1). Available from: http://biodiversityinformatics.amnh.org/open_source/maxent/
- Phillips, S. J., & Dudík, M. (2008). Modeling of species distributions with Maxent: new extensions and a comprehensive evaluation. *Ecography*, 31(2), 161-175.
- Ponnampalam, L. S., Izmal, J. F., Adulyanukosol, K., Ooi, J. L., & Reynolds, J. E. (2015). Aligning conservation and research priorities for proactive species and habitat management: the case of dugongs *Dugong dugon* in Johor, Malaysia. *Oryx*, 49(4), 743-749.
- Preen, A., & Marsh, H. (1995). Response of dugongs to large-scale loss of seagrass from Hervey Bay, Queensland Australia. *Wildlife Research*, 22(4), 507-519.
- R Core Team. (2017). R: A language and environment for statistical computing. Available from: <https://www.r-project.org>
- Read, A. J. (2008). The looming crisis: interactions between marine mammals and fisheries. *Journal of Mammalogy*, 89(3), 541-548.
- Reeves, R. R., McClellan, K., & Werner, T. B. (2013). Marine mammal bycatch in gillnet and other entangling net fisheries, 1990 to 2011. *Endangered Species Research*, 20(1), 71-97.
- Rhoden, C. M., Peterman, W. E., & Taylor, C. A. (2017). Maxent-directed field surveys identify new

- populations of narrowly endemic habitat specialists. *PeerJ*, 5, e3632.
- Samhouri, J. F., & Levin, P. S. (2012). Linking land-and sea-based activities to risk in coastal ecosystems. *Biological Conservation*, 145(1), 118-129.
- Sheppard, J. K., Preen, A. R., Marsh, H., Lawler, I. R., Whiting, S. D., & Jones, R. E. (2006). Movement heterogeneity of dugongs, *Dugong dugon* (Müller), over large spatial scales. *Journal of Experimental Marine Biology and Ecology*, 334(1), 64-83.
- Stacey, P. J., & Leatherwood, S. (1997). The Irrawaddy dolphin, *Orcaella brevirostris*: a summary of current knowledge and recommendations for conservation action. *Asian Marine Biology*, 14, 195-214.
- Stacey, P. J. & Arnold, P. W. (1999). *Orcaella brevirostris*. *Mammalian Species*, 16, 1–8.
- Vu, L., Tho, T. A., Hung, N. N., & Duy, L. (2017). Conservation of cetaceans in Kien Giang Biosphere Reserve, Vietnam. *Conservation Leadership Program*, 3234115.
- Warren, D. L., Glor, R. E., & Turelli, M. (2010). ENMTools: a toolbox for comparative studies of environmental niche models. *Ecography*, 33(3), 607-611.
- Warren, D. L., & Seifert, S. N. (2011). Ecological niche modeling in Maxent: the importance of model complexity and the performance of model selection criteria. *Ecological applications*, 21(2), 335-342.

Supplementary Tables

Table S2.1. Summary of spatial data used to map the distribution of marine mammals and fishing activities and for each field site.

	SBTI	KUCG	KGBR
References for survey methodology	Ponnampalam et al. 2015	Peter et al. 2016	Vu et al. 2017
Years	2010, 2014-2016	2008-2013	2014-2015
Focal species	<i>Dugong dugon</i>	<i>Orcaella brevirostris</i>	<i>Orcaella brevirostris</i>
Animal sightings			
Post-monsoon		364	
Dry season	1360	348	
Pre-monsoon		150	
Monsoon		20	
Total	1360	882	2
Environmental variables			
Depth	x	x	x
Distance to land	x	x	x
Distance to river mouth	x	x	x
Bathymetric slope	x		
Vessel sightings by fishery			
Pots and traps	33	133	-
Hook and line	311	230	-
Trawls	115	11	-
Nets	2152	1086	-
Longlines	0	0	-
Total	2611	1460	56

Table S2.2. Summary of Maxent runs with the occurrence data for SBTI. Outputs show: 1) the average contribution rate for each variable (and standard deviation). The variable with the largest effect is shown in bold; 2) the Maxent features: L=Linear, Q=Quadratic, H=Hinge, P=Product and T=Threshold; 3) the average AUC values from the test data (AUCTEST) with standard deviation, the average (and standard deviation) omission rate of the test data with the 10% threshold defined with the training data (OR10); 4) the average (and standard deviation) omission rate of the test data with the 0% threshold defined with the training data (ORMTP). Grey shading indicates the model selected.

		SBTI_1	SBTI_2
Environmental variable contributions (%)	Distance to river mouth	40.10 (0.96)	40.45 (0.58)
	Distance to land	34.96 (0.94)	35.20 (1.26)
	Depth	24.78 (0.86)	24.35 (1.12)
	Slope	16.34 (0.03)	-
Maxent parameters	Maxent features	LQHPT	LQHPT
	Regularization factor	3.5	3.5
Maxent validation statistics (%)	AUC _{TEST}	88.48 (0.01)	88.47 (0.01)
	OR ₁₀	10.40 (0.04)	10.32 (0.04)
	R _{MTP}	0.08 (0.002)	0.08 (0.0024)

Table S2.3. Rule-based GIS approach to map Irrawaddy dolphin habitat suitability in KGBR.

Criteria	Rule	Low suitability	High suitability
1) Depth	0 to 15m	must be	must be
2) Proximity to major river mouths	Less than 25km	can be (either 2 or 3)	must be
3) Proximity to land	Less than 10km	can be (either 2 or 3)	must be

Table S2.4. Summary of Maxent runs with the occurrence data for KUCG field site pooled together (“All_Data_” models) or divided by season (PoM, Dry, PrM). Outputs show: 1) the average contribution rate for each variable (and standard deviation). The variable with the largest effect is shown in bold; 2) the Maxent features: L=Linear, Q=Quadratic, H=Hinge, P=Product and T=Threshold; 3) the average AUC values from the test data (AUCTEST) with standard deviation, the average (and standard deviation) omission rate of the test data with the 10% threshold defined with the training data (OR10); 4) the average (and standard deviation) omission rate of the test data with the 0% threshold defined with the training data (ORMTP). Asterisks indicate a significant difference as compared to other models that used the same environmental covariates. Grey shading indicates the model selected for each scenario.

		All_ Data_1	All_ Data_2	PoM _1	PoM _2	Dry _1	Dry _2	PrM _1	PrM _2
Environmental variable contributions (%)	Distance to river mouth	35.45 (0.49)	39.46 (1.32)	31.71 (1.88)	26.87 (1.15)	55.26 (2.18)	49.98 (1.57)	48.68 (2.94)	45.23 (2.73)
	Distance to land	41.57 (0.58)	39.10 (1.03)	47.42 (2.00)	49.87 (1.19)	22.13 (1.93)	25.50 (1.29)	23.82 (2.11)	28.27 (2.52)
	Depth	22.97 (0.75)	21.43 (0.48)	20.86 (0.98)	23.25 (1.17)	22.61 (0.68)	24.52 (0.81)	27.94 (1.51)	26.50 (1.62)

Maxent parameters	Maxent features	LQHPT	LQHP	LQHP	LQHPT	LQHP	LQHPT	LQHP	LQHPT
	Regularization factor	1	1	1.5	1.5	1.5	1.5	3.5	3.5
Maxent validation statistics (%)	AUC _{TEST}	90.58* (0.01)	87.91 (0.02)	88.54 (0.03)	91.43* (0.02)	94.02 (0.01)	95.68* (0.01)	87.48 (0.04)	87.55 (0.04)
	OR ₁₀	11.48 (0.03)	10.16	10.0 (0.06)	11.21 (0.05)	9.94 (0.07)	11.13 (0.06)	10.0 (0.10)	10.0 (0.10)
	OR _{MTP}	0.13 (0.004)	0.13 (0.004)	0.3 (0.01)	0.3 (0.01)	0.0 (0.00)	0.0 (0.00)	0.0 (0.00)	0.0 (0.00)

Table S2.5. Consequence criteria scores for five fishing gears categories across three field sites. Showing scores contributing to highest risk (3), intermediate risk (2) and lowest risk (1). Scores of 0 were applied to irrelevant criteria or if not enough data exists and, consequently, these criteria were omitted from the bycatch risk equation. 'N/A' indicates gears not present in the field site. Data quality (DQ) and variable weights (W) applied as a weighted average for a site and specific gear-species interaction are listed in the Notes column.

<i>Consequence-Sensitivity</i>	SBTI (dugongs)	KUCG (dolphins)	KGBR (dolphins)	Notes
Mortality				
nets	3	3	3	
trawls	2	3	3	SBTI DQ = 3
pots and traps	2	2	2	
longlines	N/A	N/A	1	
hook and line	1	1	1	
Life stages affect by gear				
nets	0	2	0	
trawls	2	0	0	
pots and traps	0	0	0	
longlines	N/A	N/A	0	
hook and line	0	0	0	
<i>Consequence-Resilience</i>	SBTI (dugongs)	KUCG (dolphins)	KGBR (dolphins)	Notes
Age of maturity	3	3	3	

2 Management tool: Bycatch risk assessment

Reproductive strategy	3	2	2
Population connectivity	2	3	3
Local status of the species	3	3	3

Table S2.6. Exposure criteria scores for five fishing gears across three field sites. Showing scores contributing to highest risk (3), intermediate risk (2) and lowest risk (1). Scores of ‘SEC’ indicate spatially explicit criteria layers shown in S11, S12 and S13 Fig. Scores of ‘0’ were applied to irrelevant criteria or if not enough data exists and, consequently, these criteria were omitted from the bycatch risk equation. ‘N/A’ indicates gears not present in the field site. Data quality (DQ) and variable weights (W) applied as a weighted average for a site and specific gear-species interaction are listed in the Notes column.

<i>Exposure criteria</i>	SBTI (dugongs)	KUCG (dolphin)	KGBR (dolphins)	Notes
Spatial overlap	SEC	SEC	SEC	
Temporal overlap				
nets	2	3	3	KUCG DQ = 1, KGBR DQ = 3
trawls	2	2	2	KUCG DQ = 3
pots and traps	3	3	3	
longlines	N/A	N/A	2	
hook and line	2	3	3	KUCG DQ = 3
Intensity of gear use				S11 Fig
nets	SEC	SEC	0	
trawls	SEC	SEC	0	
pots and traps	SEC	SEC	0	
longlines	N/A	N/A	0	
hook and line	SEC	SEC	0	
Likelihood of interaction between gear and species	SEC	SEC	SEC	SBTI W = 1, KUCG W = 1; S13 Fig
Likelihood of capture by gear (“catchability”)				SBTI W = 1; KGBR W = 1
nets	3	3	3	

trawls	2	2	2	
pots and traps	1	1	1	KUCG DQ = 3
longlines	N/A	N/A	1	KGBR DQ = 3
hook and line	1	1	1	
Current status of management	SEC	SEC	SEC	S12 Fig

Table S2.7. Data quality ratings for bycatch risk assessment.

Data quality	Description	Example
1 (green)	Best data. Substantial information is available to support the score and is based on data collected in the study region (or nearby) for the species in question.	Animal sightings - Distribution data collected during line transect survey. Data could be used to estimate relative abundance with robust methodologies and measurements of uncertainties.
2 (yellow)	Adequate data. Information is based on data collected outside the study region, may be based on related species, may represent moderate or insignificant statistical relationships.	Habitat suitability - Estimated using non-modeled distribution methodology, minimal environmental variables collected.
3 (red)	Limited data. No empirical literature exists to justify scoring for the species but a reasonable inference can be made.	Fishing effort / gear type densities - Sparse or incomplete data, no geospatial or precise localization of the fishing effort/gear distribution.

Supplementary Figures

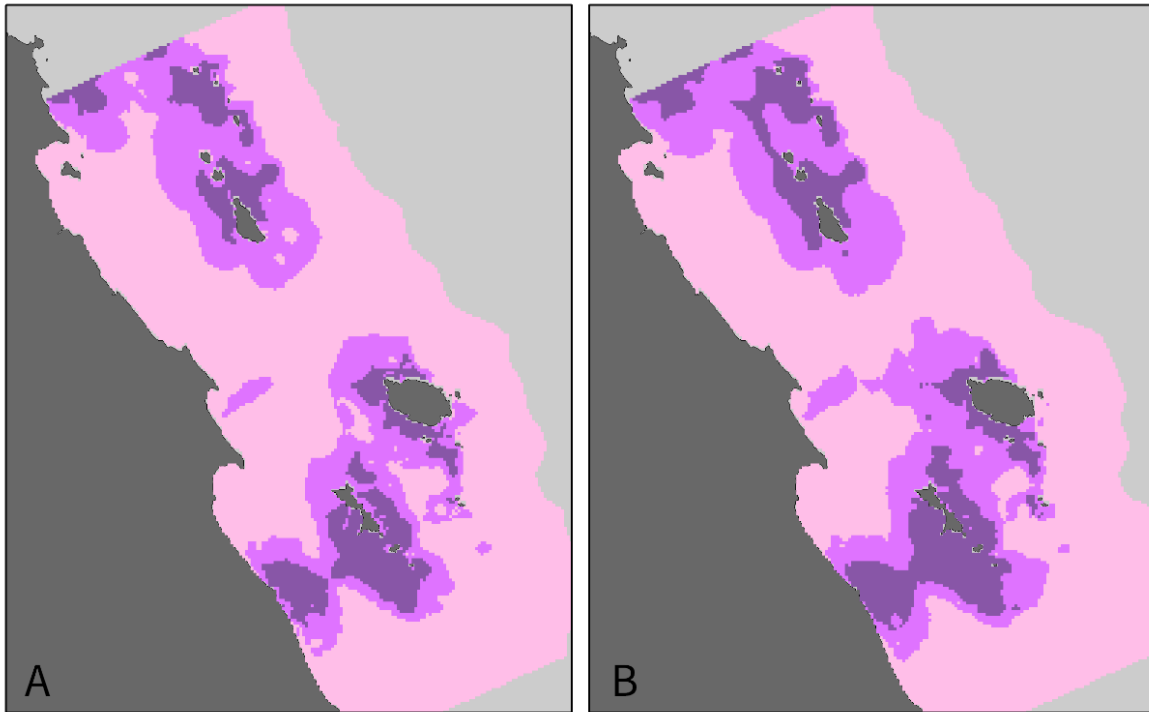


Figure S2.1. Habitat suitability model outputs for dugongs in SBTI. (A) with and (B) without bathymetric slope included as an environmental covariate. Warmer colors indicate higher predicted suitability.

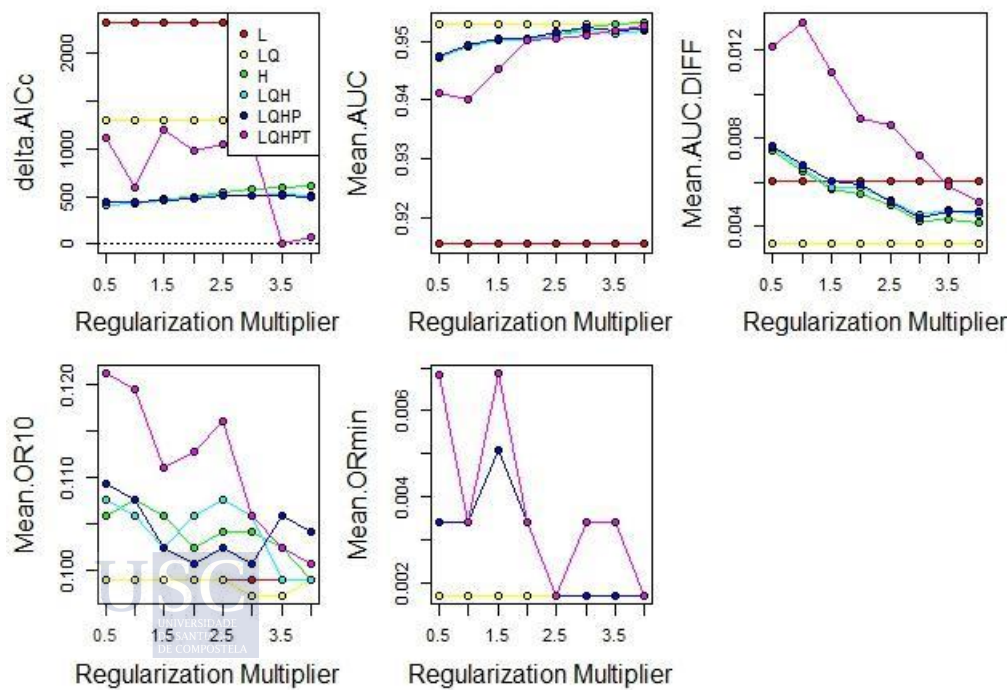


Figure S1.2. ENMeval outputs for SBTI with bathymetric slope covariate. Model of dry season only occurrence data with the environmental covariates: distance to river mouths, distance to land, water depth, and bathymetric slope.

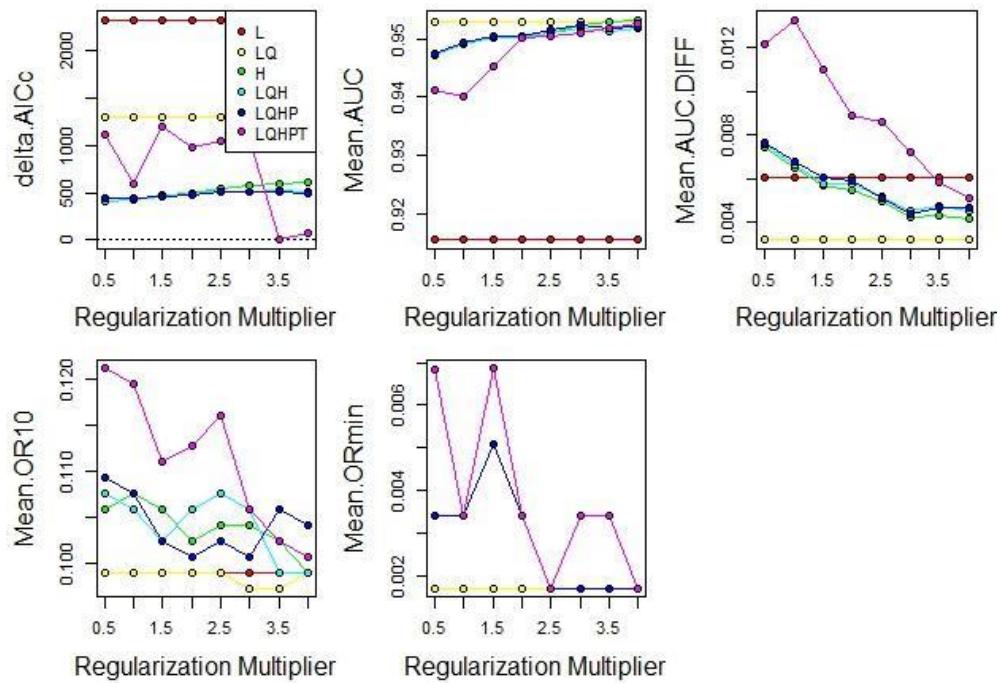


Figure S2.3. ENMeval outputs for SBTI without bathymetric slope covariate. Model of dry season only occurrence data with the environmental covariates: distance to river mouths, distance to land, and water depth.

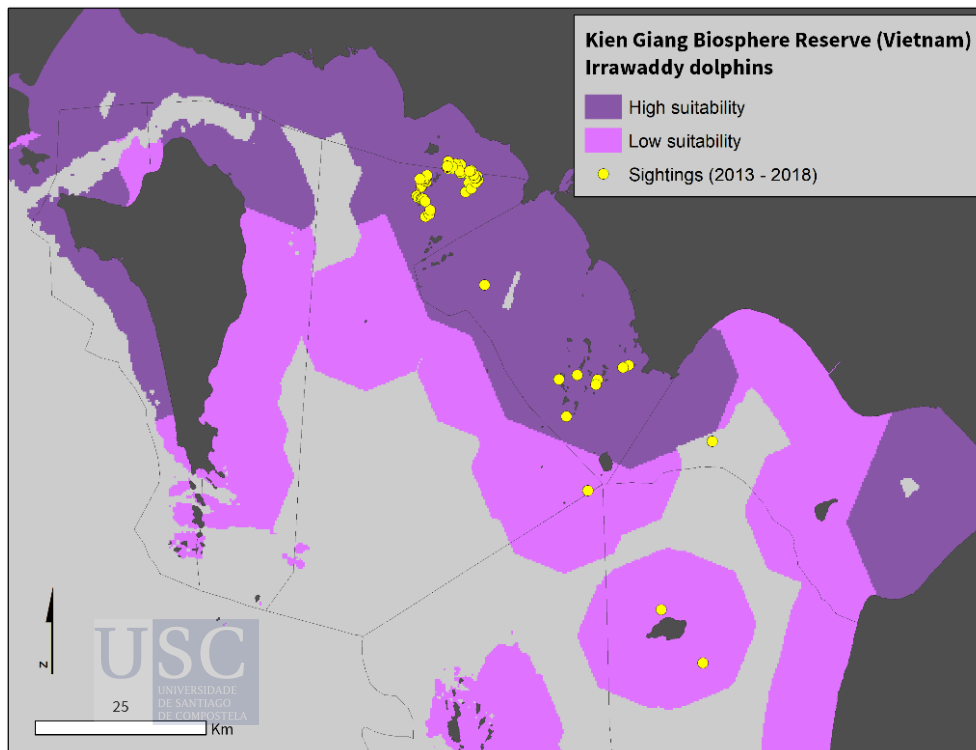


Figure S2.4. Rule-based GIS approach for estimating habitat suitability in KGBR. Yellow dot-symbols show sightings locations of Irrawaddy dolphins (*Orcaella brevirostris*) acquired from in-country partners after the ByRA. Warmer colors indicate higher predicted suitability.

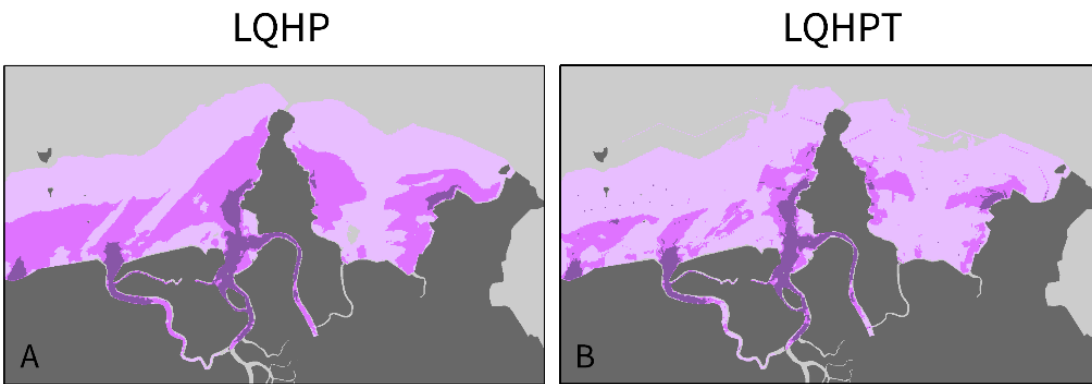


Figure S2.5. Habitat suitability model for Irrawaddy dolphins in KUCG with all the data pooled. (A) LQHP and (B) LQHPT feature classes allowed. Warmer colors indicate higher predicted suitability.

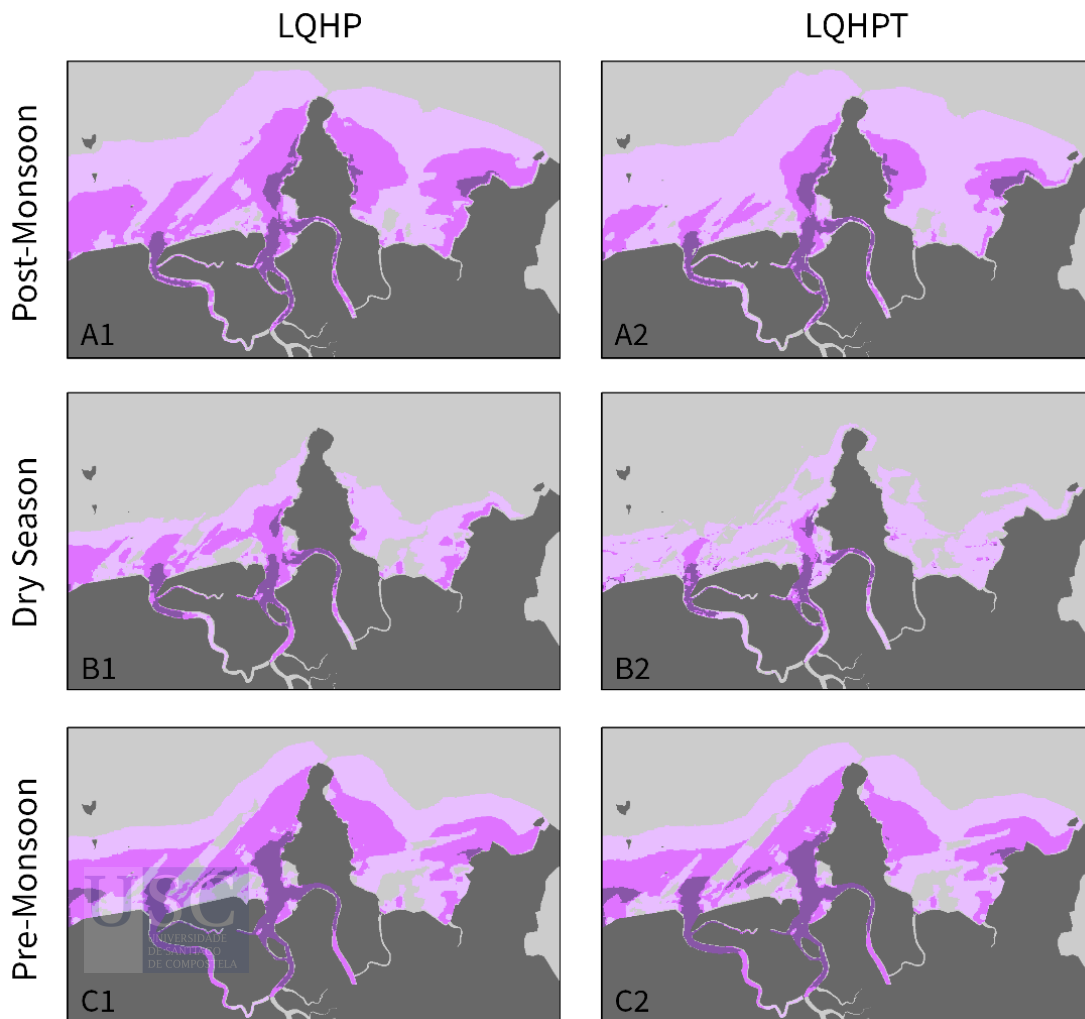


Figure S2.6. Habitat suitability model outputs for Irrawaddy dolphins in KUCG. Panels organized by season (A-C) and Maxent feature classes (1-2). Warmer colors indicate higher predicted suitability.

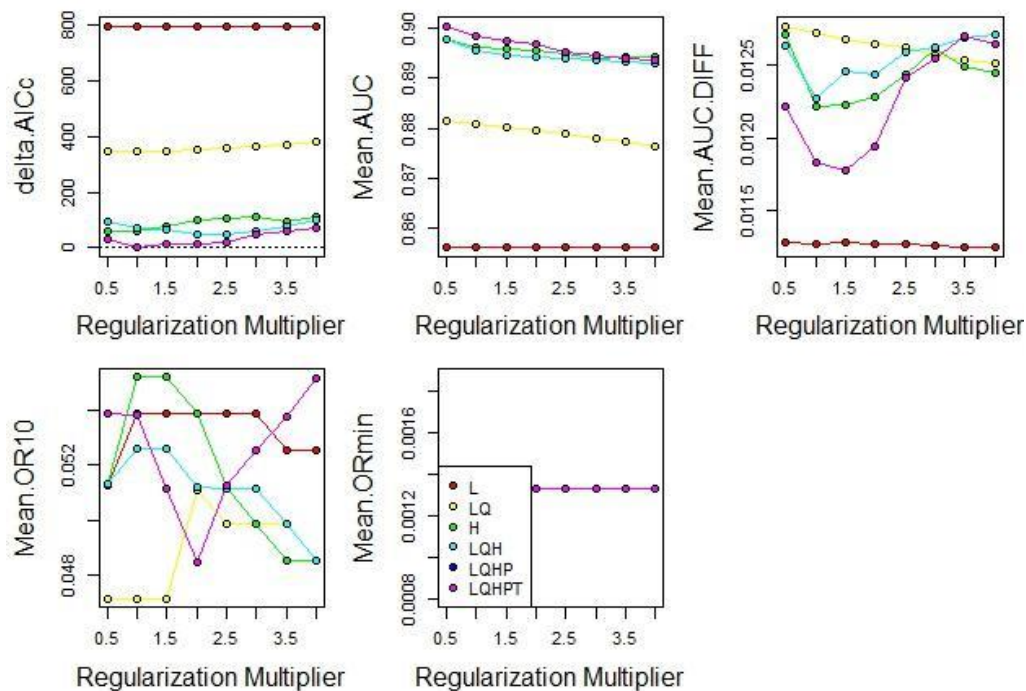


Figure S2.7. ENMeval outputs for KUCG with all data pooled. Model includes environmental covariates: distance to river mouths, distance to land and bathymetric depth.

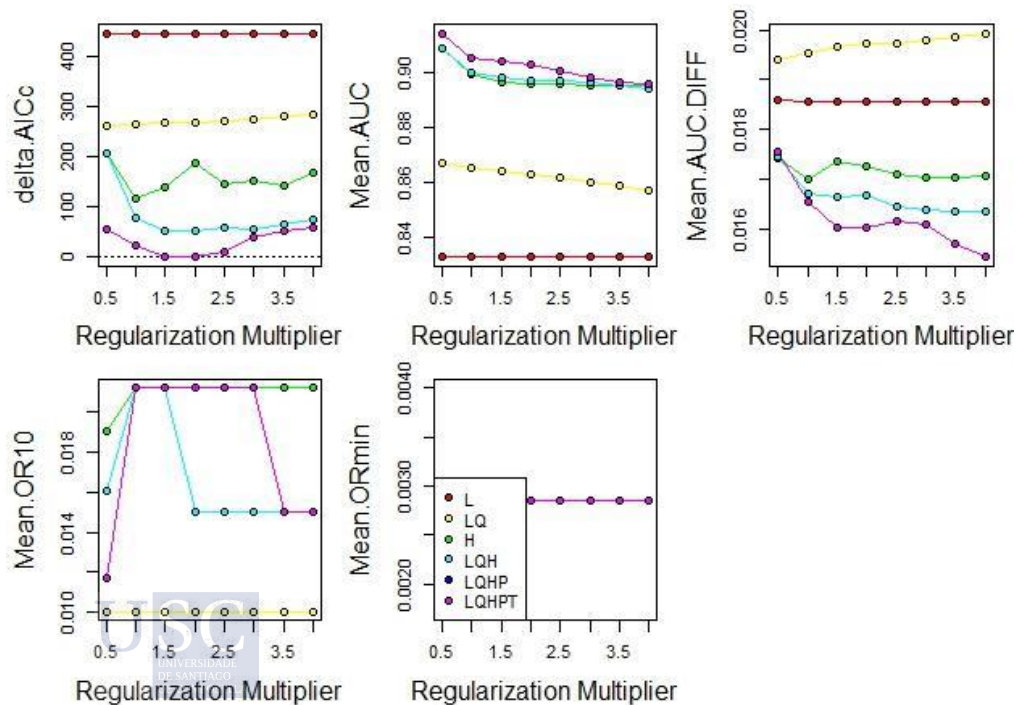


Figure S2.8. ENMeval outputs for KUCG with the post-monsoon occurrence data. Model includes environmental covariates: distance to river mouths, distance to land and bathymetric depth.

2 Management tool: Bycatch risk assessment

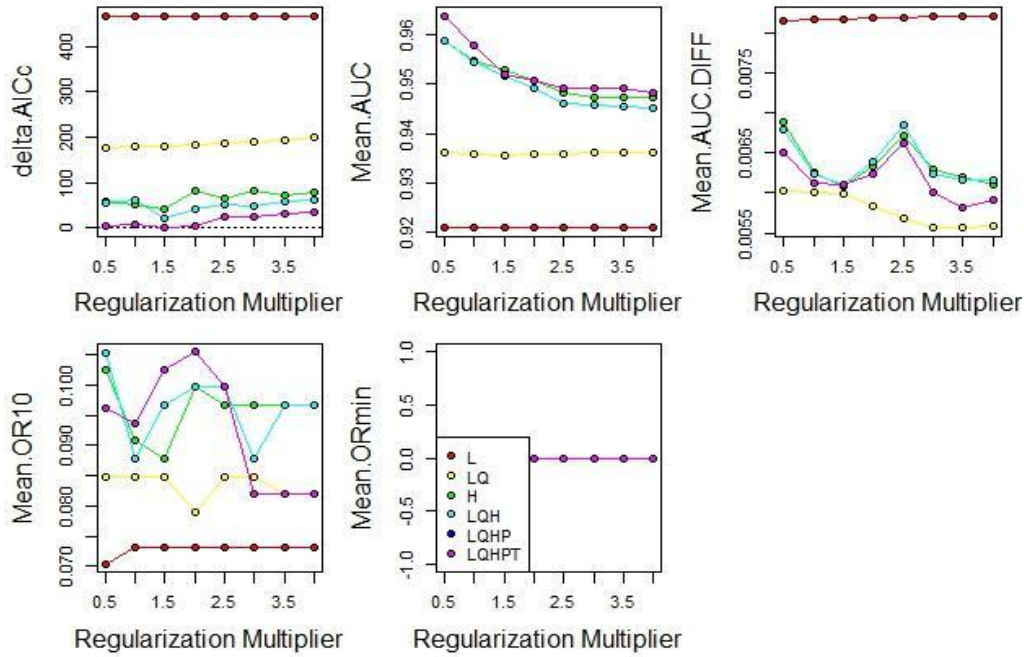


Figure S2.9. ENMeval outputs for KUCG with the dry season occurrence data. Model includes environmental covariates: distance to river mouths, distance to land and bathymetric depth.

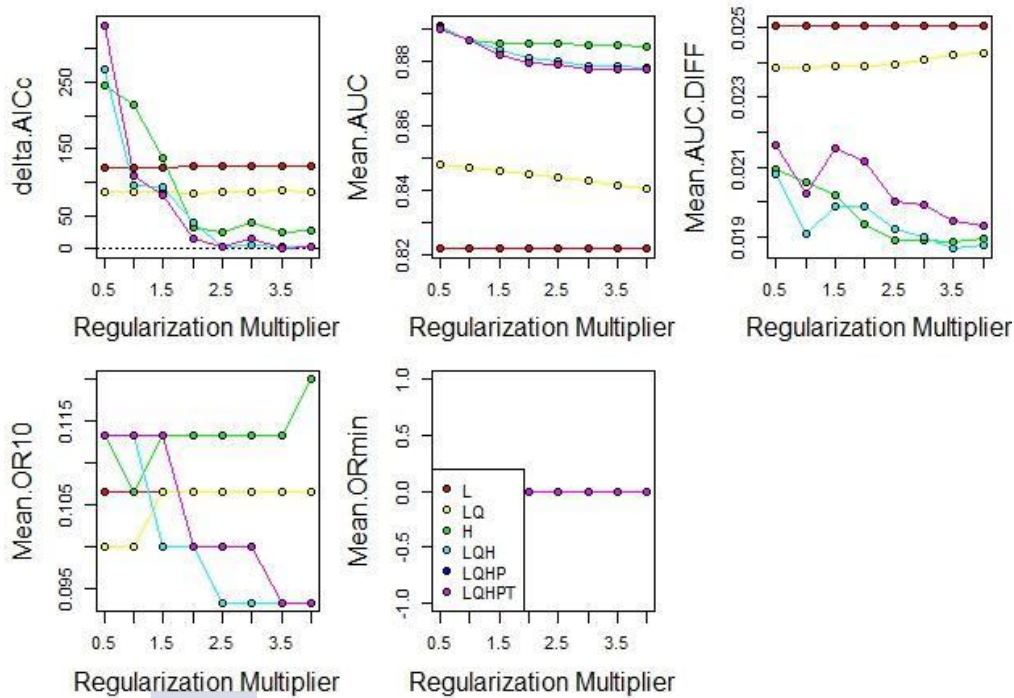


Figure S2.10. ENMeval outputs for KUCG with the pre-monsoon occurrence data. Model includes environmental covariates: distance to river mouths, distance to land and bathymetric depth.

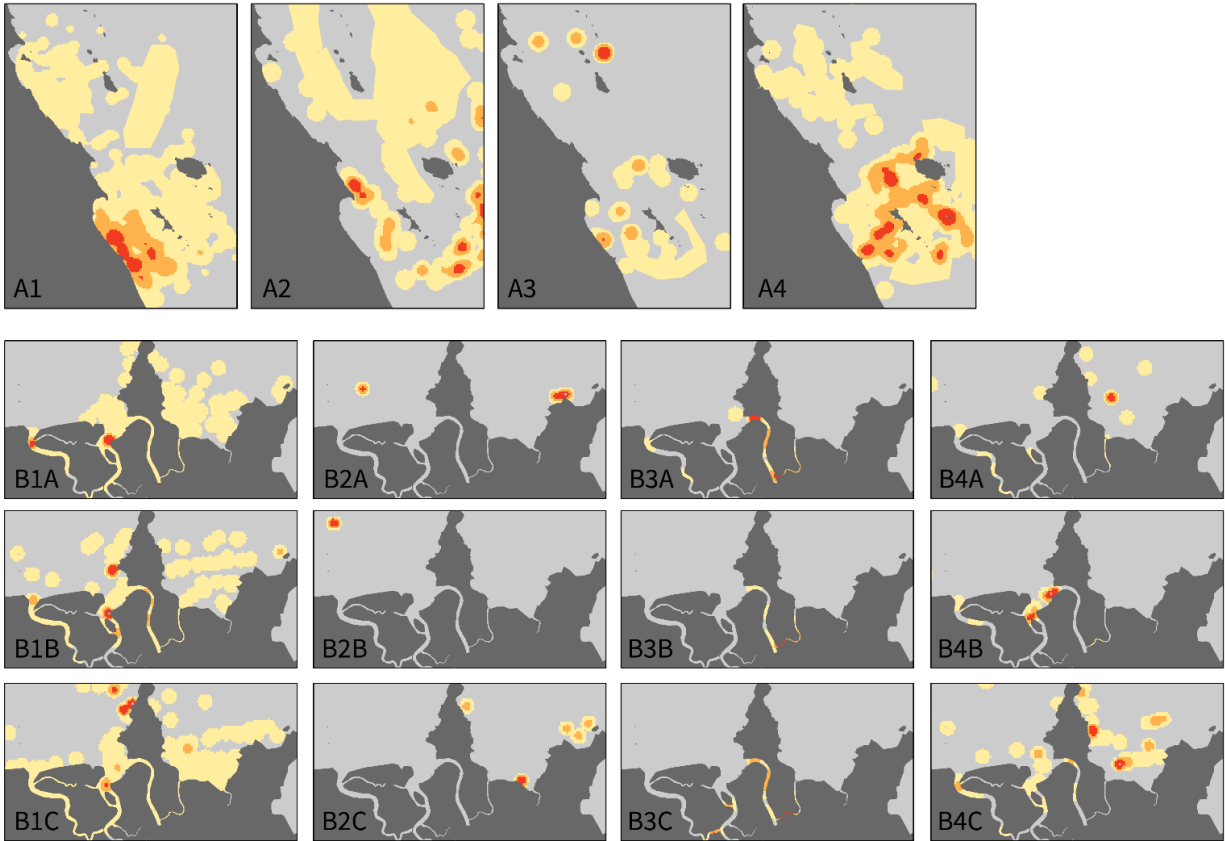


Figure S2.11. Spatially explicit layers for ‘intensity of gear use’ criterion by field site. (A) SBTI and (B) KUCG; fishing gear type: (1) nets, (2) trawls, (3) pots and traps, (4) hook and line, and (5) longlines; and season: (A) dry, (B) pre monsoon, and (C) post monsoon. Warmer colors indicate ratings that contribute to higher exposure scores.

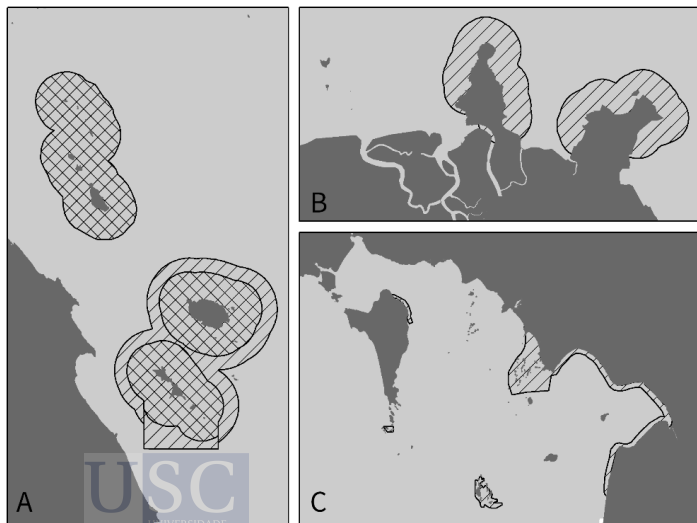


Figure S2.12. Layers used to build spatially explicit layer for ‘current status of management’ criterion by field site. (A) SBTI, (B) KUCG, and (C) KGBR. Cross-hatching indicates areas where management has been identified and implemented (score = 1), hatching indicates areas where management has been identified but not implemented (score = 2), and areas with no hatching indicate that no management has been identified (score = 3).

2 Management tool: Bycatch risk assessment



Figure S2.13. Spatially explicit layers for ‘likelihood of interaction between gear and species’ criterion by field site. (A) SBTI, (B) KUCG, and (C) KGBR; fishing gear type: (1) nets, (2) trawls, (3) pots and traps, (4) hook and line, and (5) longlines; and season: (A) dry, (B) pre monsoon, and (C) post monsoon. Warmer colors indicate ratings that contribute to higher exposure scores.

Chapter 3





3 MODELING SEASONAL DISTRIBUTION OF IRRAWADDY DOLPHINS (*ORCAELLA BREVIROSTRIS*) IN A TRANSNATIONAL IMPORTANT MARINE MAMMAL AREA²

3.1 INTRODUCTION

The globally endangered Irrawaddy dolphin (*Orcaella brevirostris*) is distributed in fragmented populations throughout the coastal, estuarine, and freshwater environments of Southeast Asia (Perrin et al., 1995, 2005; Hines et al., 2015). The species faces numerous anthropogenic threats throughout its range, including fisheries bycatch, habitat degradation and marine pollution (Reeves et al., 2003; Kannan et al., 2005; Jaaman et al., 2009). Irrawaddy dolphins are the only confirmed cetacean species to inhabit the coastal waters of the Cambodia-Vietnam border region (Beasley and Davidson, 2007; Minton et al., 2017; Tubbs et al., 2020), which includes the Kep Archipelago, Cambodia. Illegal, Unreported, and Unregulated (IUU) fishing is a daily threat to dolphins and the many species of coral, fish, and invertebrates that support local fisheries and tourism (Beasley and Davidson, 2007; Böhm, 2019; Tubbs et al., 2019). Despite regional conservation efforts, no Irrawaddy dolphin-specific conservation plans are in place. A more detailed understanding of dolphin habitat distribution could support the establishment of tailored conservation measures for the Kep Archipelago as well as have broader

² This chapter previously appeared as an article in the *Frontiers in Marine Science* journal. The original citation is as follows: Verutes, G. M., Tubbs, S. E., Selmes, N., Clark, D. R., Walker, P., & Clements, O. (2021). Modeling Seasonal Distribution of Irrawaddy Dolphins (*Orcaella brevirostris*) in a Transnational Important Marine Mammal Area. *Frontiers in Marine Science*. doi: 10.3389/fmars.2021.617921

3. Modeling: Seasonal dolphin distribution

implications for the management of Irrawaddy dolphins throughout their range.

Cetacean distribution patterns are governed by a combination of biotic and abiotic factors and the ability for species to access eco-geographical suitable locations (Baumgartner et al., 2001; O'Donoghue et al., 2010; Peterson, 2011). For Irrawaddy dolphins, previous studies indicate they inhabit shallow (2–15 m), warm (24–31°C), nearshore waters (1–20 km from the coast), of varying salinity (2–35 ppt), and in close proximity to river mouths (< 11 km; Dolar et al., 2002; Peter et al., 2016a; Kuit et al., 2019). These waters are likely to support the small fish, crustacean, and cephalopod species that Irrawaddy dolphins predate upon (Stacey and Leatherwood, 1997; Ponnampalam et al., 2013; Jackson-Ricketts et al., 2019). In the Eastern Gulf of Thailand, intense summer monsoonal rainfall precedes a period of high freshwater flows to coastal river mouths (Tsujiimoto et al., 2018). The resulting changes in water depths and primary productivity have been shown to alter coastal dolphin prey abundance and the distribution of their habitats throughout the year (Hastie et al., 2005; Bearzi et al., 2008; McCluskey et al., 2016; Sprogis et al., 2017). The coastal-marine areas in the vicinity of the Kep Archipelago are also subject to seasonal high flow events, which present an opportunity to identify and distinguish different oceanographic factors that explain seasonal variation in Irrawaddy dolphin habitat.

Species Distribution Models (SDMs), also known as habitat models, link species observations to environmental variables (Briscoe et al., 2014; Gilles et al., 2016; Becker et al., 2017), and are becoming an increasingly common conservation planning tool (Cañadas et al., 2005; Bailey and Thompson, 2009; Hammond et al., 2013). For example, SDMs have been used to identify critical habitat (Redfern et al., 2006; Gregr et al., 2013), predict responses to environmental changes (Silber et al., 2017), and assess overlap in area usage between species and fisheries (Feist et al., 2015; Giralt Paradell et al., 2019). Nevertheless, there are practical considerations for applying correlative SDMs, including limits to their accuracy for differentiating presences from absences, the reliability of predictions (Liu et al., 2009), along with pitfalls when extrapolating outside the environment used to train a model (Elith et al., 2010). For applications that produce several habitat-selection models in one area, the environmental variables found to be significant predictors of distribution often differ between species (Garaffo et al., 2011), providing baseline knowledge on subtle habitat characteristics of sympatric cetacean species (Tobeña et al., 2016; Kuit et al., 2019). There are fewer examples of

multiple SDMs developed for one species that illuminate seasonal patterns of distribution, density, or behavior (Daura-Jorge et al., 2005; Campbell et al., 2015; Verutes et al., 2020).

The Cambodian Marine Mammal Conservation Project (CMMCP) was launched in 2017 by the Non-Governmental Organization Marine Conservation Cambodia (MCC) to support the conservation of Cambodian marine mammals through research and education (Tubbs et al., 2019). Boat surveys conducted by CMMCP in the Kep Archipelago between October 2017 and September 2019 revealed that Irrawaddy dolphins were present year-round, with seasonal variation in encounter rates and distribution (Tubbs et al., 2020). Tubbs et al. (2020) also identified the need to further investigate different factors affecting Irrawaddy dolphin seasonal habitat selection, including prey abundance and other explanatory variables of seasonal distribution related to freshwater input. Previous SDMs developed for Irrawaddy dolphins have shown depth to be the strongest predictor of their distribution (Smith et al., 2008; Jackson-Ricketts et al., 2020), followed by salinity (Smith et al., 2008). Smith et al. (2009) produced two SDMs for coastal Irrawaddy dolphins in Bangladesh, showing that during the season of “high [river] flow”, their distribution was dependent on low salinity and depths, and during the season of “low [river] flow” distribution was dependent on high surface water temperatures and depths.

The current study uses CMMCP’s presence-only sightings, in combination with publicly accessible environmental data layers derived from earth observation techniques, to produce four distinct seasonal SDMs. We hypothesize that seasonal variation in habitat use by Irrawaddy dolphins of the Kep Archipelago differs from other marine populations in Southeast Asia due to local environmental conditions. Specifically, with increasing freshwater input following the summer monsoon, we expect the distribution of Kep’s Irrawaddy dolphins to expand further offshore and away from major river mouths. We test whether biophysical variables commonly associated with small cetaceans can be used to construct accurate models that describe the ecological processes governing Irrawaddy dolphin habitat selection and predict seasonal distribution of this freshwater-dependent species (Smith et al., 2009). This research aims to achieve three goals that relate to enhancing baseline knowledge of the coastal Irrawaddy dolphin population inhabiting waters of the Kep Archipelago, Cambodia: (1) to characterize their spatial distribution; (2) to map variation in seasonal occurrences and habitat preferences; and (3) to estimate the population’s ecological niche based on the influence of oceanographic variables (i.e., depth, slope, proximity to shore and river mouths, sea surface temperature, and chlorophyll-

3. Modeling: Seasonal dolphin distribution

a concentration) on predicted probability of distribution. We intend to inform spatial plans for managing high conflict areas between small cetaceans and human activities, particularly IUU fishing. As the first Irrawaddy dolphin habitat modeling study at the Cambodian-Vietnamese border region, knowledge gained will support the design of transboundary conservation measures and augment the understanding of coastal dolphin habitat selection on a wider scale.

3.2 METHODS

3.2.1 Study area

The study area comprises the coastal waters of Cambodia's Kep and Kampot provinces and Vietnam's Kien Giang Biosphere Reserve, on the eastern coast of the Gulf of Thailand (2,112 km²; **Figure 8**). The region receives freshwater input from two sources, the Kampot River from the northwest, and Giang River to the east. Here, 13 Cambodian islands, known as the Kep Archipelago, are separated from the 16 Vietnamese Pirate islands, by the maritime border. The waters are shallow, ranging from 2 to 30 m, and support coral, mangrove and seagrass habitats (Reid et al., 2019). The archipelago is at the heart of the Kien Giang–Kep Archipelago Important Marine Mammal Area (IMMA; IUCN-MMPATF, 2019), containing critical habitat for the survival of Irrawaddy dolphins, which are frequently sighted in the area (Vu et al., 2017; Tubbs et al., 2019). Inside this IMMA, is the Kep Marine Fisheries Management Area (MFMA), Cambodia's equivalent of a Marine Protected Area (Boon et al., 2014), which delineates conservation zones for the purposes of reducing maritime conflicts, controlling tourism activities, and protecting fish stocks, habitats and the breeding grounds of vulnerable species such as the Irrawaddy dolphin (MCC, 2016).

3.2.2 Boat surveys

We utilized two years of Irrawaddy dolphin sightings data collected by CMMCP between October 2017 and September 2019 (average of 2.6 surveys/month \pm SD 1.7). Surveys lasted between 3 and 5 hours and followed one of three routes: route one followed a triangular-shaped track around the islands of the Kep Archipelago, bound by the maritime border and water depth; route two traveled between Koh Ach Seh and Kampot, on dive expeditions conducted by MCC; and route three traveled between Koh Ach Seh and Kep town on an MCC supply trip (**Figure 9**).

Routes one and two took place on a converted Seine net vessel with a 200 HP inboard engine and a viewing platform 3.8 m above sea level, while route three took place on a converted trawling boat with a 120 HP inboard engine and a viewing platform 1.5 m above sea level. Vessels traveled at an average speed of 4 knots, with routes tracked using a Garmin 64s GPS.

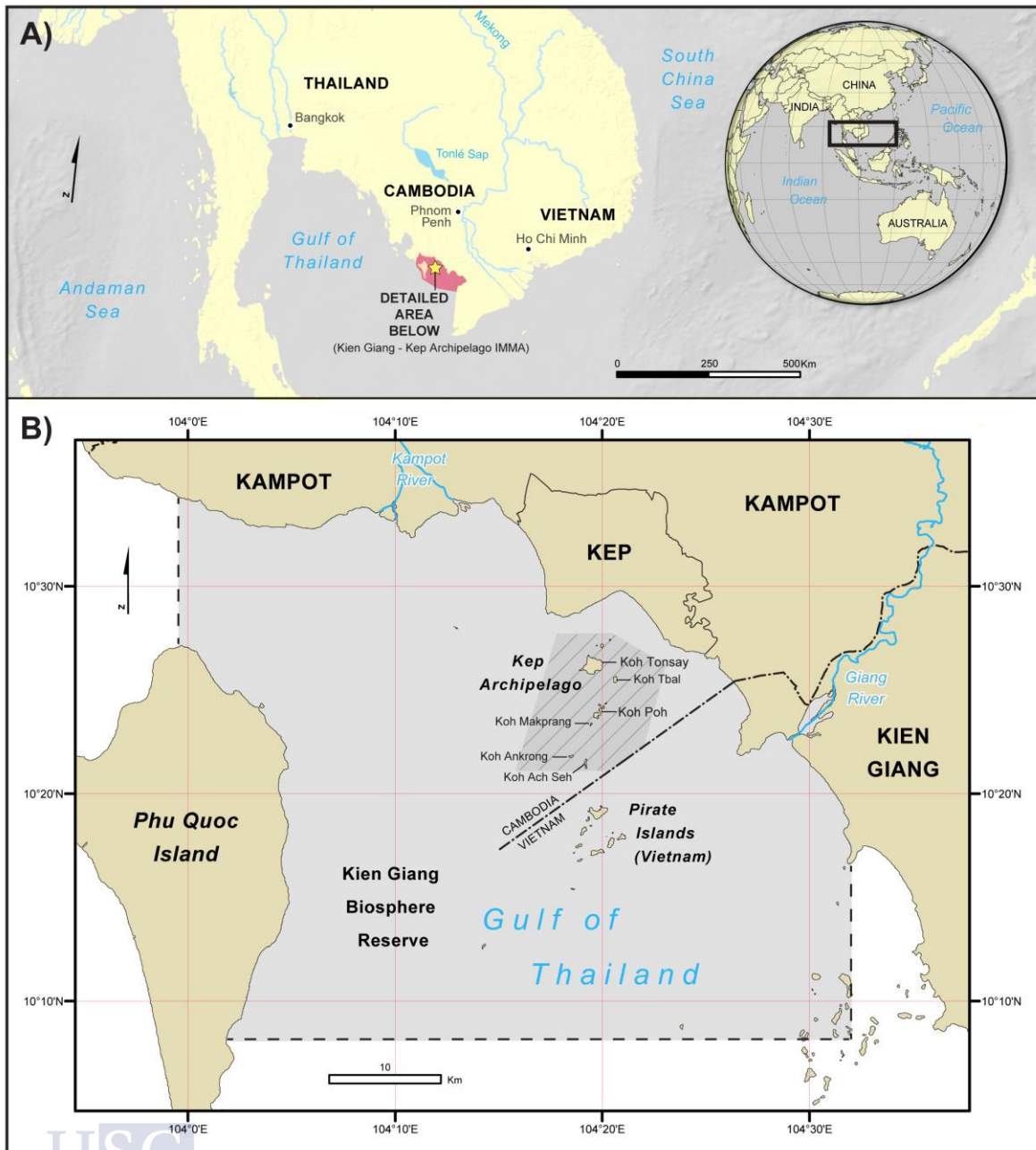


Figure 8. The study area: (A) situated in the Eastern Gulf of Thailand, including the Kien Giang-Kep Archipelago Important Marine Mammal Area (red color) and (B) The riverine inputs to the Kep Archipelago (Kampot and Giang Rivers). Light gray area indicates the extent of physiographic and remotely sensed environmental data. The darker area with gray hatching is the current extent of the 2018 Kep Marine Fisheries Management Area.

3. Modeling: Seasonal dolphin distribution

A team of five trained observers were on board each vessel. Three observers scanned the sea with binoculars in search of dolphin groups, while two rested. Observers rotated roles every 10 min to avoid fatigue effects. Environmental conditions were recorded every hour, or sooner, with surveys only taking place when the Beaufort sea state was ≤ 3 . For each sighting of one dolphin or group, defined as a collection of individuals with coordinated behavior (Connor et al., 2006), the time, group size, angle of the group from north and distance of the group from the vessel were recorded. Sighting data preparation included attaining dolphin group locations using the vessel's GPS location, the distance of the group from the vessel, and bearing angle from north using trigonometric identities (Pythagoras, sine, and cosine rules).

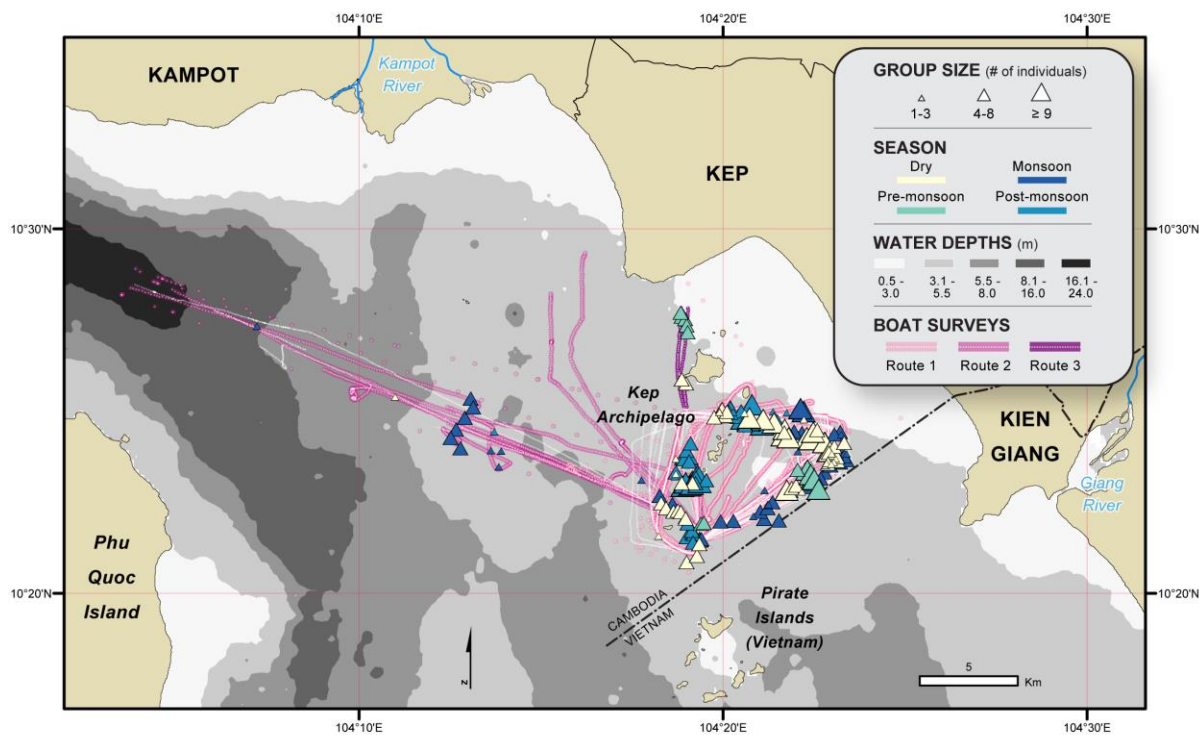


Figure 9. Irrawaddy dolphin occurrences recorded during the 2-year survey period (October 2017 through September 2019). The color of each triangle indicates the season of sighting and graduated symbols denote group size. White dotted lines with underlain colors show the different routes taken during boat surveys.

3.2.3 Environmental variables

A number of environmental factors influence cetacean distribution, and Irrawaddy dolphins are no different (Minton et al., 2011; Hines et al., 2020; Jackson-Ricketts et al., 2020). First, we acquired and prepared static oceanographic data about water depths, seafloor slope, and riverine input locations using QGIS v3.4 (QGIS Development Team, 2018). Shoreline distribution

(mainland and offshore islands) for Cambodia and Vietnam were provided by Marine Conservation Cambodia and verified with data from the GADM v2 database and OpenStreetMap project. The locations of riverine inputs from major distributaries of the Mekong Delta (Kampot and Giang Rivers) were digitized using satellite imagery. The United States nautical chart, Dao Phu Quoc and Approaches to Kampot (HO3146), was georeferenced and digitized for a total of 1727 depth soundings. Then, a continuous bathymetric surface was created using Inverse Distance Weighting (IDW) interpolation of the samples. Distance to shore and major river mouths were also calculated in GIS to compute the least cost path following a surface of marine grid cells. To minimize correlation among predictor variables, a variable inflation factor (VIF) measure was used to assess how much each independent variable is influenced by its interaction with other candidate variables. Both distance to shore measurements (all landmasses and offshore islands only) had VIF scores greater than 4, an indication of multicollinearity (Kutner et al., 2005). The distance to offshore islands variable was retained because its VIF dropped below 4 after the distance to landmass variable was removed.

To investigate the role of varying environmental conditions during the year that influence Irrawaddy dolphin habitat selection, Plymouth Marine Laboratory processed grids of two environmental variables, chlorophyll-a concentration (Chl-a) and sea surface temperature (SST). Chl-a (mg/m³) was acquired from the Copernicus Sentinel-3 Ocean and Land Color Instrument (OLCI) at 300 m spatial resolution. SST (°C) was extracted from NOAA's Advanced Very High Resolution Radiometer (AVHRR) at 1.1 km resolution. For both Chl-a and SST, we took all available satellite passes, applied the recommended quality masking, and combined them as monthly median composites to reduce the effect of contaminated pixels (Miller et al., 1997). Sea surface salinity data, from the NASA Soil Moisture Active Passive (SMAP) observatory, was not usable due to performance issues associated with land surface reflectance near the Kep offshore islands. Following the methods of Tobeña et al. (2016), we extracted values at each dolphin sighting location and, when applicable, the corresponding monthly composite for geospatial layers: depth (m); seafloor slope (degrees); distance to shore (km), time-lagged chlorophyll-a concentration for one and 2 months prior to sighting [Chl-a(-1 m), Chl-a(-2 m)], local variation of chlorophyll-a concentration (V-Chl-a; calculated as standard deviation within a 2 km focal radius); and local variation of sea surface temperature (V-SST; calculated as standard deviation within a 3 km focal radius).

3.2.4 Seasonal habitat models

To capture the spatial dimension of Irrawaddy dolphin habitat suitability in the Kep Archipelago, we built temporally stratified SDMs in Maxent (version 3.4.1; Phillips et al., 2020) following the monsoonal seasons defined by Tsujimoto et al. (2018): dry (December–February), pre-monsoon (March–April), summer monsoon (May–September), and post-monsoon (October–November). The Maxent algorithm infers species distribution as a function of relevant environmental covariates (Dudík et al., 2007). Presence-only data of Irrawaddy occurrence organized by these four seasons were used to quantify the statistical relationship between predictor environmental covariates at locations where a species had been observed vs. background locations in which no species had been observed (Phillips et al., 2006).

Sample selection bias is a key consideration when building presence-only models in terms of minimizing the risk of predictions that conflate species distribution with sampling effort (Elith et al., 2011; Merow et al., 2013). To account for environmentally biased sampling of the study area, we performed a spatial filtering routine. First, when multiple localities (species occurrence and background data) were present in a pixel of the 250 m-grid system defined by environmental data, we randomly selected one record. Consequently, a total of 125 on-effort species presence samples and 2,000+ background samples (“pseudo-absences”) remained, effectively minimizing sampling bias because it is common to both presences and absences. Next, we produced tables with the sample records corresponding to each season, the eight dynamic variables derived from SST and Chl-a measurements, and four static physiographic variables (**Table 6**). Finally, the Samples With Data (SWD) option of Maxent was used to select environmental samples from a distribution of locations with the same selection bias as the occurrence data.

Table 6. Summary of candidate environmental data used to build SDMs in Maxent.

Environmental variable	Abbrev	Resolution	Units	Transformation	Source
Water depth	Depth	250m ²	m	none	US Naval Oceanographic Office (HO3146)
Distance to offshore islands	Dist2Isl	250m ²	km	square root	Marine Conservation Cambodia; GADM; OpenStreetMap
Distance to river mouth	Dist2Riv	250m ²	km	square root	GADM; OpenStreetMap
Chlorophyll-a concentration	Chl-a	300m ²	mg/m ³	log10	Ocean and Land Colour Instrument (OLCI) of Sentinel-3
Sea surface temperature	SST	1.1km ²	°C	none	NOAA Advanced Very High Resolution Radiometer (AVHRR)
Derived variables					Source
Slope within a 1km focal radius	Slope	250m ²	degrees from the horizontal	log10	Depth
Time-lagged Chlorophyll-a concentration (-1 month)	Chl-a (-1m)	250m ²	mg/m ³	log10	Chl-a
Time-lagged Chlorophyll-a concentration (-2 months)	Chl-a (-2m)	250m ²	mg/m ³	log10	Chl-a
Chlorophyll-a local variation (calculated as standard deviation within a 2km focal radius of log-transformed Chlorophyll-a)	V-Chl-a	250m ²	SD log10(mg/m ³)	log10	Chl-a
Time-lagged Chlorophyll-a local variation (-1month)	V-Chl-a (-1m)	250m ²	SD log10(mg/m ³)	log10	Chl-a
Time-lagged Chlorophyll-a local variation (-1month)	V-Chl-a (-2m)	250m ²	SD log10(mg/m ³)	log10	Chl-a
Sea surface temperature local variation (calculated as standard deviation within a 4km focal radius of SST)	V-SST	1km ²	SD °C	none	SST

3.2.5 Model tuning, variable selection, and suitability thresholds

Parsimonious models that balance complexity and fit yield more accurate, interpretable, and transferable predictions (Liu et al., 2009; Warren and Seifert, 2011; Muscarella et al., 2014). This ensures that a model infers habitat suitability based on the most salient predictor variables, and

3. Modeling: Seasonal dolphin distribution

not simply the noise inherent in a training dataset (Hastie et al., 2009). Beginning with five model fitting functions of Maxent—linear (L), quadratic (Q), product (P), threshold (T), and hinge (H)—we sequentially reduced the number of features by screening variable response curves that depict how candidate environmental covariates affect the model prediction. For responses with biologically implausible signals (e.g., multimodal shape, jagged lines, or abrupt jumps), we removed the culprit feature(s), and rescreened variable responses. Linear and quadratic features were chosen to fit all models except for the monsoon period, which used only hinged features to produce smoothed response curves similar to Generalized Additive Models (Merow et al., 2013). During the pre-monsoon, a period characterized by temperature extremes, a product feature was also included to account for the complex interplay between SST and Chl-a variables together with water depth. **Table 7** documents the Maxent feature and parameters settings used to tune each seasonal SDM.

Table 7. On-effort Irrawaddy dolphin sightings and encounter rates by season for the survey period, from October 2017 to September 2019.

Season	Irrawaddy dolphin group sightings (#)			Survey effort (hours)	Encounter rates (# of groups/hr)
	2017	2018	2019		
Dry (Dec - Feb)	1	46	10	57.02	1.00
Pre-Monsoon (Mar - Apr)	-	0	10	40.32	0.25
Monsoon (May - Sept)	-	33	37	79.87	0.88
Post-Monsoon (Oct - Nov)	14	1	-	19.42	0.77

Next, the Maxent algorithm computes permutation importance (PI) scores to compare the overall contribution of candidate variables, and provide guidance for eliminating redundant covariates (Phillips et al., 2020). This analysis of variable contribution randomly permutes the values for each predictor on occurrence and background localities. The resulting decrease in training AUC, expected to be larger for more important variables (Zhang et al., 2018), is normalized to percentages and reported by Maxent as the variable PI score. Searcy and Shaffer (2016) argue that variables with high PI scores capture ecologically relevant factors that define environmental niche and species distribution, assuming predictor variables are not highly correlated. To select from a suite of 13 environmental variables, we used a PI threshold of 5%

(as in Tobeña et al., 2016) to iteratively prune each seasonal SDM down to the most important explanatory variables.

In the absence of population size or the location of true absences, MaxEnt predicts a relative occurrence rate (ROR) as a function of the environmental predictor values at each cell (Merow et al., 2013). To divide the study region into suitable and unsuitable areas and convert Maxent logistic outputs into discrete habitat suitability levels (lowest-intermediate-highest), we used a threshold of occurrence (minimum predicted value at a presence location) based on the data used to calibrate each model (Liu et al., 2005). A minimum ROR threshold of 5% was selected to allow for a certain amount of omission (false negatives), below which the species is not expected to occupy a given cell. While some occurrence localities were removed from the prediction, one key advantage of this classification method was to allow for standardization across multiple SDMs of the same species (Merow et al., 2013). As with three seasonal SDMs developed for Irrawaddy dolphins in Kuching Bay, Malaysia (Verutes et al., 2020), all locations with an ROR below the 10% ROR threshold were classified as limited or unsuitable habitat. The remaining cells were classified according to three levels of habitat suitability: (1) lowest, ranging from 5 to 10%; (2) intermediate, from 10 to 75%; and (3) highest suitability from 75 to 100% of the maximum ROR for each season (**Table S3.1**).

3.2.6 Model evaluation and statistical tests

The selection of SDM performance metrics should be guided by data availability, species ecology, and overall research goals (Pearson, 2007; Liu et al., 2009). First, we tested different Maxent regularization parameter settings (0.5, 1.0, 1.5, and 2.0) to constrain model complexity and minimize risk of overfitting to the training data (Elith et al., 2011; Warren and Seifert, 2011). We then assessed model performance based on the area under the curve (AUC) of the receiver operating characteristic plot, a measure of Maxent's ability to discriminate between randomly chosen presence and background records (Pearson, 2007). Cohen's kappa, a common model evaluation statistic in ecology, is highly dependent on available prevalence data and may introduce biases in its assessment of accuracy (see Allouche et al., 2006 for empirical analysis). While similar to kappa, the True Skill Statistic (TSS) is not inherently dependent on prevalence data (Liu et al., 2009) and represents an alternative to AUC for model predictions that rely on smaller sample sizes, as was the case for SDMs of the pre- and post-monsoon seasons. In

3. Modeling: Seasonal dolphin distribution

summary, AUC and TSS served as complementary performance statistics because the former is threshold independent and the latter is unaffected by the size of the validation set (Allouche et al., 2006; Merow et al., 2013).

To assess predictive performance of final models with held-out data, calculations were performed using Maxent and the biomod2 package for R (Thuiller et al., 2009; Elith et al., 2011). We used a k-fold cross-validation procedure, where 90% of data were kept for training and the remaining sample for evaluation. A total of 10 models ($k = 10$) were trained and evaluated against the excluded test data to estimate performance on the held-out folds and ensure the overall accuracy assessment was not an artifact of sub-sampling. We calculated (1) mean and standard deviation (SD) of AUC across all test models and (2) the difference between training AUC values of each species' final SDM (using all presences) and the mean AUC of the test SDMs. Low test-AUC SD and/or small differences between the training AUC and mean test-AUC values are indicators of model robustness (Warren and Seifert, 2011; Herkt et al., 2016; Tobeña et al., 2016).

When projecting habitat models outside a surveyed area, the resulting predictions are more likely to be reliable if these new locations have environmental conditions similar to the training samples (Barbosa et al., 2009; Pearson, 2007). To reveal where novel conditions exist across predictors retained for each seasonal SDMs, we conducted Multivariate Environmental Similarity Surface analysis (MESS; Elith et al., 2010). In order to take into consideration differences in temporal variability and estimate Irrawaddy dolphin habitat suitability, SDMs were projected at seasonal midpoints for months with reasonable spatial coverage of environmental predictor variables between October 2018 and September 2019. Guided by MESS analyses (**Figure S3.1**), we excluded areas of the habitat suitability maps where at least one predictor variable was found to be outside the range of data used to train each seasonal SDM.

All explanatory variables were checked for normality using a Shapiro-Wilk test and the homogeneity of variances was tested using the Fligner-Killeen test. Environmental data on Chl-a, seafloor slope, distance to islands and rivers were power transformed (log10 or square root) to normalize their respective distributions. Non-parametric tests were used for environmental variables that did not meet the assumptions of normality and homoscedasticity. We used the rank-based Kruskal-Wallis H-test to detect statistically significant differences across seasons for independent variables collected at sighting locations. For group size, a post hoc Dunn's test

pinpointed which environmental variables had significantly different mean values from season to season. An alpha value of 0.05 was used as the significance level. All statistical analyses were performed in R version 3.6.2 (R Core Team, 2020).

3.3 RESULTS

A total of 187 dolphin groups were sighted over a 24-month period (2017–2019), of which 152 (81%) were on-effort occurrences (**Table 7**). During adequate sighting conditions, encounter rates were lowest pre- and post-monsoon as previously reported by Tubbs et al. (2020). The locations of on-effort sightings suggest these dolphins are evenly distributed around the Kep Archipelago islands, and in higher densities (1) eastward toward the mouth of the Kien Giang River, (2) in the southern direction of the Cambodian-Vietnamese maritime border, and (3) in the relatively shallow waters (3–5.5 m) approaching the channel between Phu Quoc Island, Vietnam and the Kampot River, Cambodia (**Figure 9**). With the exception of one dry season encounter, all sightings > 4 km east of the Kep Archipelago were during the summer monsoon. Furthermore, there was a dearth of dolphin encounters in areas exceeding depths of 5.5 m (< 1% of sightings), despite a higher proportion (6% of total boat survey effort across all seasons) occurring in deeper waters.

Table 8. Fitting functions and environmental variables used to build final SDMs, after model tuning, by season; L, linear; Q, quadratic; P, product; H, hinge.

Season	Func- tions used to fit models	Regulari- zation multi- plier	Permutation Importance (PI) scores									
			Depth	Slope	Chl-a	SST	Dist2Isl	Dist2Riv	Chl-a (-1m)	Chl-a (-2m)	V-SST	
Dry	LQ	0.5	-	-	-	71.0	8.3	-	-	7.7	-	13.0
Pre-Monsoon	LQP	2.0	60.6	-	18.9	20.6	-	-	-	-	-	-
Monsoon	H	1.5	61.9	8.2	-	-	-	30.0	-	-	-	-
Post-Monsoon	LQ	1.5	-	-	-	22.0	-	-	-	-	36.1	41.9

Overall, Kep’s Irrawaddy dolphins displayed habitat preferences for water depths between 3.0 and 5.3 m, SST from 27 to 32°C, and in close proximity to offshore islands (< 7.5

3. Modeling: Seasonal dolphin distribution

km) based on the central 90th percentile of variable distributions. A histogram of sightings vs. water depths (**Figure 10A**) showed a clear peak between 3.5 and 4.0 m (66% of sightings), with a roughly equal contribution from all seasons. Habitat areas corresponding to GIS measurements for distance to offshore islands and river mouths, utilized by dolphins during both the wet and dry seasons, were quite diverse (**Figure 10B-C**). A bimodal pattern was detected for variables of distance to offshore islands (peaks at 1.5 and 5.5 km) and river mouths (12 and 18 km), suggesting that fluctuating high and low river flows before and after the summer monsoon were a potential driver of change in seasonal habitat and, consequently, hotspots of Irrawaddy dolphin occurrence.

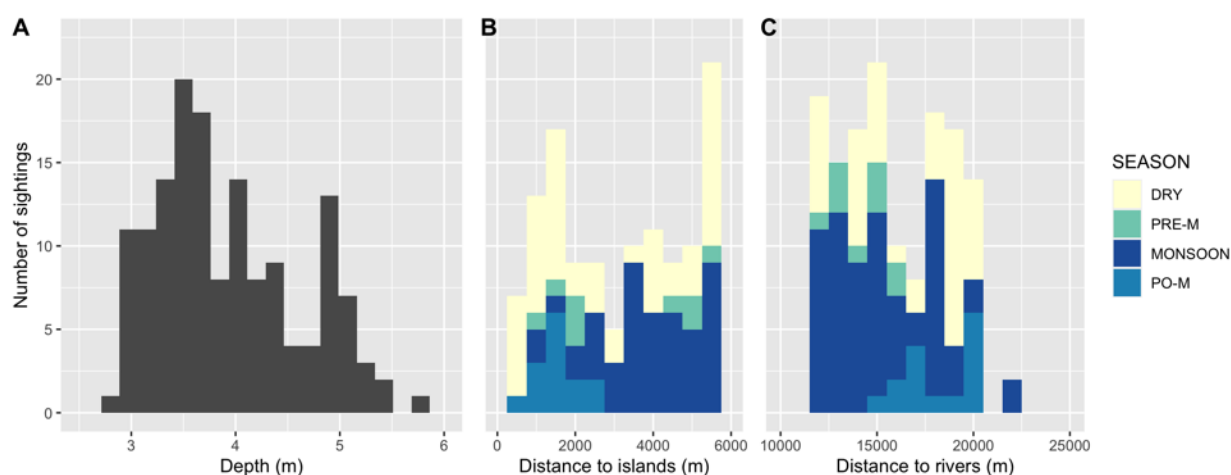


Figure 10. Histogram plots of (A) water depth, (B) distance to offshore islands, and (C) distance to river mouths. Note that there is one outlier, 8.9 m, outside the range of depth values (A).

3.3.1 Group size and seasonal habitat patterns

Irrawaddy group sizes were significantly different across the four seasons ($H = 27.94$, $P < 0.001$). Post-monsoon season had the largest mean group size of 9.0 individuals ($SE = 1.2$; range = 1–32; $n = 47$), followed by the pre-monsoon with a mean group size of 7.1 individuals ($SE = 0.7$; range = 4–10; $n = 12$). The dry and the monsoon seasons had the smallest mean group sizes of 5.8 ($SE = 0.8$; range = 1–14; $n = 58$) and 4.0 individuals ($SE = 0.4$; range = 1–9; $n = 70$), respectively. Of the 187 Irrawaddy dolphin groups sighted between 2017 and 2019, the most frequently encountered group size was 3 individuals ($n = 30$), followed closely by groups of 4 individuals ($n = 27$). Following the group size definitions of Tubbs et al. (2020)—small, 1–3; medium, 4–8; and large, ≥ 9 individuals—pre-monsoon sightings were predominately medium to large-sized groups. Interestingly, this shifted to groups of small and medium sizes during the

higher flow period of the monsoon season (**Figure 11F**). Because the Kruskal-Wallis H-test is a global test statistic and cannot determine which specific seasons are significantly different from each other, a Dunn's test (with Bonferroni correction for the accepted p-values) confirmed significant seasonal differences between wet and both the dry and pre-monsoon periods for mean group size ($P < 0.015$). Following the summer monsoon and through the dry season (October to February), sightings were more evenly distributed across the three group sizes.

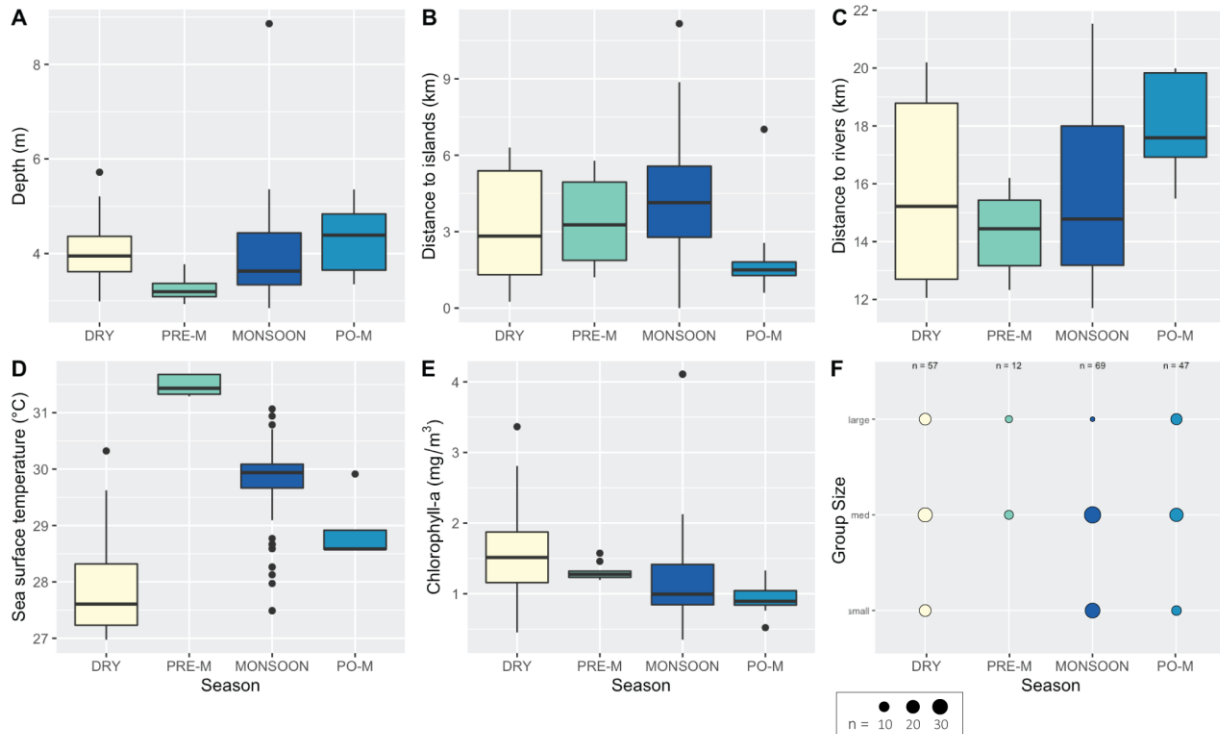


Figure 11. Box and dot-density plots of the habitat characteristics and group size of Irrawaddy dolphins as sighted in Kep waters during the four seasons in terms of: (A) water depth, (B) distance to offshore islands, (C) distance to river mouths, (D) sea surface temperature, (E) chlorophyll-a concentration, and (F) group size.

Boxplots revealed extreme environmental data values for the pre-monsoon (e.g., **Figure 11D**), which could be limiting suitable dolphin habitat prior to the wet season and was the period with the fewest dolphins encountered. All pre-monsoon Irrawaddy sightings ($n = 12$) were found to have the highest SST levels, as compared to other seasons. Median SST, based on monthly composites collected for the entire study area from March to April in 2018 and 2019, did not drop below 32°C during the pre-monsoon period. In comparison, only one sighting (during the summer monsoon) was found to exceed sea surface temperatures of 31°C . Low precipitation

3. Modeling: Seasonal dolphin distribution

rates and higher air temperatures from December to March may initiate a shift to weak river flows and shallow coastal waters, which can result in the highest sea surface temperature and salinity levels in the region from March to May (see Section 3.4.2: ‘Limitations and simplifications’ for further discussion of limiting factors to Irrawaddy habitat models during the pre-monsoon period).

Relative to other seasons, Irrawaddy dolphins were encountered closer to major river mouths and at greater distances from the offshore islands during the summer monsoon. The inverse was true post-monsoon, as dolphins gravitate back to the islands of the Kep Archipelago and away from two major river mouths (**Figure 11B-C**). This pattern of dolphin occurrence was less apparent during the dry and pre-monsoon seasons, as sightings were more evenly distributed across a range of environmental variables, especially proximity to rivers and offshore islands. Kruskal-Wallis rank sum tests confirmed the possibility of significant seasonal differences in habitat use for depth ($H = 17.06$, $P < 0.001$), distance to islands ($H = 12.88$, $P < 0.005$), distance to river mouths ($H = 16.21$, $P < 0.001$), chlorophyll-a ($H = 25.82$, $P < 0.001$), and sea surface temperature ($H = 80.86$, $P < 0.001$), but not seafloor slope [one-way analysis of variance (ANOVA), $F = 1.298$, $P = 0.278$]. This finding supports the use of variable permutation importance (PI) scores to discern the relative importance of environmental variables to explain seasonal variation in dolphin habitat use.

3.3.2 Spatially explicit seasonal habitat models

Variable PI scores indicated conditional dependence of Irrawaddy dolphin habitat on the majority of predictors considered (9 of 13 had scores greater than the 5% threshold). Not surprisingly, no one variable combination was retained consistently across all four seasons and, ultimately, either 3 or 4 environmental predictors were used to build final SDMs (**Table 8**). PI scores pointed to water depth as a key explanatory variable prior to and during the wet season (61 and 62% overall contribution). Additionally, distance to rivers (30%), especially at intermediate distances, and either gradual or steep seafloor slopes (8%) were factors in Irrawaddy dolphin habitat selection during the monsoon period (**Figure S3.2C**). Following the wet season (October–November), peaking during the dry season (January), and then waning pre-monsoon (March–April), sea surface temperature (22, 71, and 21%) was a strong contributor to predicted probability of dolphin presence along with time-lagged Chl-a (8–36%) and local

variation in SST (13–42%) for the latter two seasons. Interestingly, the relative importance of SST and local variation in surface water temperature (V-SST) inverted from post-monsoon to the dry season.

Cross validation determined that all four SDMs had scores for test-AUC > 0.8 and TSS > 0.6, an indication of moderate to good discrimination (**Table 9**). Performance metrics for the monsoon SDM were lowest, followed by the dry season (TSS scores of 0.604 and 0.773, respectively). As evidence of model robustness, 3 of the 4 SDMs (all except summer monsoon) had small differences (< 5%) between mean test-AUC and the corresponding AUC score of the training set.

Table 9. Presences used to fit seasonal SDMs and performance statistics.

Season	All sightings (count)	On-effort sightings (count)	Training presences (count)	Training AUC	Test AUC (mean)	Test AUC SD	AUC diff (training-mean test)	AUC diff (training -mean test) (as %)	TSS
Dry	58	57	48	0.853	0.869	0.120	-0.016	-1.9	0.773
Pre-Monsoon	12	10	10	0.970	0.978	0.014	-0.008	-0.8	0.977
Monsoon	70	70	52	0.883	0.802	0.235	0.081	10.1	0.604
Post-Monsoon	47	15	15	0.926	0.942	0.095	-0.016	-1.6	0.933
Total	187	152	125						

Maxent outputs revealed site fidelity as well as temporally distinct patterns in Irrawaddy dolphin habitat use (**Figure 12**). For instance, both the pre-monsoon and monsoon seasons had overlapping areas of high habitat suitability inside the Kep MFMA (**Figure 12B-C**). Beginning in the wet season, however, suitability estimates suggested a preference for waters closer to major river mouths and with shallower depths, as indicated by the orange and red-colored areas surrounding the Kep Archipelago (**Figure 12C**). Post-monsoon, highest habitat suitability levels were more dispersed southwest of the offshore islands (**Figure 12D**), which corresponds to areas with less local variation in SST and medium levels of Chl-a two months prior to a sighting of the species. It is worth noting that the majority of these critical habitat areas were found to be outside the MFMA, in areas directly northwest and southeast of the Kep Archipelago. For coastal areas of Kampot, Cambodia and the Vietnamese Pirate Islands — well beyond the survey tracks of this

3. Modeling: Seasonal dolphin distribution

study — Irrawaddy dolphin habitat suitability estimates tended to be in the low to intermediate range, with large gaps in predicted probability of occurrence due to MESS exclusions.

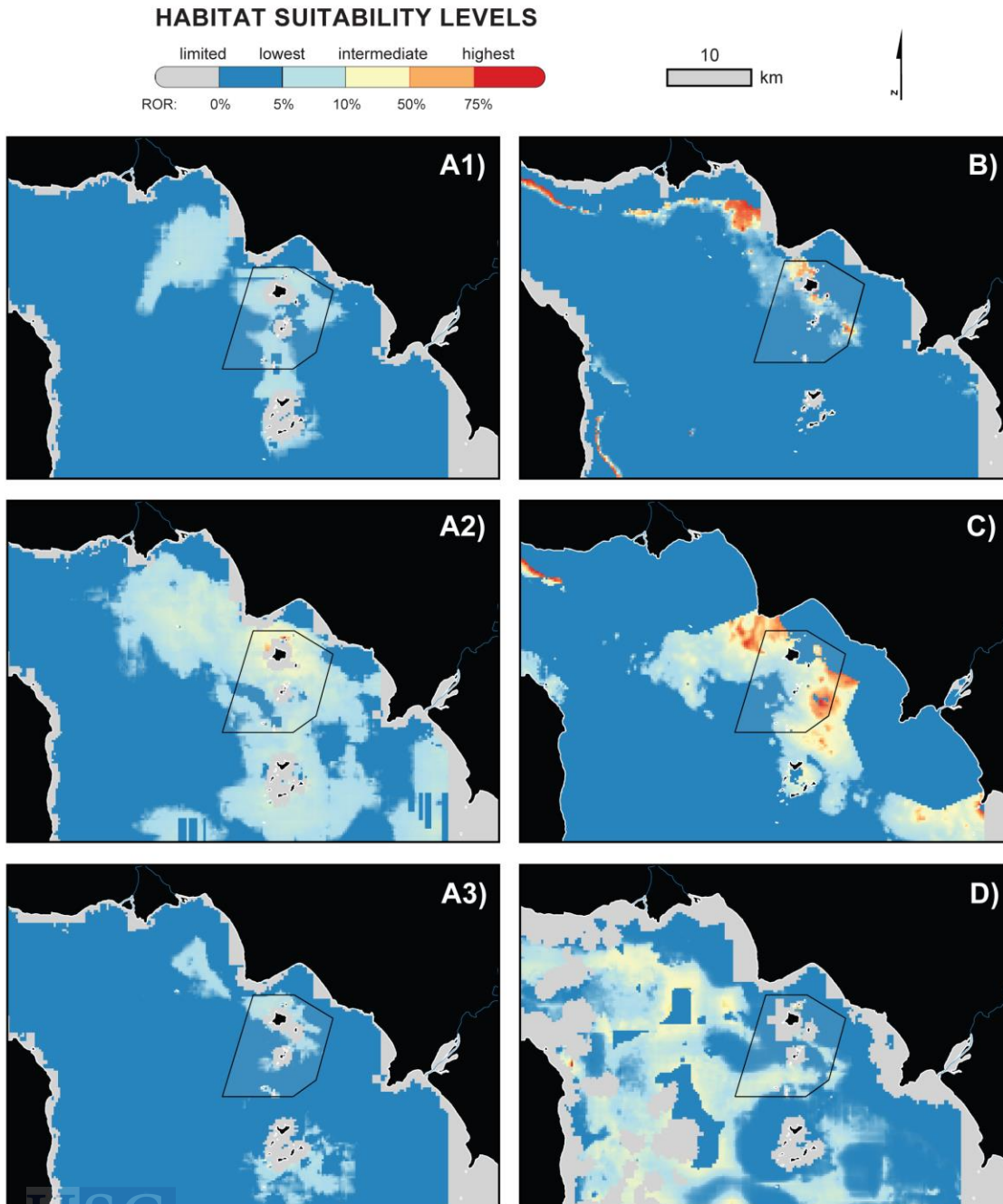


Figure 12. Maps of Irrawaddy dolphin habitat suitability based on the best performing models projected to seasonal midpoints for months between 2018 and 2019: (A1) December, (A2) January, and (A3) February 2019 of the dry season; (B) April 2019, pre-monsoon; (C) May to September 2019 of the summer monsoon; and (D) October 2018, post-monsoon. Some habitat suitability areas were masked out based on Multivariate Environmental Similarity Surface analyses (Elith et al., 2010), which coincide with the most restrictive results for each seasonal SDM. The black outline demarcates the Kep Marine Fisheries Management Area.

3.4 DISCUSSION

In this article we present new evidence about spatiotemporal patterns in Irrawaddy dolphins' occurrence and habitat suitability predictions for the Kien Giang–Kep Archipelago Important Marine Mammal Area. Habitat models were built, validated and projected across a transboundary region to map seasonal distributions of an endangered species of small cetacean. Overall, Irrawaddy dolphins from the Kep Archipelago displayed habitat preferences that were similar to the suite of environmental variables commonly associated with coastal-estuarine Irrawaddy populations (Minton et al., 2011; Mahmud et al., 2018; Jackson-Ricketts et al., 2020). Previous studies have linked Irrawaddy dolphins to shallow areas, close to river mouths, and with changing tidal states; conditions associated with low sea surface salinity and high turbidity (Dolar et al., 2002; Peter et al., 2016b). Specific to this study and based on the central 90th percentile of environmental data distributions, Irrawaddy dolphins were sighted in water depths 3.0–5.3 m, with SST between 27 and 32°C, and < 8 km from offshore islands. With the exception of two sightings, there were no dolphin encounters in the deepest waters (> 5.5 m) surveyed between Phu Quoc Island, Vietnam and Kampot Province, Cambodia (**Figure 9**).

Irrawaddy dolphins of the Kep Archipelago are likely year-round inhabitants, yet questions remain about population size and their exact whereabouts prior to the summer monsoon. Kep's dolphin population consists of at least 32 individuals (Tubbs, pers. observ.), and the only historical abundance estimates come from systematic line transect surveys in neighboring Trat province, Thailand (Hines et al., 2015). Spatiotemporal variation in Irrawaddy occurrences first reported by Tubbs et al. (2019; 2020) was the impetus for acquiring spatially explicit environmental data used by this study to detect emergent patterns in seasonal habitat use. Exploratory analysis and visualization (**Figure 11**) confirmed statistically significant differences in habitat preferences across seasons, warranting further investigation of which environmental variables could be used to explain changes in dolphin habitat suitability in the Kien Giang–Kep Archipelago IMMA.

3.4.1 Emergent patterns of habitat suitability

Geographically, the Kep Archipelago is nestled inside the Eastern Gulf of Thailand, home to a wealth of natural assets, including coral and seagrass habitats (Reid et al., 2019), and

3. Modeling: Seasonal dolphin distribution

phenological dynamics that influence river flows. Freshwater input to the Kep Archipelago from two major rivers (Giang and Kampot) is at its lowest pre-monsoon due to limited rainfall in the months prior to the wet season (Tsujimoto et al., 2018). Consequently, coastal water depths are low, while SST and salinity are at the highest levels from January through April. In the neighboring Kien Giang Biosphere Reserve during the month of April, 8-day running averages of salinity and SST measurements approaching 36°C (Vu, unpubl. data) suggest that less precipitation and river discharge into the ocean (Learmonth et al., 2006) is correlated with increasing SST and salinity levels. Despite a balanced survey effort throughout the year (**Table 7**), dolphin sightings were scant during the pre-monsoon ($n = 12$; Tubbs et al., 2020). While this study could not definitively determine Irrawaddy dolphin response to changes in salinity, there was relatively low habitat suitability predicted for when and where SST levels were highest. The higher proportion of medium to large group size encounters between December and April (**Figure 11F**) may also be a limiting factor to Irrawaddy prevalence prior to the wet season. Monitoring of areas closer to river mouths, pre-monsoon, is needed to determine if Kep's dolphin population is adapted to tolerate extreme levels of salinity and SST, similar to the ecophysiological responses of other marine mammals (Fiedler, 2009).

Population-level studies are also needed to inform the design of new habitat models that detect foraging decisions based on the diversity of fish species known to comprise dolphin diets (Win and Bu, 2019), and the availability of cephalopods, crustaceans, and other prey (Santos et al., 2013). At least three fishing communities (Ankgrong, Phun Thmey, and Preak Tanin) use trawling and longtail boats to catch cephalopods, primarily squid, in the waters of the Kep Archipelago (Ferber et al., unpubl. data). Monthly self-reports from squid fishers indicate the highest levels of effort between November and January (post-monsoon), followed by January and February (dry season) and then June to September (summer monsoon). Lower fishing effort prior to the wet season may be related to a scarcity of dolphin prey, specifically during the months of March, April and May. Because Irrawaddy dolphins are generalist feeders (Parra, 2005) and maps of their prey are difficult to find, we included Chl-a and SST as dynamic variables in our predictor set. Variables retained in final SDMs (**Table 8**) suggest that time-lagged chlorophyll-a concentration [Chl-a (-1 m) and Chl-a (-2 m)] can play an important role in defining the distribution of Irrawaddy dolphins following the wet season, when a combination of low SST and higher Chl-a levels are present. Further study is needed to determine if a strong link

exists between Irrawaddy prey abundance and seasonal habitat use, and to what extent this can be explained using proxy variables for primary productivity.

3.4.2 Limitations and simplifications

When population size is known, Maxent predicts the species occurrence rate for each grid cell, which translates into the expected number of individuals in that location. Here, model predictions were interpreted as indices of habitat suitability, primarily for exploratory purposes. We deliberately avoided a reliance on default settings when making decisions about data preparation, parameter selection, and variables to retain. The regularization parameter in Maxent is conceptually similar to the Akaike Information Criterion (AIC), as it penalizes model complexity and can enhance the transferability of SDM predictions beyond locations used to train each model (Dudík et al., 2007). We could not use AICc to compare the quality of different model iterations, following a continuous distribution of regularization coefficients, due to the Samples with Data (SWD) approach used to train each seasonal SDM. Techniques that incorporate automated tuning of the regularization parameter into correlative SDMs are still under development for SWD, and this functionality is expected in the R package, ENMeval v2.0 (Muscarella et al., 2014). The true skill statistic (TSS) assesses model accuracy independent of species prevalence, and is preferable to the kappa statistic when relying on small sample sizes (Allouche et al., 2006), as was the case with two seasonal SDMs utilized by this study. When applied judiciously, Maxent performs well relative to other habitat models (Merow et al., 2013). Nevertheless, the acquisition of additional sightings records will be important for testing these SDMs against independent datasets, as only 9% of published studies report this type of performance assessment (Robinson et al., 2011).

In summary, this research was limited by a paucity of dolphin sightings prior to and following the wet season, along with gaps in spatial data to characterize the nearshore marine environment. All pre-monsoon dolphin encounters occurred during 1 month (April 2019), and all but one post-monsoon sighting was in October 2017. It is difficult to determine why Irrawaddy dolphin encounter rates were lowest during these two periods (**Table 7**) without a detailed water parameter analysis. It is possible that certain areas of the Kep Archipelago may not offer suitable habitat at this time of year, leading the species to stray elsewhere. As previously mentioned, we expect salinity and SST levels to be highest in months leading up to the wet season, and before

3. Modeling: Seasonal dolphin distribution

freshwater input increases. SST may be correlated with salinity and, as a consequence, dolphins avoid high surface water temperatures and/or extreme salinity areas, which are widespread during the pre-monsoon period. Additional monitoring could help detect these and other subtle environmental cues that influence seasonal dolphin habitat selection (Parra et al., 2006; Smith et al., 2009). More specifically, boat surveys would help overcome limitations of the L-band microwave radiometer instrument, which measures sea surface salinity at a relatively coarse spatial resolution (between 40 and 70 km²) and is subject to contamination by bright land signals (Miller et al., 1997). Artifacts in remotely sensed data utilized by this study were most commonly found in nearshore areas of the Kep islands (**Figure 12**).

3.4.3 Conservation and management opportunities

Evidence is mounting that illegal fishing activities, especially bottom-trawling, are ubiquitous to the Vietnam-Cambodia border region (Vu et al., 2017; Böhm, 2019; Reid et al., 2019). Addressing the vast monitoring deficiencies of the Southeast Asia region (Teh et al., 2015; Hines et al., 2020) is a necessary first step to understand where and when IUU fishing impacts, such as bycatch and habitat destruction, are most consequential to Irrawaddy dolphins and other marine mammals (Read, 2008; Jackson-Ricketts et al., 2020; Verutes et al., 2020). Moving forward, systematic surveys of the Kep Archipelago are needed to challenge our assumptions related to seasonal variability of the marine environment and fill gaps of earth observation data layers near shorelines and river mouths. We anticipate that emerging networks to monitor marine megafauna and fisheries of the Kien Giang–Kep Archipelago IMMA (e.g., Vu et al., 2017; Tubbs et al., 2020) will continue to expand boat survey coverage, public participation, and socio-ecological research that further defines threats to and the range of Kep’s resident Irrawaddy dolphin population. A recent genetic study by Caballero et al. (2018) suggests connectivity between the Irrawaddy populations of India, Thailand and Cambodia, which could have implications for SDM projection space (MESS) used to define species’ niche (Elith et al., 2010; Merow et al., 2013).

Against the backdrop of persistent, harmful, and unregulated threats to marine mammals and their habitats, the Kep Marine Fisheries Management Area (MFMA) is an opportunity to promote biodiversity conservation measures that spatially manage multiple human uses (Fisheries Administration Cambodia, 2018). For example, the highest density trawling areas

mapped by Böhm (2019) appear to overlap dolphin hotspots identified by this research, specifically during the wet season (yellow and red-colored areas of **Figure 12C**). Cambodia's 2016 international obligations via the Aichi Biodiversity Target 11 states that: "10 percent of coastal and marine areas, especially areas of particular importance for biodiversity and ecosystem services, are conserved through effectively and equitably managed, ecologically representative and well-connected systems of protected areas..." (Secretariat of the Convention on Biological Diversity [SCBD], 2010, p. 9). This could be achieved by expanding the recently enacted Kep MFMA toward critical dolphin habitat areas where Marine Conservation Cambodia already promotes mixed human uses such as recreational activities, sustainable tourism, and the protection of biodiversity resources (MCC, 2016).

Fisheries management, especially for data-limited small-scale fisheries, is more effective when considering the different objectives of communities participating in the process, and the existing local conditions (e.g., governance, socioeconomic, research and education) that enable or limit conservation success (Berkes, 2007; Teh et al., 2015). In one form or another, multi-sectoral zoning at the MFMA scale should continue to be implemented through a co-management program between local agencies and community organizations. Recent monitoring and evaluation along the maritime border suggests this area could be classified as in a critical state, due in large part to impacts from destructive fishing, unsustainable bycatch and marine pollution (Vu et al., 2017; Reid et al., 2019; Böhm, 2019). The data presented here serves as a baseline for comparison against future studies and to help formulate new hypotheses about dolphin spatiotemporal occurrence, abundance and habitat quality. Potential next steps include IUCN status assessment for the Kien Giang–Kep Archipelago IMMA (Minton et al., 2017) and mark-recapture studies to estimate population size of Irrawaddy dolphins and other marine mammals recorded in the area [e.g., Indo-Pacific finless porpoises (*Neophocaena phocaenoides*), Indo-Pacific humpback dolphins (*Sousa chinensis*), dugongs (*Dugong dugon*)].

3.5 CONCLUSION

The present study identified emergent patterns of habitat use by Irrawaddy dolphins inside the dynamic, transnational waters of the Kien Giang–Kep Archipelago Important Marine Mammal Area. Despite substantial data limitations, habitat suitability estimates identified where and when significant seasonal changes to the marine environment are likely to alter the distribution of a

3. Modeling: Seasonal dolphin distribution

cetacean species of conservation significance. As the first fine-scale spatial characterization of Irrawaddy dolphin habitat in Cambodia's Kep Archipelago, the results presented here suggest there are: (1) hotspots of dolphin use, which vary seasonally, (2) areas with highest habitat suitability situated along the active Cambodia-Vietnam border region, and (3) additional patterns, indicators, and habitat that remain to be uncovered, such as how changing freshwater flows affect water depth, salinity, primary productivity, and resource abundance. Most importantly, our findings have implications for the urgent need to spatially manage fisheries and other sectors of economic and traditional importance in the region. It is the intent of this research to set the stage for future assessments that consider cumulative impacts posed by anthropogenic activities to Irrawaddy dolphins and other species of conservation concern.

3.6 REFERENCES

- Allouche, O., Tsoar, A., and Kadmon, R. (2006). Assessing the accuracy of species distribution models: prevalence, kappa and the true skill statistic (TSS). *J. Appl. Ecol.* 43, 1223–1232. doi: 10.1111/j.1365-2664.2006.01214.x
- Bailey, H., and Thompson, P. M. (2009). Using marine mammal habitat modelling to identify priority conservation zones within a marine protected area. *Mar. Ecol. Prog. Ser.* 378, 279–287. doi: 10.3354/meps07887
- Barbosa, A. M., Real, R., and Vargas, J. M. (2009). Transferability of environmental favourability models in geographic space: the case of the Iberian desman (*Galemys pyrenaicus*) in Portugal and Spain. *Ecol. Model.* 220, 747–754. doi: 10.1016/j.ecolmodel.2008.12.004
- Baumgartner, M. F., Mullin, K. D., May, L. N., and Leming, T. D. (2001). Cetacean habitats in the northern Gulf of Mexico. *Fish. Bull.* 99, 219–219.
- Bearzi, G., Azzellino, A., Politi, E., Costa, M., and Bastianini, M. (2008). Influence of seasonal forcing on habitat use by bottlenose dolphins *Tursiops truncatus* in the Northern Adriatic Sea. *Ocean Sci. J.* 43, 175–182. doi: 10.1007/BF03029922
- Beasley, I., and Davidson, P. (2007). Conservation status of marine mammals in Cambodian waters, including seven new cetacean records of occurrence. *Aquat. Mamm.* 33, 368–379. doi: 10.1578/AM.33.3.2007.368
- Becker, E. A., Forney, K. A., Thayre, B. J., Debich, A. J., Campbell, G. S., Whitaker, K., et al. (2017). Habitat-based density models for three cetacean species off Southern California illustrate pronounced seasonal differences. *Front. Mar. Sci.* 4:121. doi: 10.3389/fmars.2017.00121
- Berkes, F. (2007). Community-based conservation in a globalized world. *Proc. Natl. Acad. Sci. U.S.A.* 104, 15188–15193. doi: 10.1073/pnas.0702098104
- Böhm, A. (2019). Marine Harvesting Network in Cambodia: Technical Report on Transnational Fishing Activities, Marine Conservation Cambodia. Available online at: <https://www.marineconservationcambodia.org/> (accessed February 5, 2019).
- Boon, P. Y., Mulligan, B., Benbow, S. L. P., Thorne, B. V., Leng, P., and Longhurst, K. (2014). Zoning Cambodia's first Marine Fisheries Management Area. *Cambodian J. Nat. Hist.* 2014, 55–65.

- Briscoe, D. K., Hiatt, S., Lewison, R., and Hines, E. (2014). Modeling habitat and bycatch risk for dugongs in Sabah, Malaysia. *Endanger. Species Res.* 24, 237–247. doi: 10.3354/esr00600
- Caballero, S., Dove, V., Jackson-Ricketts, J., Junchompoo, C., Cohen, S., and Hines, E. (2018). Mitochondrial DNA diversity and population structure in the Irrawaddy dolphin (*Orcaella brevirostris*) from the Gulf of Thailand and the Mekong River. *Mar. Mamm. Sci.* 35, 300–310. doi: 10.1111/mms.12518
- Campbell, G. S., Thomas, L., Whitaker, K., Douglas, A. B., Calambokidis, J., and Hildebrand, J. A. (2015). Inter-annual and seasonal trends in cetacean distribution, density and abundance off southern California. *Deep Sea Res. II Top. Stud. Oceanogr.* 112, 143–157. doi: 10.1016/j.dsr2.2014.10.008
- Cañadas, A., Sagarminaga, R., De Stephanis, R., Urquiola, E., and Hammond, P. S. (2005). Habitat preference modelling as a conservation tool: proposals for marine protected areas for cetaceans in southern Spanish waters. *Aquat. Conserv. Mar. Freshw. Ecosyst.* 15, 495–521. doi: 10.1002/aqc.689
- Connor, R. C., Smolker, R., and Bejder, L. (2006). Synchrony, social behaviour and alliance affiliation in Indian Ocean bottlenose dolphins, *Tursiops aduncus*. *Anim. Behav.* 72, 1371–1378. doi: 10.1016/j.anbehav.2006.03.014
- Daura-Jorge, F. G., Wedekin, L. L., Piacentini, V. D. Q., and Simões-Lopes, P. C. (2005). Seasonal and daily patterns of group size, cohesion and activity of the estuarine dolphin, *Sotalia guianensis*, in southern Brazil. *Rev. Bras. Zool.* 22, 1014–1021. doi: 10.1590/S0101-81752005000400029
- Dolar, M. L. L., Perrin, W. F., Gaudio, J. P., Yaptinchay, A. A. S. P., and Tan, J. M. L. (2002). Preliminary report on a small estuarine population of Irrawaddy dolphins *Orcaella brevirostris* in the Philippines. *Raffles Bull. Zool.* 155–160.
- Dudík, M., Phillips, S. J., and Schapire, R. E. (2007). Maximum entropy density estimation with generalized regularization and an application to species distribution modeling. *J. Mach. Learn. Res.* 8, 1217–1260.
- Elith, J., Kearney, M., and Phillips, S. (2010). The art of modelling range-shifting species. *Methods Ecol. Evol.* 1, 330–342. doi: 10.1111/j.2041-210X.2010.00036.x
- Elith, J., Phillips, S. J., Hastie, T., Dudík, M., Chee, Y. E., and Yates, C. J. (2011). A statistical explanation of MaxEnt for ecologists. *Divers. Distrib.* 17, 43–57. doi: 10.1111/j.1472-4642.2010.00725.x
- Feist, B. E., Bellman, M. A., Becker, E. A., Forney, K. A., Ford, M. J., and Levin, P. S. (2015). Potential overlap between cetaceans and commercial groundfish fleets that operate in the California Current Large Marine Ecosystem. *NOAA Prof. Pap. NMFS* 17, 1–27. doi: 10.7755/PP.17
- Fiedler, P. C. (2009). “The ocean environment,” in *Encyclopedia of Marine Mammals*, eds W. F. Perrin et al. (San Diego, CA: Academic Press), 792–797.
- Fisheries Administration Cambodia (2018). Royal Decree of Community Fisheries. Available online at: <http://www.fia.gov.kh/english/index.php?page=legislation>
- Garaffo, G. V., Dans, S. L., Pedraza, S. N., Degradi, M., Schiavini, A., González, R., et al. (2011). Modeling habitat use for dusky dolphin and Commerson’s dolphin in Patagonia. *Mar. Ecol. Prog. Ser.* 421, 217–227. doi: 10.3354/meps08912
- Gilles, A., Viquerat, S., Becker, E. A., Forney, K. A., Geelhoed, S. C. V., Haelters, J., et al. (2016). Seasonal habitat-based density models for a marine top predator, the harbor porpoise, in a dynamic environment. *Ecosphere* 7:e01367. doi: 10.1002/ecs2.1367
- Giralt Paradell, O., López, B. D., and Methion, S. (2019). Modelling common dolphin (*Delphinus delphis*) coastal distribution and habitat use: insights for conservation. *Ocean Coast. Manage.* 179:104836. doi: 10.1016/j.ocecoaman.2019.104836
- Gregg, E. J., Baumgartner, M. F., Laidre, K. L., and Palacios, D. M. (2013). Marine mammal habitat

3. Modeling: Seasonal dolphin distribution

- models come of age: the emergence of ecological and management relevance. *Endanger. Species Res.* 22, 205–212. doi: 10.3354/esr00476
- Hammond, P. S., Macleod, K., Berggren, P., Borchers, D. L., Burt, L., Cañadas, A., et al. (2013). Cetacean abundance and distribution in European Atlantic shelf waters to inform conservation and management. *Biol. Conserv.* 164, 107–122. doi: 10.1016/j.biocon.2013.04.010
- Hastie, G. D., Swift, R. J., Slessor, G., Thompson, P. M., and Turrell, W. R. (2005). Environmental models for predicting oceanic dolphin habitat in the Northeast Atlantic. *ICES J. Mar. Sci.* 62, 760–770. doi: 10.1016/j.icesjms.2005.02.004
- Hastie, T., Tibshirani, R., and Friedman, J. (2009). *The Elements of Statistical Learning: Data Mining, Inference, and Prediction*. Berlin: Springer.
- Herkt, K. M. B., Barnikel, G., Skidmore, A. K., and Fahr, J. (2016). A high-resolution model of bat diversity and endemism for continental Africa. *Ecol. Model.* 320, 9–28. doi: 10.1016/j.ecolmodel.2015.09.009
- Hines, E., Ponnampalam, L. S., Junchompoo, C., Peter, C., Vu, L., Huynh, T., et al. (2020). Getting to the bottom of bycatch: a GIS-based toolbox to assess the risk of marine mammal bycatch. *Endanger. Species Res.* 42, 37–57. doi: 10.3354/esr01037
- Hines, E., Strindberg, S., Junchompoo, C., Ponnampalam, L. S., Ilangakoon, A. D., Jackson-Ricketts, J., et al. (2015). Line transect estimates of Irrawaddy dolphin abundance along the eastern Gulf Coast of Thailand. *Front. Mar. Sci.* 2:63. doi: 10.3389/fmars.2015.00063
- IUCN-MMPATF (2019). Kien Giang and Kep Archipelago IMMA, Global Dataset of Important Marine Mammal Areas (IUCN-IMMA). Available online at: www.marinemammalhabitat.org/imma-eatlas (accessed September 10, 2020).
- Jaaman, S. A., Lah-Anyi, Y. U., and Pierce, G. J. (2009). The magnitude and sustainability of marine mammal by-catch in fisheries in East Malaysia. *J. Mar. Biol. Assoc. U.K.* 89, 907–920. doi: 10.1017/S002531540800249X
- Jackson-Ricketts, J., Junchompoo, C., Hines, E. M., Hazen, E. L., Ponnampalam, L. S., Ilangakoon, A., et al. (2020). Habitat modeling of Irrawaddy dolphins (*Orcaella brevirostris*) in the Eastern Gulf of Thailand. *Ecol. Evol.* 10, 2778–2792. doi: 10.1002/ece3.6023
- Jackson-Ricketts, J., Ruiz-Cooley, R. I., Junchompoo, C., Thongsukdee, S., Intongkham, A., Ninwat, S., et al. (2019). Ontogenetic variation in diet and habitat of Irrawaddy dolphins (*Orcaella brevirostris*) in the Gulf of Thailand and the Andaman Sea. *Mar. Mamm. Sci.* 35, 492–521. doi: 10.1111/mms.12547
- Kannan, K., Ramu, K., Kajiwarra, N., Sinha, R. K., and Tanabe, S. (2005). Organochlorine pesticides, polychlorinated biphenyls, and polybrominated diphenyl ethers in Irrawaddy dolphins from India. *Arch. Environ. Contam. Toxicol.* 49, 415–420. doi: 10.1007/s00244-005-7078-6
- Kuit, S. H., Ponnampalam, L. S., Ng, J. E., Chong, V. C., and Then, A. Y. H. (2019). Distribution and habitat characteristics of three sympatric cetacean species in the coastal waters of Matang, Perak, Peninsular Malaysia. *Aquat. Conserv. Mar. Freshw. Ecosyst.* 29, 1681–1696. doi: 10.1002/AQC.3121
- Kutner, M. H., Nachtsheim, C. J., Neter, J., and Li, W. (2005). *Applied Linear Statistical Models*, Vol. 5. New York: McGraw-Hill Irwin.
- Learmonth, J. A., MacLeod, C. D., Santos, M. B., Pierce, G. J., Crick, H. Q. P., and Robinson, R. A. (2006). Potential effects of climate change on marine mammals. *Oceanogr. Mar. Biol.* 44, 431–464. doi: 10.1016/j.envint.2009.10.008
- Liu, C., Berry, P. M., Dawson, T. P., and Pearson, R. G. (2005). Selecting thresholds of occurrence in the prediction of species distributions. *Ecography* 28, 385–393. doi: 10.1111/j.0906-7590.2005.03957.x
- Liu, C., White, M., and Newell, G. (2009). “Measuring the accuracy of species distribution models: a

- review,” in Proceedings of the 18th World IMACs/MODSIM Congress, Cairns, 4241,4247.
- Mahmud, A. I., Jaaman, S. A., Muda, A. M., Muhamad, H. M., Zhang, X., and Scapini, F. (2018). Population estimation, distribution, and habitat preference of Irrawaddy dolphins *Orcaella brevirostris* (Owen in Gray, 1866) in the Brunei Bay, Malaysian waters. *Wildl. Biol.* 2018:00383. doi: 10.2981/wlb.00383
- Marine Conservation Cambodia (MCC) (2016). Marine fisheries management area. Fisheries Administration, Fisheries Conservation Department. Available online at: www.marineconservationcambodia.org/kep-reports/file/32-kep-mfma-revised-finaldraft.pdf (accessed August 7, 2020).
- McCluskey, S., Bejder, L., and Loneragan, N. (2016). Dolphin prey availability and calorific value in an estuarine and coastal environment. *Front. Mar. Sci.* 3:30. doi: 10.3389/fmars.2016.00030
- Merow, C., Smith, M. J., and Silander, J. A. Jr. (2013). A practical guide to MaxEnt for modeling species’ distributions: What it does, and why inputs and settings matter. *Ecography* 36, 1058–1069. doi: 10.1111/j.1600-0587.2013.07872.x
- Miller, P., Groom, S., McManus, A., Selley, J., and Mironnet, N. (1997). “Panorama: a semi-automated AVHRR and CZCS system for observation of coastal and ocean processes,” in Proceedings of the Remote Sensing Society, Reading, 539–544.
- Minton, G., Peter, C., and Tuen, A. A. (2011). Distribution of small cetaceans in the nearshore waters of Sarawak, East Malaysia. *Raffles Bull. Zool.* 59, 91–100.
- Minton, G., Smith, B. D., Braulik, G. T., Krebs, D., Sutaria, D., and Reeves, R. R. (2017). *Orcaella brevirostris* (errata version published in 2018). IUCN Red List Threatened Species 2017:e.T15419A123790805. doi: 10.2305/IUCN.UK.2017-3
- Muscarella, R., Galante, P. J., Soley-Guardia, M., Boria, R. A., Kass, J. M., Uriarte, M., et al. (2014). ENM eval: an R package for conducting spatially independent evaluations and estimating optimal model complexity for Maxent ecological niche models. *Methods Ecol. Evol.* 5, 1198–1205. doi: 10.1111/2041-210X.12261
- O’Donoghue, S. H., Drapeau, L., and Peddemors, V. M. (2010). Broad-scale distribution patterns of sardine and their predators in relation to remotely sensed environmental conditions during the KwaZulu-Natal sardine run. *Afr. J. Mar. Sci.* 32, 279–291. doi: 10.2989/1814232X.2010.501584
- Parra, G. J. (2005). Behavioural Ecology of Irrawaddy, *Orcaella brevirostris* (Owen in Gray, 1866), and Indo-Pacific Humpback Dolphins, *Sousa chinensis* (Osbeck, 1765), in Northeast Queensland, Australia: A Comparative Study. Ph.D. dissertation. Douglas: James Cook University.
- Parra, G. J., Schick, R., and Corkeron, P. (2006). Spatial distribution and environmental correlates of Australian snubfin and Indo-Pacific humpback dolphins. *Ecography* 29, 396–406.
- Pearson, R. G. (2007). Species’ distribution modeling for conservation educators and practitioners. *Synth. Am. Mus. Natl. Hist.* 50, 54–89.
- Perrin, W., Reeves, R., Dolar, M., Jefferson, T., Marsh, H., Wang, J., et al. (2005). Report of the Second Workshop on The Biology and Conservation of Small Cetaceans and Dugongs of South East Asia. CMS Technical Series Publication No. 9. Paper Presented at the Meeting of the Scientific Committee of the International Whaling Commission SC/66b/SM09, Bonn.
- Perrin, W. F., Leatherwood, S., and Dolar, M. L. L. (1995). The status of marine mammal research in Southeast Asia. *IBI Reports* 5, 1–16. doi: 10.14203/mri.v39i1.80
- Peter, C., Ngeian, J., Minton, G., Zulkifli Poh, A., Grinang, J., and Tuen, A. (2016a). Artisanal Fisheries and Cetaceans in Kuching Bay, Sarawak, East Malaysia: Threats and potential mitigation (SC/66b/SM09). Report Presented to the Meeting of the Scientific Committee of the International Whaling Commission. Cambridge: International Whaling Commission.

3. Modeling: Seasonal dolphin distribution

- Peter, C., Poh, A. N. Z., Ngeian, J., Tuen, A. A., and Minton, G. (2016b). “Identifying habitat characteristics and critical areas for Irrawaddy dolphin, *Orcaella brevirostris*: implications for conservation,” in *Naturalists, Explorers and Field Scientists in South-East Asia and Australasia*, eds I. Das and A. A. Tuen (Cham: Springer), 225–238. doi: 10.1007/978-3-319-26161-4_15
- Peterson, A. T. (2011). Ecological niche conservatism: a time-structured review of evidence. *J. Biogeogr.* 38, 817–827. doi: 10.1111/j.1365-2699.2010.02456.x
- Phillips, S. J., Anderson, R. P., and Schapire, R. E. (2006). Maximum entropy modeling of species geographic distributions. *Ecol. Model.* 190, 231–259. doi: 10.1016/j.ecolmodel.2005.03.026
- Phillips, S. J., Dudík, M., and Schapire, R. E. (2020). Maxent Software for Modeling Species Niches and Distributions (Version 3.4.1). Available online at: http://biodiversityinformatics.amnh.org/open_source/maxent (accessed May 22, 2021)
- Ponnampalam, L. S., Hines, E. M., Monanunsap, S., Ilangakoon, A. D., Junchompoo, C., Adulyanukosol, K., et al. (2013). Behavioral observations of coastal Irrawaddy dolphins (*Orcaella brevirostris*) in Trat province, eastern Gulf of Thailand. *Aquat. Mamm.* 39, 401–408. doi: 10.1578/AM.39.4.2013.401
- QGIS Development Team (2018). QGIS Geographic Information System. Open Source Geospatial Foundation Project. Available online at: <http://qgis.osgeo.org> (accessed January 10, 2020).
- R Core Team (2020). R: A Language and Environment for Statistical Computing. Available online at: <https://www.r-project.org/> (accessed March 20, 2020).
- Read, A. J. (2008). The looming crisis: interactions between marine mammals and fisheries. *J. Mammal.* 89, 541–548. doi: 10.1644/07-MAMM-S-315R1.1
- Redfern, J. V., Ferguson, M. C., Becker, E. A., Hyrenbach, K. D., Good, C., Barlow, J., et al. (2006). Techniques for cetacean–habitat modeling. *Mar. Ecol. Prog. Ser.* 310, 271–295. doi: 10.3354/meps310271
- Reeves, R. R., Smith, B. D., Crespo, E. A., and di Sciara, G. N. (2003). Dolphins, Whales, and Porpoises: 2002–2010 Conservation Action Plan for the World’s Cetaceans, Vol. 58. Gland: IUCN. doi: 10.2305/IUCN.CH.2003.SSC-AP.2.en
- Reid, A. E. A., Haisoune, A., and Ferber, P. (2019). The status of coral reefs and seagrass meadows in the Kep Archipelago. *Cambodian J. Nat. Hist.* 2019, 24–39.
- Robinson, L. M., Elith, J., Hobday, A. J., Pearson, R. G., Kendall, B. E., Possingham, H. P., et al. (2011). Pushing the limits in marine species distribution modelling: lessons from the land present challenges and opportunities. *Glob. Ecol. Biogeogr.* 20, 789–802. doi: 10.1111/j.1466-8238.2010.00636.x
- Santos, M. B., German, I., Correia, D., Read, F. L., Cedeira, J. M., Caldas, M., et al. (2013). Long-term variation in common dolphin diet in relation to prey abundance. *Mar. Ecol. Prog. Ser.* 481, 249–268. doi: 10.3354/meps10233
- Searcy, C. A., and Shaffer, H. B. (2016). Do ecological niche models accurately identify climatic determinants of species ranges? *Am. Nat.* 187, 423–435. doi: 10.1086/685387
- Secretariat of the Convention on Biological Diversity [SCBD] (2010). COP-10 Decision X/2. Secretariat of the Convention on Biological Diversity, Nagoya. Available online at: <https://www.cbd.int/doc/decisions/cop-10/cop-10-dec-02-en.pdf> (accessed August 7, 2020).
- Silber, G. K., Lettrich, M. D., Thomas, P. O., Baker, J. D., Baumgartner, M., Becker, E. A., et al. (2017). Projecting marine mammal distribution in a changing climate. *Front. Mar. Sci.* 4:413. doi: 10.3389/fmars.2017.00413
- Smith, B. D., Ahmed, B., Mowgli, R. M., and Strindberg, S. (2008). Species occurrence and distribution ecology of nearshore cetaceans in the Bay of Bengal, Bangladesh, with abundance estimates for Irrawaddy dolphins *Orcaella brevirostris* and finless porpoise *Neophocaena phocaenoides*. *J. Cetacean Res. Manage.* 10, 45–58.

- Smith, B. D., Braulik, G., Strindberg, S., Mansur, R., Diyan, M. A. A., and Ahmed, B. (2009). Habitat selection of freshwater-dependent cetaceans and the potential effects of declining freshwater flows and sea-level rise in waterways of the Sundarbans mangrove forest, Bangladesh. *Aquat. Conserv. Mar. Freshw. Ecosyst.* 19, 209–225. doi: 10.1002/aqc.987
- Sprogis, K., Christiansen, F., Wandres, M., and Bejder, L. (2017). El Niño Southern Oscillation influences the abundance and movements of a marine top predator in coastal waters. *Glob. Change Biol.* 24, 1085–1096. doi: 10.1111/gcb.13892
- Stacey, P. J., and Leatherwood, S. (1997). The Irrawaddy dolphin, *Orcaella brevirostris*: a summary of current knowledge and recommendations for conservation action. *Asian Mar. Biol.* 14, 195–214.
- Teh, L. S., Teh, L. C., Hines, E., Junchompoo, C., and Lewison, R. L. (2015). Contextualising the coupled socio-ecological conditions of marine megafauna bycatch. *Ocean Coast. Manage.* 116, 449–465. doi: 10.1016/j.ocecoaman.2015.08.019
- Thuiller, W., Lafourcade, B., Engler, R., and Araújo, M. B. (2009). BIOMOD—a platform for ensemble forecasting of species distributions. *Ecography* 32, 369–373. doi: 10.1111/j.1600-0587.2008.05742.x
- Tobeña, M., Prieto, R., Machete, M., and Silva, M. A. (2016). Modeling the potential distribution and richness of cetaceans in the Azores from fisheries observer program data. *Front. Mar. Sci.* 3:202. doi: 10.3389/fmars.2016.00202
- Tsujimoto, K., Ohta, T., Aida, K., Tamakawa, K., and Im, M. S. (2018). Diurnal pattern of rainfall in Cambodia: its regional characteristics and local circulation. *Prog. Earth Planet. Sci.* 5:39. doi: 10.1186/s40645-018-0192-7
- Tubbs, S. E., Baş, A. A., Côté, G., Jones, A. L., and Notman, G. (2019). Sighting and stranding reports of Irrawaddy dolphins (*Orcaella brevirostris*) and Dugongs (*Dugong dugon*) in Kep and Kampot, Cambodia. *Aquat. Mamm.* 45, 563–568. doi: 10.1578/AM.45.5.2019.563
- Tubbs, S. E., Keen, E., Jones, A. L., and Thap, R. (2020). On the Distribution, Behaviour and Seasonal Variation of Irrawaddy Dolphins (*Orcaella brevirostris*) in the Kep Archipelago, Cambodia. *Raffles Bull. Zool.* 68, 137–149. doi: 10.26107/RBZ-2020-0015
- Verutes, G. M., Johnson, A. F., Caillat, M., Ponnampalam, L. S., Peter, C., Vu, L., et al. (2020). Using GIS and stakeholder involvement to innovate marine mammal bycatch risk assessment in data-limited fisheries. *PLoS One* 15:e0237835. doi: 10.1371/journal.pone.0237835
- Vu, L., Tho, T. A., Hung, N. N., and Duy, L. (2017). Conservation of cetaceans in Kien Giang Biosphere Reserve, Vietnam. Conservation Leadership Program, 3234115. Available online at: <https://www.conservationleadershipprogramme.org/media/2017/12/03234115-Conservation-of-Cetacean-in-Kien-Giang-Biosphere-Reserve-Vietnam.pdf> (accessed February 5, 2019).
- Warren, D. L., and Seifert, S. N. (2011). Ecological niche modeling in Maxent: the importance of model complexity and the performance of model selection criteria. *Ecol. Appl.* 21, 335–342. doi: 10.1890/10-1171.1
- Win, N., and Bu, S. S. H. (2019). Food and feeding aspect of Irrawaddy dolphin *Orcaella brevirostris* (Owen in gray, 1866) related to fish abundance. *Int. J. Fish. Aquat. Stud.* 7, 321–326.
- Zhang, K., Yao, L., Meng, J., and Tao, J. (2018). Maxent modeling for predicting the potential geographical distribution of two peony species under climate change. *Sci. Total Environ.* 634, 1326–1334. doi: 10.1016/j.scitotenv.2018.04.112

3.7 SUPPORTING INFORMATION

Supplementary Figures and Tables

Table S3.1. Logistic threshold values corresponding to training omission rates used to transform the probability maps to comparable levels of habitat suitability (limited-lowest-intermediate-highest).

Season	Omission Rate			
	5%	10%	50%	75%
Dry	0.110	0.144	0.635	0.695
Pre-Monsoon	0.458	0.640	0.724	0.778
Monsoon	0.106	0.147	0.661	0.770
Post-Monsoon	0.076	0.399	0.615	0.687

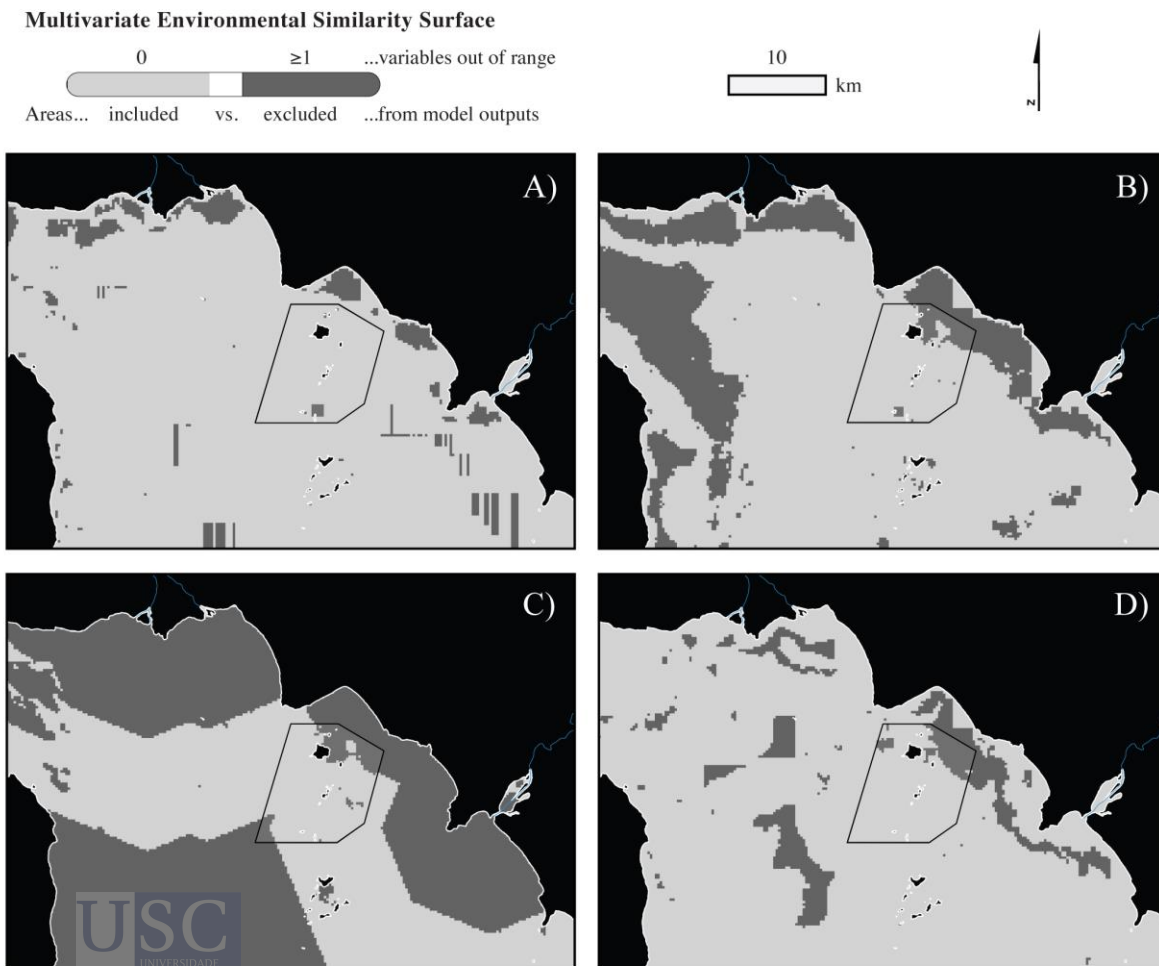
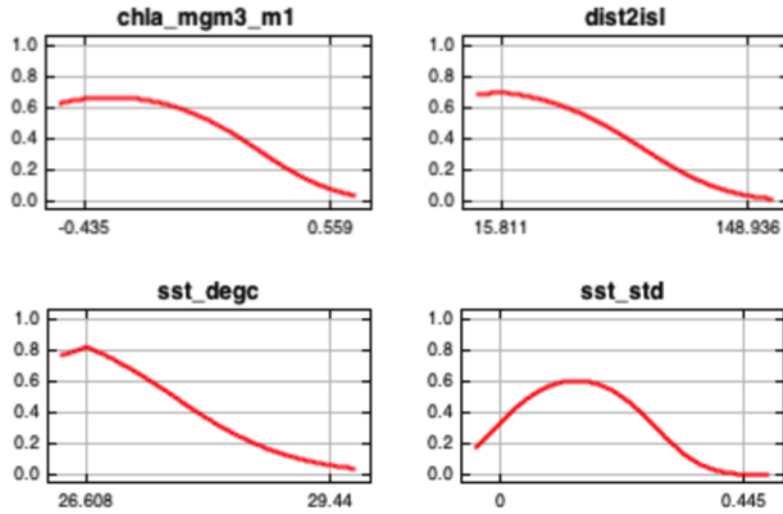
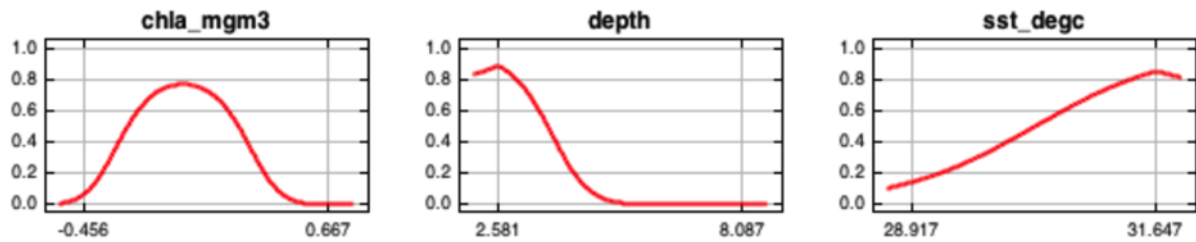


Figure S3.1. Most constrained multivariate environmental similarity surface (areas shown in light grey color) based on analyses for each of the four seasons: (A) Dry, (B) Pre-Monsoon, (C) Monsoon, (D) Post-Monsoon. Darker gray areas represent pixels where at least one variable is outside the range of environmental data used to fit each corresponding seasonal SDM.

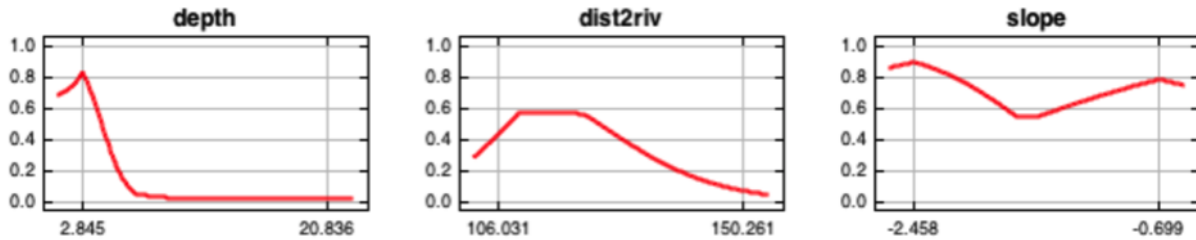
A) Dry



B) Pre-Monsoon



C) Monsoon



D) Post-Monsoon

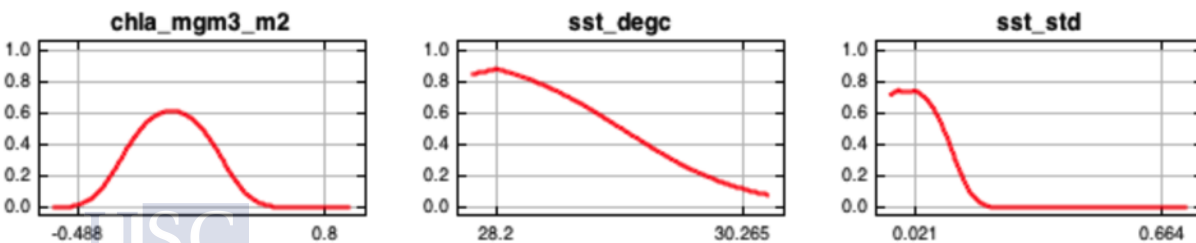


Figure S3.2. Response curves visualizing how each environmental variable affects the Maxent predictions with seasonal SDMs: (A) Dry, (B) Pre-Monsoon, (C) Monsoon, (D) Post-Monsoon. The curves show how the predicted probability of presence changes as each environmental variable is varied, keeping all other environmental variables at their average sample value.

3. Modeling: Seasonal dolphin distribution



Chapter 4





4 ADVANCING THE IMPLEMENTATION OF POLICIES TO MONITOR AND REDUCE SMALL CETACEAN BYCATCH

4.1 INTRODUCTION

Fisheries bycatch, the incidental capture of non-target species, is considered the greatest threat to many species of cetaceans (D'Agrosa et al., 2000; Brownell et al., 2019), a group of marine mammals that include whales, dolphins, and porpoises. Cetacean diet often consists of the target species of commercial fisheries, and as a result, they are attracted to prey, bait, and fishing discards or become entangled in fishing gear (Hamilton and Baker, 2019). Active fishing components (e.g., nets, hooks, traps) and supporting gear and lines (Hamer et al., 2012) can entangle air-breathing marine species and prevent them from reaching the surface. Small cetacean bycatch in gillnets, in particular, has been well-documented but poorly addressed over the last 30 years (Reeves et al., 2013; Dawson et al., 2013; Brownell et al., 2019). Gillnets are a widely used fishing gear because they are relatively low cost (Read, 2013; Chladek et al., 2020) and can be quickly set and retrieved from vessels of most sizes (Orphanides and Palka, 2013). Gillnets are a key contributor to high mortality rates of common dolphins (*Delphinus delphis*) in the Bay of Biscay (Peltier et al., 2020), and 84% of documented cases of bycaught marine mammals in the United States between 1994 and 2006 were in gillnets (Geijer and Read, 2013).

Cetacean-fishery interactions are difficult to observe and address because they are rare. Relative to overall fishing activity, they are disaggregated in space and time, may not be visible at the water surface, and do not adhere to geopolitical boundaries (Michelin et al., 2018; Nelms et al., 2021). With a few exceptions, fisheries bycatch is under-reported and unregulated worldwide (Lukoschek et al., 2009; Pauly and Zeller, 2016), especially in small-scale gillnet fisheries (Brown et al., 2015; Dolman et al., 2016, Anderson et al., 2020). Given these

challenges, various strategies are designed to monitor and mitigate small cetacean bycatch in fishing nets (**Table 10**). Monitoring is typically conducted through a combination of visual or acoustic surveys, fisher interviews (e.g., Pilcher et al., 2017), onboard observer programs or remote electronic cameras (e.g., Kelleher, 2005; Bartholomew et al., 2018), obligatory reporting in captain's logbooks, and strandings monitoring networks. Various mitigation devices have been developed for different species of marine mammals (see Hamilton and Baker, 2019 for a comprehensive review). Measures to mitigate cetacean bycatch include, but are not limited to, time-area fishery restrictions, gear or fishing modifications, and gear switching (Nelms et al., 2021). The most common deterrent in the European Union (E.U.) and United States (U.S.) for small cetaceans interacting with gillnet fisheries is acoustic alarms or “pingers” (Kastelein et al., 2007, Orphanides and Palka, 2013; Hastie et al., 2019).

The E.U. and U.S. use various policy instruments to monitor and protect marine mammal populations, including those of small cetaceans, from the harmful effects of fisheries bycatch. The legislation for cetacean bycatch in E.U. fisheries includes the Common Fisheries Policy (in particular amendments under Regulation N° 1380/2013), Habitats Directive (1992/43/EEC), Marine Strategy Framework Directive (MSFD; 2008/56/EC), and Regulation N° 2019/1241. These regulations and policy directives also intend to establish specific monitoring and reporting requirements for E.U. Member States (MS) regarding the protection of marine mammals. Yet the E.U. Habitats Directive sets a vague target for conservation measures: “to ensure the restoration or maintenance of natural habitats and species...at a favourable conservation status [Habitats Directive, 1992, L206/7]”. Similarly, the MSFD requires that MS monitor and manage their marine environment and species so that Good Environmental Status of their seas can be achieved (European Commission, 2008) without actually defining the terminology. Regulation N° 2019/1241 states the objective to “ensure that incidental catches of sensitive marine species, including those listed under [the Habitats and Birds Directives], that are a result of fishing, are minimised and where possible eliminated so that they do not represent a threat to the conservation status of these species [Regulation N° 2019/1241, L198/112]”. However, it fails to specify how to meet this objective and, in most cases, leaves it up to the MS to act as they see fit.

The U.S. Marine Mammal Protection Act (MMPA) established a national policy in 1972 to protect marine mammals by prohibiting hunting, harassment, capture, or their killing in U.S. waters (Moore et al., 2009), including fishing-related mortality and serious injury. In 1994, the

MMPA was reauthorized to include specific amendments for reducing bycatches in commercial fisheries (Geijer and Read, 2013) and required the National Oceanic and Atmospheric Administration (NOAA) to use science-based research to monitor marine mammal populations. Specifically, MMPA Sections 117 and 118 require regular assessments of strategic stocks and a mortality threshold, Potential Biological Removal (PBR), to indicate the maximum number of animals that can be safely removed from a population by human-related causes (Wade, 1998). The revised legislation is designed to ensure that commercial fisheries do not deplete strategic stocks at unsustainable levels [16 U.S.C. 1387(b)(1)] and, when necessary, to develop and implement a Take Reduction Plan to assist in their recovery (McDonald et al., 2016a).

Overall, the legal requirements to monitor and protect small cetaceans from fisheries bycatch in the E.U. and U.S. have achieved limited conservation success (Geijer and Read, 2013; Orphanides and Palka, 2013; Bellas, 2014). In part, this is the result of challenges with estimating population-level bycatch impacts (Soykan et al., 2008), identifying high-risk fishing areas and gears (e.g., Peltier et al., 2016; 2020), and persuading stakeholders to act (Brownell et al., 2019). Since Soykan et al. (2008) identified emerging needs to tackle fisheries bycatch from global to local scales effectively, substantial knowledge gaps remain. For instance, bycatch management programs rely on multiple monitoring levels to gauge their effectiveness. This monitoring includes observing the distribution and abundance of sensitive species and problematic fisheries, bycatch events (species-gear interactions), and post-implementation of mitigation strategies in operational fisheries (Hamilton and Baker, 2019). With regards to the current E.U. and U.S. regulations, there is a need to better monitor small-scale fishing vessels (James et al., 2018; STEFC, 2019; Dolman et al., 2021) and to identify mitigation interventions that do not also result in serious economic impacts to fisher livelihoods (Campbell and Cornwell, 2008; Goetz et al., 2014). Given these challenges in monitoring vast stretches of ocean and implementing comprehensive international policies, consensus-based decision-making, guided by science and local knowledge, is key to ensuring that natural resources are managed in ways that both conserve biodiversity and sustain fisheries (Lewison et al., 2011; McDonald and Rigling-Gallagher, 2015, Dolman et al., 2016).

There is a growing demand for stakeholder-driven frameworks to rapidly evaluate the risk posed to marine populations by fishing, including the impacts of bycatch on marine megafauna (Stobutzki et al., 2002; Bærum et al., 2019), and to prioritize management among

species (Hordyk and Carruthers, 2018). Community-based research that directly engages fishers and other salient stakeholders has the potential to tap into local expert knowledge (Berkes, 2007; Goetz et al., 2014), navigate complicated political landscapes (Teh et al., 2015), and serve as a bridge to more complex, non-linear approaches as data availability increases (Lewison et al., 2018). Risk assessment is one approach to advance understanding the spatio-temporal distribution of bycatch events and their socio-ecological consequences, and to identify strategies that are likely to reduce impacts to sensitive species. New tools for conducting spatially explicit assessment are designed to be additive rather than replace costly observer-based methods required by law (Verutes et al., 2020). For example, Hines and colleagues (2020) systematically screened four coastal areas with high rates of marine mammal bycatch in Southeast Asia to facilitate new stakeholder involvement, identify critical knowledge gaps, and set priorities for future monitoring and research. Risk assessment techniques are also being developed for data-limited cetacean species in E.U. waters (Evans and Baines, 2013) to demonstrate their potential to integrate diverse information sources such as fishers' opinion with regional surveys of cetacean abundance and strandings.

This paper analyzes three case studies – common dolphins (*Delphinus delphis*) in the Bay of Biscay and harbor porpoises (*Phocoena phocoena*) of the Baltic Proper and U.S. Gulf of Maine – to consider how these areas compare relative to recognized ingredients for addressing bycatch: community involvement, data collection, quantitative analysis, and governance (*sensu* Lewison et al., 2011). First, we summarize and compare the current E.U. and U.S. legal requirements for monitoring fishing fleets, species conservation objectives, bycatch mitigation measures, and provisions for enforcement. Then, to contextualize these regulations within an international policy analysis, we take a structured approach that summarizes current knowledge about examples of well-documented and poorly managed cetacean stocks. We identify fishing gears, areas, and seasons of concern for a threatened or endangered small cetacean population. The research then highlights current strategies identified and implemented to monitor and mitigate bycatch in the context of ongoing needs, challenges, and opportunities to address the issue. In addition to more financial resources to spend in the U.S. and the complexity of unified action across E.U. MS, why has the U.S. MMPA apparently been more successful than similar legislation in the E.U. to regulate cetacean bycatch? Given the importance of stakeholder engagement to identify and implement bycatch risk-reduction interventions, we also examine

how active the fishing industry is in bycatch mitigation measures for each case. Our analysis sets the stage for science-policy processes of engagement that could shed additional light on patterns of bycatch occurrence, pinpoint where and when to focus monitoring effort, and guide the implementation of existing policies for reducing small cetacean bycatch in fishing nets.

Table 10. Strategies to monitor, research, and mitigate small cetaceans, fisheries, and bycatch. Monitoring methods are followed in italics by what is being monitored (distribution, abundance, and/or bycatch). The table does not refer to a specific case study but rather a suite of potential management measures.

Strategy	Advantages	Disadvantages
Monitoring		
Stranding networks <i>(bycatch)</i>	Gathering information on data-deficient, elusive and difficult to study species; sentinel value; detecting previously unknown problems	Unpredictable nature of currents that transport carcasses to final location; animals may be too decomposed to determine cause of bycatch; substantial resources (financial, expertise) needed to ensure detection and recovery of carcasses and an adequate necropsy
Fisher interviews <i>(distribution, bycatch)</i>	Identify communities, gear types, and bycatch species of concern, especially in small-scale fisheries	Participants may not be truthful; may yield imprecise data; species may not be recognized; imperfect memory
Remote electronic monitoring (REM) <i>(bycatch)</i>	Does not require space to accommodate human observers; less susceptible than human observers to fatigue, distraction, coercion and corruption	Devices can be disabled, have blind spots, and yield excessive amounts of data to analyze for advice; privacy concerns and restrictions
Visual and acoustic surveys <i>(distribution, abundance)</i>	Sightings data can inform species distribution models and abundance estimates	May miss marine mammals that only surface occasionally; privacy concerns and restrictions
On board observers <i>(bycatch)</i>	Document specific bycatch events by species and gear type	Difficult to accommodate observers on smaller vessels and obtain adequate fleet coverage; reliance on voluntary cooperation by the fishing sector such as in the E.U.; can lead to temporary change in fishing practices and data biases
Research (Indirect measures for bycatch reduction from sightings, strandings and expert knowledge)		
Risk assessment	Identify hotspots in spatiotemporal occurrence and data gaps for further monitoring and research	Semi-quantitative, based at least partially on expert-judgment or opinion
Drift modeling	Identify emergent bycatch trends and unusual mortality events based on tracing strandings to vessel monitoring data	Difficult to pinpoint a specific fishery, gear, and flag; models need experimental verification to estimate the proportion of carcasses reaching the shore

4 Policy analysis: Case studies of cetacean bycatch

Mortality limits	Quantitative estimate such as PBR encourages transparent reporting of targets	Each method to calculate bycatch threshold levels has different data requirements; all methods, including PBR, have elements of subjectivity
Mitigation (Technical and non-technical measures)		
Time-area closures; “move on” procedures	Can help stock recover quickly by closing areas to fishing during certain months; very short-term closures (e.g., avoid night fishing for pair trawls, reduced soak time for gillnets)	Costly to enforce and likely economic losses to fishers; fishing displacement
Changes in gear deployment	Retain the same fishing gear but change the way it is deployed	Catch reductions and economic losses to the fishery
Gear switching or modifications	Modify fishing practices to alternative, and potentially less impactful gear; modification intended to be easier for animal to detect with sonar and low maintenance option for fishers	Research, education, and implementation costs; gear switch or modification is not always an effective mitigation strategy; may reduce catch of target species
Excluder devices (e.g., on trawls)	Physical barrier and additional section of netting that directs the animal to an escape hole	Requires careful design, specific to the fishery, to avoid target fish loss and blockage
Acoustic alarms (“pingers”) on nets	Becoming cheaper and effective, especially with neophobic species such as harbor porpoises	May impact fishery catch; devices break and require maintenance and training to deploy; post-implementation monitoring; different kinds of pingers and different issues apply depending on whether this is for fixed or towed gear; hearing damage caused to cetaceans by some types of devices; displacement of cetaceans from preferred feeding areas

4.2 BACKGROUND

Policy compliance – adherence to formal rules – can be enhanced when there are explicit requirements to act following evidence of illegal behavior. For the protection of natural resources, effective enforcement has been shown to discourage rule-breaking and ensure compliance (Keane et al., 2008; Da Rocha et al., 2012). In this section, we describe the existing laws, policy directives, and international agreements designed to monitor and detect fisheries bycatch in E.U. and U.S. waters, emphasizing primary data sources, reporting requirements, and mortality limits for listed species. A thorough review of the literature, legal documents, and reports from scientific bodies and international agreements revealed pertinent information about population status, fishing gears and fleets, conservation strategies, and ongoing challenges in

each case study area. These cases provide insights into the capacity of different policies and the associated management and regulatory frameworks to implement measures that conserve a vital marine biological resource.

4.2.1 Legislative context

4.2.1.1 European Union

The E.U. has several legal instruments in place to protect cetaceans. At the highest level, the Common Fisheries Policy (CFP) aims to minimize negative impacts of fishing activities, such as bycatch, in a way that is consistent with other E.U. legislation. At the next level and underneath the CFP, Regulation 812/2004 previously served as the primary fisheries legislation governing cetacean bycatch. It obliged MS to monitor, mitigate and report incidental take and capture using onboard observer schemes (Northridge et al., 2015). However, it is worth noting that compliance with this regulation was highly variable. While, for example, the United Kingdom undertook the required monitoring, Spain launched a single pilot project (Lens and Diaz, 2009) and never instigated dedicated monitoring programs for cetacean bycatch.

In 2019, Regulation N° 812/2004 was repealed and replaced with Regulation 1241/2019: the conservation of fisheries resources and the protection of marine ecosystems through technical measures. Despite targets for marine mammals and other commercially exploited species that “do not exceed [removal] levels provided for in Union legislation and international agreements that are binding on the Union [Article 4, L198/112]”, Regulation N° 1241/2019 is recognized as being severely limited in its stated objectives for monitoring and mitigating bycatch. For one, MS are no longer required to report monitoring results of incidental bycatches to the E.U. Data Collection Framework sampling program (STECF, 2019). Consequently, obligations to monitor bycatch now lie squarely with E.U. MS, which should “take the necessary steps to collect scientific data on incidental catches of sensitive species” and, given “scientific evidence, validated by ICES, STECF, or in the framework of GFCM, of negative impacts of fishing gear on sensitive species”, to “submit joint recommendations for additional mitigation measures for the reduction of incidental catches [Annex XIII, L198/198]”. In addition, Regulation N° 1241/2019 weakens other provisions of the previous legislation, such that few E.U. fisheries are required to implement mitigation methods or demonstrate the efficacy of these measures (Dolman et al., 2021). For example, to minimize or eliminate bycatch, the Regulation states that:

“on the basis of the best available scientific advice a Member State *may*, for vessels flying its flag, put in place mitigation measures or restrictions on the use of certain gear [Article 11, L198/121]”.

The harbor porpoise and common dolphin are listed in Annexes II and IV of the Habitats Directive as species whose conservation requires the designation of Special Areas of Conservation (SAC) and which are in need of strict protection. Article 12.4 specifies that MS are to establish a system of monitoring and research (Benke et al. 2014) to “ensure that incidental capture and killing does not have a significant negative effect on the species concerned [Habitats Directive, 1992, L206/12]”. In addition to requirements to obtain Good Environmental Status of their marine waters, the MSFD has specific obligations for MS concerning incidental non-targeted catches. MS governments must establish threshold values for the mortality rate from incidental bycatch per species and deliver bycatch assessment reports by 2024 (European Commission Directive, 2008). Methods for setting bycatch thresholds are the subject of ongoing discussion within several inter-governmental bodies such as the Baltic Marine Environment Protection Commission (HELCOM) and The Convention for the Protection of the Marine Environment of the North-East Atlantic (OSPAR). Notably, OSPAR is developing a series of bycatch limits for the harbor porpoise and common dolphin in the E.U. waters (STECF, 2021). While not explicitly focused on bycatch, The Convention of Migratory Species (CMS) Regional Agreement on the Conservation of Small Cetaceans of the Baltic, North East Atlantic, Irish and North Seas (ASCOBANS) facilitates transnational cooperation for the management and restoration of small cetaceans. ASCOBANS covers the harbor porpoise and common dolphin and has various E.U. MS as signatories (Dolman et al., 2021).

Several international organizations contribute to bycatch monitoring, assessment, and mitigation efforts by compiling relevant data, supporting collaborations among MS, developing action and recovery plans, and providing scientific advice about the protection of small cetaceans, most notably the International Council for the Exploration of the Sea (ICES), International Whaling Commission (IWC), North Atlantic Marine Mammal Commission (NAMMCO), HELCOM, OSPAR, and ASCOBANS. Although it is not required by E.U. law, some countries, including ASCOBANS signatories, fund national networks or rely on volunteers to monitor vast stretches of E.U. coastline and record the location and condition of stranded cetaceans. Reverse drift modeling can then relate stranding records to Vessel Monitoring System

(VMS) data to suggest fishing fleets, gears, and flags most responsible for bycatch occurrence (Peltier et al., 2016; 2020). E.U. fishing fleet activities are typically classified by gear type (“métier”) according to target species, fishing area, and season (Deporte et al., 2012). Then, bycatch-specific data, organized by fleet segments, are used to identify métiers of greatest concern (e.g., ICES, 2020c). In the most dire circumstance, Article 12 of the CFP allows for Fishery Emergency Measures, such as those endorsed by ICES to address unsustainable levels of small cetacean bycatch in the Bay of Biscay and Baltic Proper (Dolman et al., 2021).

4.2.1.2 United States of America

The U.S. Federal Government is obligated to establish programs that monitor human-caused injury and mortality of marine mammals during fishing activities [16 U.S.C. 1387(d)]. NOAA uses a 3-part strategy to govern interactions between marine mammals, including cetaceans, and commercial fisheries under the authority of the MMPA. Specific actions to guide research and management of bycatch include: (1) a registry and marine mammal mortality monitoring program for certain commercial fisheries such as the gillnet fisheries of the U.S. Gulf of Maine (Moore et al., 2009), (2) stock assessment reports (SARs), and (3) implementation of Take Reduction Plans. Altogether, the National Bycatch Strategy (see Benaka and Dobrzynski, 2004) supports publicly accessible data and a transparent reporting system on marine mammal stock abundance and bycatch (Moore et al., 2009). When necessary, the MMPA facilitates a “negotiated rulemaking process that empowers stakeholders...to generate novel [bycatch] mitigation strategies” (Geijer and Read, 2013, p. 57).

The 1994 amendments to the MMPA mandated the National Marine Fisheries Service, also known as NOAA Fisheries, to manage stocks based on quantitative targets of bycatch levels (or PBR), the maximum number of marine mammals that can be safely removed from a population (Moore et al., 2009). NOAA Fisheries maintains a list of commercial fisheries that it updates annually and publishes in the Federal Register (NOAA, 2021a). Vessels are divided into three categories based on the frequency and severity of commercial fisheries interacting with marine mammals; those that have: (1) frequent, (2) occasional, and (3) remote likelihood of incidental mortality or serious injury (McDonald et al., 2016a). The first two categories (I and II) require a separate governmental authorization for the incidental take of marine mammals, must accommodate observers onboard their vessels upon request [16 U.S.C. 1387(d)(4)], and report

incidental mortality and injuries to marine mammals within 48 hours of the conclusion of a trip [16 U.S.C. 1387(e)]. When bycatch levels in a Category I or II fishery exceed PBR, a Take Reduction Team (TRT) is formed [16 U.S.C. 1387(f)(6)(A)(i)]. TRTs are convened as professionally facilitated, multi-stakeholder meetings (Read, 2013; McDonald & Rigling-Gallagher, 2015) to develop a Take Reduction Plan (TRP). Within six months of TRP implementation, the primary goal is to reduce human-caused mortality below the PBR level (McDonald et al., 2016a). More broadly, TRPs are designed to assist in the recovery of marine mammal stocks that interact with a commercial fishery and encourage the adoption of mitigation measures such as acoustic alarms on nets (Geijer and Read, 2013) to prevent stock depletion.

According to the 1994 MMPA reauthorization, strategic stocks include all marine mammal populations where the level of direct human-caused mortalities exceeds PBR (Moore et al., 2009). NOAA Fisheries considers the Gulf of Maine-Bay of Fundy harbor porpoise subpopulation of the Northwest Atlantic a “strategic stock” (Read, 2013). For these stocks, observer data on individual marine mammals injured, taken, or stranded due to direct interactions with commercial fisheries are analyzed by the Northeast Fisheries Science Center (Protected Species Branch) and included in their annual stock assessment reports (Geijer and Read, 2013). The NOAA database covers the U.S. Gulf of Mexico and Northeast Atlantic coast (including harbor porpoises of the Gulf of Maine) and was first published in 1999. Mortality and serious injury reports for select species of cetacean document operations by fishery (e.g., gillnets and trawls) are available for 1 or 2-year periods, and by region (Northeast, New England, and Mid-Atlantic), since 2007 (NOAA, 2021c). Each report documents serious injuries and mortalities by U.S. region and statistical area over 5-year periods. Additional metrics tracked consistently across reports include (1) number of observer trips, (2) observer coverage, and (3) coefficient of variation (CV; dispersion around the mean).

4.2.2 Case studies

In the following subsection, we present a primer for readers unfamiliar with the three cases, including background on the cetacean species, the bycatch situation, problematic fishery interactions, and management strategies proposed and implemented (**Table 11**). Then, section 4.3: ‘Comparisons among case studies and regions’ analyzes the bycatch problem in the context of the two systems (E.U. CFP and U.S. MMPA), including conservation objectives, proposed

management measures, the status of implementation, and the extent in which bycatch has been reduced.

4.2.2.1 Common dolphins (*Delphinus delphis*) of the Bay of Biscay

Common dolphins are one of the most abundant cetaceans worldwide, with an estimated 250,000 individuals in the Northeast (NE) Atlantic (Hammond et al., 2017) and considerable seasonal variation in distribution (Laran et al., 2017). Short-beaked common dolphins of the Bay of Biscay belong to a wide-ranging population in the NE Atlantic waters surveyed by SCANS in 1994, 2005, and 2016 (Hammond et al., 2017). National surveys conducted by Laran et al. (2017) to assess seasonal distribution and abundance inside the French territorial waters of the Bay indicate alternating patterns of habitat use, from proximity to the shelf break during the winter and further offshore in the summer. Abundance estimates for Northwestern Spain, including the Bay of Biscay, suggest an upward trend in this dolphin population (Saavedra et al., 2018).

Common dolphin diet is predominantly composed of small pelagic shoaling fishes such as horse mackerel, sardine, and anchovy (Pusineri et al., 2007; Murphy et al., 2021). Spitz et al. (2010) found they prefer high energy density prey species in the Bay of Biscay, and temporal variation in diet choice is likely the result of changes in prey availability (Meynier et al., 2008). Common dolphins also have a solid affinity for vessels and are concentrated in shelf waters (Cañadas et al., 2009), making them challenging to census from boats (e.g., Hammond et al., 2013) and vulnerable to fisheries bycatch (Peltier et al., 2016; ASCOBANS, 2019). IUCN classifies NE Atlantic common dolphins as ‘Data Deficient’ according to the Red List Criteria (Laran et al., 2017). To fulfill reporting requirements of the Habitats Directive (Article 17), France and Spain assessed common dolphin conservation status from 2013-2018 as ‘Unfavourable’ and ‘Unknown,’ respectively, with fishery bycatch being the primary human pressure (ICES, 2020c; <https://nature-art17.eionet.europa.eu/article17>). The conservation status for the greater European Marine Atlantic during the same 6-year period is ‘Unfavourable-Inadequate’, due in part to few abundance estimates covering their entire range, which are needed to evaluate population trends (Murphy et al., 2021).

The Bay of Biscay is one of the most intensively fished areas of the world, according to VMS transmitted data compiled by Global Fishing Watch (Kroodsma et al., 2018). While the

Bay includes French and Spanish exclusive economic zones, access to these waters for E.U. vessels is a consequence of the CFP, with primarily commercial fisheries operating by multiple MS (Evans et al., 2021). Small cetacean bycatch occurs year-round (Peltier et al., 2019) and mainly in fisheries that deploy gillnets or mobile gears, including pelagic trawls and purse seine fisheries (Murphy et al., 2019). Substantial common dolphin bycatch in the Bay of Biscay was first reported in the 1990s by observers of French pair trawlers, primarily targeting seabass, along with gillnet and trammel net fisheries (Morizur et al., 1999; Northridge et al., 2006). Declared fishing effort data submitted to ICES in 2017 suggests that nets, seines, and pelagic trawls are the gears with the highest rates of common dolphin bycatch in the Bay of Biscay and along the Iberian Coast (ICES, 2019).

The French National Stranding Network comprises approximately 400 volunteers and is funded by government ministries since 1972 to monitor bycatch in the Bay (Peltier et al., 2021). Two unusual mortality events (UME) occurred during the winter months of 2017 and 2019 (Peltier et al., 2019) where more than 3,500 common dolphins died in fishing gear between February and March, and approximately 11,000 more perished in 2019 (Peltier et al., 2021). Reverse drift modeling can relate bycaught and stranded dolphins to fishing effort tracked by VMS, a required monitoring system for E.U. fishing vessels >12 meters in length (James et al., 2018), to suggest the sources of UMEs (Peltier et al., 2016; 2020). While the suspected fisheries differed in gear type, they shared two important characteristics: (1) they targeted predatory fishes (i.e. sea bass, hake) in winter, and (2) they used fishing gears with high vertical openings similar to pair trawlers of the NW Spanish coast (Fernández-Contreras, et al., 2010). Peltier and colleagues (2021) suggest some combination of French, German and Spanish otter bottom trawlers, French otter twin trawlers, French midwater pair trawlers, and French / Danish seiners were responsible for the UMEs. Furthermore, the high vertical opening of Danish seine nets used to target seabass and hake in winter suggests this gear may be similar to pair trawls in terms of dolphin ‘catchability’ (Table 12).

The European NGO community proposed a combination of acoustic alarms, seasonal fishing closures, and monitoring enhancements as the most effective means to mitigate common dolphin UME in the Bay of Biscay (ICES, 2020c). Pingers already installed on French midwater pair trawls yielded a 65% reduction in the bycatch rate (Rimaud et al., 2019), and there are now calls for mandatory pingers on all French pelagic trawls (Dolman et al., 2021). Saavedra et al.

(2018) proposed between 56 and 115 dolphins per year as safe removal levels in Spanish waters of the southern Bay of Biscay based on local abundance estimates and the 1.7% annual anthropogenic mortality limit proposed by the IWC. Given the high degree of uncertainty in common dolphin abundance and bycatch estimates for the region (Fernández-Contreras et al., 2010; Goetz et al., 2014; Saavedra et al., 2018), ICES evaluated three alternative management scenarios that can be expected to reduce bycatch-induced mortality of common dolphins below PBR (ICES 2019). These scenarios recommend fishing closures during the winter months of January-February and inside the ICES subarea VIII (ICES, 2020c). To meet these PBR targets, the proposed emergency measures include temporal fishing closures of all métiers of concern and the deployment of pingers on pair trawlers to reduce bycatch during periods when closures are not in effect. As of early 2022, only some monitoring and mitigation such as pingers on French trawlers have been introduced (Ministry of the Sea, 2021), and this is likely because the common dolphin is not perceived as threatened with extinction. The European Commission is taking action to enforce emergency measures in the Bay of Biscay, which if unresolved may result in fines to France and Spain (European Commission, 2020).

4.2.2.2 Harbor porpoise (*Phocoena phocoena*) subpopulation of the Baltic Proper

Harbor porpoises are the only year-round resident cetacean species in the Baltic Sea (SAMBAH, 2016; Carlén et al., 2021). Significant genetic differences between the Baltic Proper and Belt Sea porpoises suggest they are polytypic in the region and should be managed as separate units (Benke et al., 2014; Lah et al., 2016; NAMMCO-IMR, 2019). The Baltic Proper porpoise is likely to be spatially distinct from the neighboring Belt Sea porpoise during the summer reproductive period (May to October), with the mixing of the two subpopulations in the southwestern Baltic occurring primarily in the winter (Carlén et al., 2018). While winter distribution limits remain unclear (Jüssi et al., 2016), acoustic monitoring suggests that an annual migration precedes segregation during the summer breeding season (Benke et al., 2014; Carlén et al., 2018). A precipitous decline in Baltic harbor porpoise abundance over the recent decades (Scheidat et al., 2008) was caused by cumulative impacts from anthropogenic activities (Berggren et al., 2002; Evans and Similä, 2018) and, most notably, bycatch in synthetic net fisheries (Hammond et al., 2008; HELCOM, 2013). Here, we refer to the once common harbor porpoise of the Baltic Proper as a *subpopulation*, listed as Critically Endangered by the IUCN

(Hammond et al., 2008). Only a few hundred individuals of this subpopulation remain, and their recovery is unlikely if fishing levels persist (Brownell et al., 2019; NAMMCO-IMR, 2019).

High rates of porpoise bycatch were observed throughout the Baltic and Northeast Atlantic region in static fishing gears such as gillnets, entangling nets, and trammel nets (e.g, Nabe-Nielsen et al., 2014; Calderan and Leaper, 2019; Chladek et al., 2020), and reported under previously mandated observer programs of Regulation N° 812/2004 (Northridge, 2015). The main fishing fleets operating in the Baltic Sea include the nations of Germany, Poland, and Sweden, and to a lesser extent, Denmark, Latvia, Estonia, Lithuania, Finland, and the Russian Federation (ICES, 2017). Many fishing vessels in the Baltic Proper use medium to large mesh size gillnets set offshore or in coastal areas to harvest many fish species such as hake, cod, sprat, and turbot (Koschinski and Wolff, 2013; NAMMCO-IMR, 2019). VMS data suggest a peak in set net usage during the winter months (Sonntag et al., 2012), which may correspond to porpoise migration through the Baltic Proper as they mix with the Belt Sea subpopulation near the eastern management border (Fig. 1 in Carlén et al., 2018). Therefore, it is likely that porpoise-gillnet interactions are seasonally distributed, with the highest risk of bycatch in the southwestern Baltic Sea during the winter months (ICES, 2017; NAMMCO-IMR, 2019). Yet it is challenging to assess spatio-temporal overlap with gillnet fisheries as the Baltic Proper subpopulation is estimated to be less than 500 individuals (IWC, 2017), and there is limited monitoring of smaller fishing vessels <15 meters (Dolman et al., 2016). Nevertheless, subregions such as the Northern and Southern Midsea Bank, which monitoring suggests are important Baltic porpoise breeding areas (Carlén et al., 2018), have been prioritized for management by the NGO community (ICES, 2019; 2020c).

All conservation status assessments by MS of the Baltic Marine Region were “Unfavourable-Bad” for the last three reports covering six-year periods from 2001 to 2018 (<https://nature-art17.eionet.europa.eu/article17>). HELCOM is “convinced that the critical status of harbor porpoises in the Baltic Sea calls for immediate actions to safeguard their survival” (HELCOM, 2019, p. 1). ASCOBANS has developed recovery plans for the Baltic Proper porpoise because it considers this subpopulation in serious danger (Evans and Similä, 2018; Carlén et al., 2021). PBR calculations based on abundance estimates with a high CV and a variable recovery factor (F_R) translate to only 10 to 35 animals that can be lost per decade (NAMMCO-IMR, 2019), and suggest that the Baltic Proper subpopulation is unlikely to recover

due to its very small population size and current rates of bycatch (NAMMCO-IMR, 2019). To improve the population's status assessment and the resulting PBR calculations, NAAMCO recommends more precise abundance estimates (with smaller CV) and additional fisheries monitoring because bycatch rates for the Baltic Proper were obtained and extrapolated from electronic monitoring in the neighboring Belt Sea. In addition, ICES cautions that current monitoring of bycatch in Baltic gillnet fisheries is “not sufficient to support the development and timely implementation of appropriate adaptive mitigation measures (ICES, 2020a, p. 7).”

The technical measures of Regulation N° 1241/2019 have struggled to monitor and reduce cetacean bycatch in particular areas of the E.U. (Dolman et al., 2021). Consequently, European NGOs requested the introduction of Fishery Emergency Measures to address harmful porpoise-fishery interactions in the Baltic. The proposal emphasizes the exclusion of static net fisheries from Natura 2000 sites in the German, Polish, Swedish and Danish waters of the Baltic Proper, especially in the Northern Midsea Bank, where porpoise detection rates are highest year-round (ICES, 2020a). According to ICES, for the Baltic Proper harbor porpoise to meet the management unit objective of achieving bycatches below the PBR limit (1 to 3.5 individuals per year), all fisheries of concern that are within the management range of this subpopulation would need to be closed (ICES, 2020c). In addition to time-area static net fishing closures and bycatch monitoring enhancements, ICES supports the NGO proposal for mandatory pingers in all commercial gillnet fisheries outside Natura 2000 areas (ICES, 2019). As of late 2021, there has been limited action by the Baltic MS and European Commission. The closure of semi-driftnet fisheries throughout the Baltic Proper was opposed by BALTFISH, and some compromises proposed. The closure areas within existing marine protected areas have been agreed to and the details are being worked out (BSAC, 2021). Similar to the Bay of Biscay situation, infringement proceedings by the Commission extend further than the proposed emergency measures for the Baltic. They urge the nation of Sweden to take action to reduce bycatch as required under the Habitats Directive (European Commission, 2020).

4.2.2.3 Harbor porpoises of the U.S. Gulf of Maine

The Gulf of Maine is home to one of four discrete harbor porpoise subpopulations of the Northwest Atlantic. Mitochondrial DNA evidence collected over the entire North Atlantic range suggests this subpopulation should be managed as a single stock under the authority of the U.S.

MMPA (Waring et al., 2011). The subpopulation ranges from North Carolina (U.S.) to the Bay of Fundy and Nova Scotia (Canada) (Read, 2013). Seasonal distribution of this designated strategic stock reflects a preference for cold, inshore waters and tracking the migration of their prey (Orphanides and Palka, 2013). In summer, harbor porpoises are concentrated in the northern Gulf of Maine and southern Bay of Fundy (Fig. 2 in Read, 2013), away from most U.S. gillnet fisheries. Harbor porpoises are more widely dispersed during fall and spring, and their distribution extends as far south as North Carolina from January through April (Orphanides, 2009; Waring et al. 2011). The latest estimate of the Gulf of Maine – Bay of Fundy subpopulation is 80,000 animals based on 2011 aerial surveys (Palka, 2012).

Gillnet and trawl fisheries of New England and Mid-Atlantic coasts are likely the most significant source of incidental mortality of marine mammals inside the U.S. Atlantic EEZ (Moore et al., 2009). During the early 1990s, harbor porpoise bycatch mortality rates were the highest of all U.S. marine mammal stocks (Geijer and Read, 2013). An estimated 3,000 harbor porpoises were taken each year by the New England sink (bottom-set) gillnet fishery during the 1990s (Read et al., 2006). Gillnets in the Gulf of Maine are typically set on the seafloor and secured with anchors to catch high-value groundfish such as cod and dogfish (Orphanides and Palka, 2013; Geijer and Read, 2013). Harbor porpoises dive to depths of 200m, where they are likely to encounter bottom-set gillnets (Read, 2013). Static entangling fishing gears can soak for a day or more and are strung together as arrays of nets that sometimes reach 90m in length. In 1991, the National Marine Fisheries Service (NMFS) listed the Gulf of Maine - Bay of Fundy harbor porpoise stock as threatened under the Endangered Species Act (Read, 2013). U.S. northeast sink gillnets and midwater/bottom trawls are considered MMPA Category I and II vessels (Moore et al., 2009), respectively, and therefore must accommodate observers if requested by NMFS.

Stock Assessment Reports required by 1994 amendments to the MMPA revealed that harbor porpoise bycatch rates in the U.S. Gulf of Maine were the highest of any strategic marine mammal stock (Geijer and Read, 2013). For example, annual bycatch estimates between 1989-1993 were greater than four times the PBR (Read, 2013). Consequently, the Harbor Porpoise Take Reduction Team (TRT) was formed in 1996 and later merged with the Mid-Atlantic TRT to identify specific measures to reduce gillnet bycatch from the Gulf of Maine and Southern New England to the southern limit of the stock's range (Orphanides and Palka, 2013). The New

England Fishery Management Council began employing fishing closures in 1994 (Murray et al., 2000) followed by a series of rolling closures in the late 1990s (Palka et al., 2008). In addition, conservation measures were designed to protect overfished groundfish stocks (Geijer and Read, 2013) including limits on total catches, limits on effort (number of vessel trips and days at sea), and to prevent gillnets arrangements that increase the bycatch risk (Waring et al., 2011). In 1998, NMFS implemented the Harbor Porpoise Take Reduction Plan (HPTRP), which included a series of bycatch mitigation measures for fisheries operating inside the Gulf of Maine, specifically (1) gear modifications, (2) the mandatory use of pingers on gillnets (Palka et al., 2008; Geijer and Read, 2013), and (3) a mixture of time-area closures (Orphanides and Palka, 2013; McDonald & Rigling-Gallagher, 2015).

Monitoring bycatch of the Gulf of Maine - Bay of Fundy harbor porpoise stock is difficult for a number of reasons. The subpopulation covers a large area (180,000 km²) subject to different legal and management regimes and diverse fishing practices throughout U.S. and Canadian waters (Trippel et al., 1999; Read, 2013; Orphanides and Palka, 2013). Since the late 1980s, NMFS has trained fishery observers on gillnet vessels in the Gulf of Maine to estimate annual bycatch for the entire gillnet fishery and, beginning in 1999, to monitor the effectiveness of HPTRP implementation. The Northeast Fisheries Observer Program sampled about 5% of trips across a representative number of fisheries annually between 1999 and 2010 (Orphanides and Palka, 2013). This observer program records information on characteristics of the vessel, fishing trip, gear, and incidental bycatch (Waring et al., 2011). As part of the HPTRP monitoring plan, NMFS prepares reports summarizing bycatch rates, plan compliance, and pinger use rates. However, on the Canadian side, Fisheries and Oceans Canada (DFO) has no scientific monitoring program to observe bycatch in gillnet fisheries of the Bay of Fundy (Read, 2013).

Table 11. Case study summaries of current issues, strategies, and opportunities to advance the implementation of policies and agreements and reduce cetacean bycatch.

Case study	Population status; fishing gears, fleets, and subregions of concern	Strategies identified or implemented	Ongoing challenges and needs
Common dolphins (Bay of Biscay)	<p>High abundance and seasonal variation in distribution; 'Data Deficient' (IUCN) and 'Unfavourable-Inadequate' conservation status in NE Atlantic</p> <p>Gillnets and mobile gears (pair trawls and purse seines); nets with high vertical openings</p> <p>Primarily fishing vessels from France, Spain, and Germany; Denmark, Holland, UK, Belgium and Poland to a lesser extent</p> <p>Unusual mortality events in 2017 and 2019 winter traced to nets in ICES fishing subareas 8.a and 8.b. with high density of commercial vessels</p>	<p>Monitoring and research VMS and AIS monitoring data for vessels >15 m and >12 m, respectively</p> <p>French National Stranding Network in operation since 1972; drift prediction model used to connect stranding records to fishing areas and gears of concern</p> <p>ICES responds to the lack of methods to assess/quantify bycatch mortality risk and adopts the PBR method</p> <p>Since early 2021, France has fitted 87 trawling vessels with pingers and 20 gillnet vessels with on-board cameras for research purposes</p> <p>Mitigation measures NGO emergency measures proposal includes: (1) 4-month temporal closures in ICES subarea 8 to métiers of concern (at a minimum, pair trawls and gillnet fisheries); (2) application of pingers on pelagic and bottom pair trawls; (3) daylight fishing and move-on procedure</p>	<p>Challenges Generally ineffective legislation; common dolphin population too large to be considered threatened with extinction</p> <p>Paucity of data to spatially disaggregate fishing effort and gears used by all vessels operating in the region Scant evidence of pinger effectiveness in reducing common dolphin bycatch</p> <p>Needs Dedicated monitoring to assess how seasonal changes in fishing practices and species distribution affect interactions with high-impact gears, which are known to differ between spring and summer bycatch events</p> <p>Additional research on the socio-economic consequences of time-area closures and how effort could be redistributed if restrictions for certain fishing gears are implemented</p>
Harbor porpoises (Baltic Proper)	<p>Small population (<500 individuals); declining abundance; Critically Endangered' (IUCN) and 'Unfavourable-Bad' conservation status</p> <p>Static net fisheries (gill, semi-drift, trammel nets) primarily deployed by small-scale vessels of Baltic Range States (Germany, Poland, Sweden, and Finland)</p> <p>Likely overlap of breeding and static net fishing areas (No. and So. Midsea Banks)</p>	<p>Monitoring and research Static acoustic and aerial surveys to detect spatiotemporal changes in occurrence</p> <p>ICES responds to the lack of methods to assess/quantify bycatch mortality risk and adopts the PBR method (PBR <1 individual per year for this subpopulation)</p> <p>Mitigation measures Deployment of pingers on some gillnet fisheries since 2004; Porpoise Alert (PAL) has shown to significantly</p>	<p>Challenges Seasonal mixing between Belt and Baltic Proper complicates population estimates</p> <p>Patchy data on harbor porpoise distribution and bycatch occurrence in the Baltic Proper; limited monitoring of and compliance with existing regulations by small-scale fishing vessels</p> <p>Transboundary issues too because not all of the Baltic area belongs to the E.U.; low observer coverage (<1%) limits certainty as to which vessels,</p>

		reduce harbor porpoise bycatch in western Baltic gillnet fisheries	gears, and areas have highest rates of bycatch
		Proposed NGO emergency measures for spatiotemporal fishing closures in certain Natural 2000 sites and pingers on all commercial gillnets outside these sites	Needs Resolution of the ongoing debate about whether Baltic Proper porpoises are a population or a subpopulation / separate management unit
Harbor porpoises (U.S. Gulf of Maine)	Wide ranging and abundant population (U.S. to Canada), considered one strategic stock by the U.S. MMPA; 'Threatened' according to the Endangered Species Act (1991) Distribution varies by season and year, driven by changes in sea surface temperatures and prey abundance Bottom-set gillnets are classified as Category I vessels (frequent incidental mortality or serious injury of marine mammals), have long soak times (24-48+ hours) and target commercially-valuable fish species of similar size to harbor porpoises	Monitoring and research Observers on board commercial gillnets fisheries since 1989 (classified as Category I vessels) Annual bycatch estimates in early 1990s were greater than four times the stock's PBR level Regular Stock Assessment Reports (SAR) and Take Reduction Planning (TRP) since implementation of HPTRP in 1998 Mitigation measures Time area closures beginning in 1994; pinger experiments followed by HPTRP requirements: outreach and education efforts such as pinger training program, and mandatory pingers on Category I gillnet vessels in certain areas of the Gulf of Maine	Challenges Transboundary stock which has implications for monitoring (via stock assessment), management and enforcement Seasonal and annual variability in environmental conditions alters prey abundance and species distribution Maintain the momentum generated by previous TRPs (late 1990s to early 2000s), specifically stakeholder engagement, socio-economic impact analyses, and the identification and deployment of targeted bycatch mitigation measures Needs Further research to augment the effectiveness of and fisher compliance to pinger requirements

4.3 COMPARISONS AMONG CASE STUDIES AND REGIONS

We reviewed information about existing legal instruments designed to conserve marine mammals in the E.U. and the U.S. Here, relevant instruments included regulations, directives, agreements, and conservation action plans developed by decision-makers to reduce cetacean bycatch. We emphasized measures designed specifically for or relating to the three case studies.

Provisions to address bycatch of small cetaceans and other marine mammals in the E.U. and U.S. are similar, but policy objectives and outcomes vary greatly. While the legislation in

both regions establishes norms for protecting cetacean populations relative to their nominal carrying capacity, similarities end there. The U.S. MMPA covers all strategic stocks in one coherent national strategy that explicitly targets reducing and potentially eliminating marine mammal mortality in certain commercial fisheries. Despite various requirements for MS to protect listed marine mammals (e.g., Habitats Directive and MSFD), the E.U. lacks a comprehensive legislative framework to ensure their protection from bycatch mortality. E.U. policy compliance is arguably poor due to less than watertight regulations and inconsistent conservation objectives across relevant directives, which have to be respected in the context of broader fisheries legislation (the CFP). For example, the E.U. objective to minimize bycatch of marine mammals is qualified by the addition, “so that they do not represent a threat to the conservation status of the species [Regulation 2019/1241, L198/112]”. This is less stringent than the wording in the MMPA, which offers the explicit goal, “incidental kill or incidental serious injury of marine mammals permitted in the course of commercial fishing operations be reduced to insignificant levels approaching a *zero mortality* and serious injury rate [16 U.S.C. 1387(b)(1)]”. The meaning of “a threat to the conservation status” is undefined in the context of the CFP and its policy directives.

The most striking difference between the U.S. MMPA and comparable E.U. legislation is the requirement to act following evidence of bycatch. In the U.S., PBR is the accepted biological reference point regarding the maximum number of animals that can be safely taken from a population (Wade, 1998). Any notion or mechanism to develop and implement a take reduction plan, similar to the MMPA when the mortality rate exceeds PBR, is absent from E.U. legislation. E.U. Regulation N° 1241/2019 fails to explicitly define quantitative limits to identify and manage unsustainable levels of bycatch, which has softened the legal obligations for MS. While the European Commission does have the power to levy fines, measures to monitor and mitigate bycatch are not always directed at the most problematic fisheries (Peltier et al., 2020), and there is a general lack of provisions for results-based management and enforcement. The Habitats and Marine Strategy Framework Directives do provide specific requirements for MS concerning the protection of marine mammals. Yet in the absence of E.U. provisions on the bycatch issue, the legislation governing MS cannot adequately provide measures to protect these species. For instance, Article 4 of Regulation N° 1241/2019 specifies that one of its targets ensures that incidental catches of marine mammals do not exceed unsustainable levels. However, there are

currently no such levels fixed in law or agreements binding on the E.U. or its MS. These mortality threshold values are the subject of ongoing discussion within several international bodies, including OSPAR, HELCOM, and ASCOBANS.

Since the repeal of E.U. Regulation N° 812/2004, direct monitoring of bycatch in European fisheries is less common because there is no longer a requirement to accommodate dedicated observers and E.U. fishery observers have other responsibilities that take priority over monitoring mammal bycatch. Its replacement with the generally weaker Regulation N° 1241/2019 occurred despite the European Commission recognizing that “the only reliable method of estimating by-catches is observation (SEC, 2002, p. 37).” Further, MS are expected to cooperate with the Commission to implement regional monitoring programs. Sparse data and high uncertainty are increasingly cited by E.U. MS when translating current monitoring information for reporting and mitigation actions required by law. No one body in the E.U. is responsible for overseeing and collecting bycatch information, although ICES has unofficially taken on this role.

On the other side of the Atlantic, the U.S. MMPA requires monitoring of certain commercial fishing operations. These monitoring programs aim to obtain statistically reliable estimates of incidental mortality and serious injury to identify and track high-risk fisheries and, if necessary, inform take reduction planning. Within six months of implementing a Take Reduction Plan (TRP), the primary goal is to reduce human-caused mortality below the PBR level (McDonald et al., 2016a). More broadly, TRPs are designed to assist in the recovery of marine mammal stocks, which interact with a commercial fishery and encourage experimentation with mitigation measures such as pingers on nets (Geijer and Read, 2013), to prevent the depletion of strategic stocks. The U.S. Federal Government may transfer enforcement to the states, provided that a state has previously established measures to comply with requirements of the MMPA. The State must then report annually on implementing measures taken [16 U.S.C. 1379].

In summary, legal instruments to monitor and mitigate bycatch are limited by the quantity and quality of data available. In terms of which fisheries are covered and how well they are covered, that in turn is down to the legislation, and the extent to which it is implemented. Unwanted catches are primarily addressed by the Common Fisheries Policy (CFP), to which the E.U. has exclusive competence. The CFP, however, is more focused on commercial fisheries than broader conservation issues, such as addressing unsustainable rates of cetacean bycatch.

Also, E.U. law cites vague conservation goals that *aim* to reduce bycatch and, consequently, the European Commission has struggled to ensure effective compliance. The trend since the adoption of Regulation N° 1241/2019 has been a transfer of competence from the European Commission to MS, resulting in regional differences in the number of resources available to ensure compliance. Bycatch management for cetaceans is typically based on a reference population size and the desired rate of increase in population size to achieve recovery of the population within three generations (Taylor et al., 2007); a rate of increase which monitoring needs to be able to detect. Although PBR is used by the E.U. scientific community to recommend safe mortality limits, it has yet to gain traction. In the U.S., marine fish bycatch and discards are handled exclusively through the Magnuson-Stevens Fishery Conservation and Management Act and marine mammal bycatches are the core competence of the MMPA. Unlike the E.U. legislation, the MMPA offers specific, quantifiable metrics (McDonald et al., 2016a) and requires the design and implementation of a Take Reduction Plan [16 U.S.C. 1387(f)] to assist in the recovery or prevent the depletion of a strategic stock that interacts with a high-risk fishery, when the PBR limit is exceeded.

4.3.1 Enabling and limiting conditions for reducing cetacean bycatch

Overall, provisions are more robust in the U.S. than the E.U for implementing and enforcing cetacean conservation policies. Relative to the E.U. cases of this study, efforts to minimize harbor porpoise bycatch in the U.S. Gulf of Maine are furthest along. Ongoing challenges in the U.S. example relate to compliance with and enforcement of management strategies developed and implemented under the HPTRP. Both E.U. cases are emblematic of a more considerable challenge facing marine mammal scientists and managers: governments and fishers hiding behind the problem of questionable data quality and information gaps. Some scientists and NGOs are also guilty, as they seek funding for additional surveys to reach unattainable monitoring targets. There is sufficient data in both regions to establish biological reference points (Orphanides, 2009; Rogan et al., 2021), including extensive analytical capabilities, such as population dynamics models in data-rich situations (e.g., Christiansen et al., 2018; Barratclough et al., 2021), and alternative approaches for managing data-poor marine mammal stocks (e.g., NAAMCO-IMR, 2019; Rouby et al., 2020; Wade et al., 2021). Supposedly, the E.U. follows the precautionary principle to avoid high levels of bycatch. Yet, in the E.U. and to a lesser extent the

U.S., slow movement from industry, governments, and even the scientific community can cripple policy implementation to conserve endangered, threatened, and protected cetacean species (Symes, 2009; Dolman et al., 2021). The following summary offers comparative insights across the three cases related to critical ingredients for effectively reducing bycatch.

4.3.1.1 Community involvement

The involvement of fishers, port operators, coastguards, and other relevant stakeholders improves data collection, knowledge sharing, the design of research methods, and evaluation of bycatch management strategies (McDonald et al., 2016a). For example, a questionnaire designed to assess previously unknown harbor porpoise population size in the Baltic Proper revealed an alarming 99.8% decrease in sightings over 30 years (Carlén et al., 2021). Ultimately, fisheries representatives need to be convinced of the value of providing accurate, albeit sensitive, data. This will increase the probability that conservation outcomes lead to a more efficient allocation of human and financial resources (Dolman et al., 2021). Buy-in is essential when implementing costly bycatch monitoring and mitigation approaches that could impact fisher livelihoods (see “Disadvantages” in Table 10). For identifying appropriate mitigation strategies, locally vetted data derived from scientific analyses are more likely to include salient factors that influence bycatch rates and, therefore, avoid unintended consequences resulting from ineffective measures (Pullin and Knight, 2009).

A lengthy prior history of informal discussions among stakeholders facilitated successful knowledge exchange and negotiation within the U.S. HPTRP process (Read, 2013). The availability of independent and unbiased estimates of bycatch rates was critical in re-engaging the fishing industry towards effective solutions in the Gulf of Maine when bycatch rates increased in the early 2000s (Orphanides and Palka, 2013). Credible scientific information on porpoise abundance and bycatch levels was presented to a cross-sectoral team of fisheries representatives, federal agencies, coastal states, and fishery management councils (McDonald et al., 2016b). Professional mediators, with experience in dispute resolution, facilitated team meetings in order to move towards consensus decisions (Read, 2013). Stakeholders could evaluate different mitigation measures and offer suggestions for compromise, substitution, or alteration. They were able to reach a consensus because members viewed the HPTRP as imperfect but workable in terms of advancing shared socio-ecological objectives (McDonald et

al., 2016b).

The HPTRT reconvened in 2007 to discuss another increase in harbor porpoise bycatch rates in the mid-2000s (Orphanides and Palka, 2013). This time, members raised concerns over the low level of enforcement and the lack of compliance with HPTRP regulations, specifically pinger requirements. The perceived lack of enforcement together with seasonal changes in the distribution of harbor porpoise bycatch led to proposals for additional time-area closures (McDonald and Rigling-Gallagher, 2015). Not surprisingly, these closures were unpopular among fishers, who suggested acoustic alarms as an alternative. The use of science quotas by MS governments in exchange for REM system installations in fisheries (e.g., Scheidat et al., 2018) seems to be the best option to foster cooperation with E.U. fishers in the data collection. Despite being a short-term, transactional solution that does not change attitudes, quotas represent progress in adaptively managing fisheries via bycatch monitoring and mitigation initiatives.

There is no shortage of scientific organizations involved with E.U. cetacean research, recovery, and bycatch mitigation. In the Baltic, for example, the list includes NAMMCO, CMS, HELCOM, and ICES). The Static Acoustic Monitoring of the Baltic Sea Harbour Porpoise (SAMBAH) is a promising collaboration among the eight E.U. MS of the Baltic to survey harbor porpoises (Carlén et al., 2018). This joint effort compiles evidence about seasonal distribution and abundance (SAMBAH, 2016) and could answer lingering questions about the Baltic Proper subpopulation, which has implications for harbor porpoise management and ongoing negotiations. However, there are fewer examples of community and, more specifically, fisher involvement in designing strategies to monitor and mitigate bycatch in the Bay of Biscay. Disagreement during earlier steps of the management process (e.g., paucity of data to agree on mortality limits or the most problematic métiers) is likely a contributing factor (Peltier et al., 2021). Despite the evidence from drift modeling for spatio-temporal co-occurrence of bycaught dolphins and certain fisheries (Peltier et al., 2021), legal confrontations are expected in France as conservation and fisheries organizations lobby for public support (Authier et al., 2021). When there is pushback from industry, MS governments inevitably take the side of fishers. For example, Germany's Federal Ministry of Food and Agriculture has been outspoken about the impacts of proposed management measures on small-scale net fisheries, refuting evidence that the Baltic Proper harbor porpoise is a distinct population (Carlén et al., 2021). The way stakeholders are involved is critical. Credible data and continued involvement of fisheries

stakeholders, directly engaged with scientists and available data, will be essential to advance these stalemates over the interpretation and implementation of conservation policy. Ideally, progress on this front will come with pressure from the E.U. to fund new research initiatives that consider both short and long-term interests rather than imposing emergency measures or fines.

4.3.1.2 Data collection

Bycatch evidence, especially from primary data sources such as observer programs, is key to effectively managing and mitigating unwanted removals (Dolman et al., 2016; ICES, 2020b). Not all data are equal, however, and the breadth and quality of information available across the three case study areas have undoubtedly affected policy implementation and conservation outcomes. The E.U. Data Collection Framework (DCF) requires “data to assess the impact of Union fisheries on the marine ecosystem in and outside Union waters, including data on by-catch of non-target species, in particular species protected under Union or international law [Regulation N° 2017/1004, p. L157/9].” Data collected through the E.U. DCF program is the domain of the European Commission’s Scientific, Technical and Economic Committee for Fisheries (STECF) and fishing data are typically organized in métiers based on the target species, gears used, season, and area (Deporte et al., 2012). Bycatch-specific data required by the E.U. DCF include days at sea, fishing days, landings, and métiers (Peltier et al., 2021). To improve access to standardized bycatch data for the scientific community, ICES has initiated annual calls for data through expert working groups since 2018 (ICES, 2020b).

Specifics are lacking as to exactly *how* and *where* MS should compile relevant bycatch information. In addition to questions about data coverage, there has been a precipitous drop in overall data quality, especially on small-scale fisheries, since the repeal of Regulation N° 812/2004 (Carlén et al., 2021; Rogan et al., 2021). Without dedicated monitoring programs that deploy trained observers focused on marine mammals, monitoring has been inadequate to accurately assess rates of small cetacean bycatch in the E.U. (Dolman et al., 2021). There are also inconsistencies in reporting across the E.U. as bycatch data arrive in different formats, are based on disparate data collection procedures, and lack specifics about the fishing gear in question. For example, Norway, a European nation but not an E.U. MS, uses official landings to estimate total bycatch, while Iceland uses kilometers of nets from observed fishing effort data. Total fishing time (days at sea) is meaningful for trawling but not fixed gears, where net length

and soak time metrics are more relevant.

Data collection to detect changes in small-scale fisheries effort is not prioritized in the E.U. (Peltier et al., 2020). In the absence of requirements to accommodate at-sea observers or conduct remote electronic monitoring, the conservation status of cetaceans listed in the Habitats Directive cannot be effectively assessed (Rogan et al., 2021). E.U. fisheries management relies primarily on VMS tracking of larger vessels, but these activities are only part of the bycatch picture. Despite the high rates of cetacean bycatch attributed to static nets of the Bay of Biscay (Peltier et al., 2016; 2020), small-scale vessels less than 12 m in length constitute the majority (94%) of the European gillnet fleet (Rogan et al., 2021) and are mainly absent from DCF sampling. The métiers consistently monitored by the DCF and later identified through drift modeling as highly correlated with common dolphin bycatch were generally under-sampled by DCF observer programs, leading to underestimating bycatch (STECF, 2019). In addition, the French marine mammal bycatch observer program merged with another program that was designed specifically for commercial fish catch. As a result, cetacean bycatch is no longer the focus of France's contribution to the E.U. DCF (Peltier et al., 2021). Broadening the use of remote monitoring could help narrow this gap in observer coverage as ASCOBANS has demonstrated that REM can provide cost savings over human observers, depending on the levels of monitoring required and techniques implemented (Course, 2021). Since 2014, AIS data is required on all fishing vessels >15 m (James et al., 2018), and some voluntary adoption by boats 10 to 15 m in length (Evans et al., 2021). Gears type groupings classified and tracked by Global Fishing Watch represent an additional form of satellite-based small-scale fisheries monitoring in E.U. waters (Kroodsma et al., 2018).

The Gulf of Maine-Bay of Fundy harbor porpoise is considered a strategic stock under the U.S. MMPA. As a result, annual stock assessment reports (SAR) provide estimates of marine mammal abundance (e.g., Palka, 2012) and PBR (Waring et al., 2011). Longitudinal datasets for certain species that date back to 1995 are available via a public website (NOAA, 2021b). Supplements to the SARs are available as observed mortality and serious injury statistics for many fisheries (NOAA, 2021c). Scientists, fisheries observers, and analysts can leverage these data to calculate annual human-caused mortality estimates (Geijer and Read, 2013) and conduct comparative analyses (McDonald et al., 2016a). The HPTRP monitoring program has benefited from the availability of these data when evaluating mitigation strategies following plan

implementation. Monitoring and evaluation provided critical feedback on the efficacy of management strategies to reduce bycatch prescribed by the plan. Unlike the E.U. cases, these data were available during multiple iterations of TRP development and were instrumental in persuading stakeholders of the need to act when bycatch rates exceeded PBR (Read, 2013).

4.3.1.3 Quantitative analysis

Despite elements of subjectivity, consistent reporting, with data uncertainty acknowledged, allows for robust estimation of PBR. Because the U.S. Federal Government conducts regular stock assessments, estimates of human-caused mortality of harbor porpoises were available following HPTRP implementation in 1998. During this period, the PBR level was exceeded four times and ranged from 403 to 747 (Geijer and Read, 2013) because calculations are based on estimates of abundance, the reproductive capability of the stock, and the coefficient of variance of the bycatch removal estimate, all of which can vary over time (Orphanides and Palka, 2013). The overall bycatch trend following 1998 was a sharp decline in the early years, a substantial increase during the middle years, and modest fluctuations in later years. More specifically, anthropogenic mortality of harbor porpoises in the Gulf of Maine gillnet fishery declined from thousands of animals in 1990 to less than 80 in 2001 (Orphanides and Palka, 2013). An overall decrease in harbor porpoise removals since the HPTRP's inception would suggest that the plan effectively reduced the scale of the U.S. Gulf of Maine bycatch problem. Relative to other U.S. TRPs, however, McDonald et al. (2016a) found the recovery of this harbor porpoise stock to rank as one of the lowest.

Quantitative objectives for setting bycatch limits for listed species are not well-defined in Europe (Rogan et al., 2021). The lack of reliable fisheries bycatch data hinders the assessment and reporting of cetaceans conservation status for European waters over the longer term. These limitations are most apparent in the Baltic Proper, with an extremely low abundance of harbor porpoises, insufficient fisheries monitoring, and few reliable estimates of bycatch per métier. Existing estimates of annual bycatch are based on porpoise removals extrapolated from electronic monitoring and observer schemes in neighboring subregions and adjusted for the Baltic Proper subpopulation (NAMMCO–IMR, 2020). OSPAR is in the process of revising marine mammal bycatch mortality limits in the context of MSFD biodiversity indicators that, when data permit, will include PBR (STECF, 2021). HELCOM produces quarterly bycatch risk

maps in Swedish waters (Glemarec et al., 2021) that combine the fishing effort of static net fisheries with seasonal maps of harbor porpoise distribution. Based on these findings, ICES proposed emergency measures that emphasize spatial closures of all fisheries of concern in the Baltic Proper (ICES, 2020a) to reduce harbor porpoise bycatch below the PBR limit of 0.7 individuals per year (NAMMCO–IMR, 2020).

Correlative analysis in the Bay of Biscay suggests that the dramatic increase in common dolphin bycatch could be driven by multiple factors, including changes in species distribution, feeding patterns, and fishing practices (Peltier et al., 2021). Apart from observer schemes, there are two approaches to estimating bycatch mortality, via drift modeling or life tables. The latter is useful – as an addition to and not replacement of on-board monitoring – but can be very biased if the catchment area is unknown but assumed to cover the whole population range. Despite this evidence, some scientists question whether reliable quantitative estimates of mortality are possible from drift modeling. Arguably, it is important to make use of all available data sources and an approach that combines both would produce mortality estimates and thus help achieve conservation goals. In the absence of E.U. policy decisions for consistently tracking removals and setting anthropogenic mortality limits, ICES (2020c) estimated dolphin bycatch rates from both strandings and observer data in the Bay of Biscay and calculated PBR levels based on a suite of management scenarios. Specifically, two precautionary anthropogenic mortality limits (below 75% and 50% of PBR) were calculated to account for high interannual variation in bycatch estimates based on removals detected by at-sea monitoring and strandings. For each scenario, forecasts of bycatch reduction, effort reduction needed, and efficiency scores were summarized based on management strategies combining temporal fisheries closures, year-round fishing effort reductions for métiers of concern, and the installation of acoustic alarms (ICES, 2020a; 2020c). This effort by ICES suggests an initial shift towards approaches for calculating bycatch thresholds in the E.U. that explicitly take uncertainty into account, such as the IWC Catch Limit Algorithm or, in this case, PBR. For both approaches, removal limits increase with more precise abundance estimates, thus providing an incentive to collect better data. Nevertheless, bycatch reduction scenarios using the PBR method may not be sufficient to meet the current E.U. legislative requirements for FCS under the Habitats Directive (ICES, 2020a).

4.3.1.4 Governance

A solid legal basis for cetacean monitoring and protection exists in Europe (Dolman et al., 2016). The E.U. embraces the precautionary principle and, as a multistate structure with agreements that exceed national boundaries, is typically more protective of marine resources. The relevant legislation states that the removal of marine mammals should not exceed predetermined levels. However, such levels have not been agreed upon by MS (Dolman et al., 2021). Consequently, no methodology for setting bycatch limits has legal status. In the U.S., strong fisheries governance relies on a stable regulatory framework, where there is both the authority and capacity for NOAA Fisheries to implement marine mammal conservation strategies (Kuiper et al., 2018). Through the TRTs mandated by law, multisectoral engagement and deliberation about available data and resources have, at times, delivered swift and meaningful action. The MMPA clearly defines measurable bycatch limits, PBR and Zero Mortality Rate Goal (ZMRG), which can be reassessed with regular monitoring and evaluation.

4.3.1.4.1 Monitoring and evaluation

As the quantitative backbone of the MMPA, the goal of PBR requires, not recommends, convening a Take Reduction Team to develop a plan for reducing bycatch when this goal is not met. Then, ongoing monitoring and evaluation gauge compliance with measures prescribed by a TRP. Despite these crucial guardrails, the system of governance according to the U.S. MMPA is not without its challenges. Team negotiations can “occur in the shadow of regulation, meaning that if necessary, the agency will create regulations without their input (McDonald and Rigling-Gallagher, 2015, p. 815)”. For instance, a boycott of the meeting for scientific members of the HPTRP followed a 2012 decision by the regional administrator to adjust the timing of closure areas, even after monitoring indicated mortality levels that exceeded PBR. Ultimately, due to a lack of team consensus, NOAA Fisheries eliminated certain closure areas initially prescribed in the plan (McDonald and Rigling-Gallagher, 2015).

While the HPTRP likely played a role in reducing bycatch levels below PBR initially, harbor porpoise removals often exceeded annual mortality limits after 2003 (Cox et al., 2007; Dawson et al., 2013). Broadly speaking, U.S. TRPs have less than a stellar track record of achieving their goals. Only two of five plans evaluated by McDonald et al. (2016a) successfully met at least one statutory requirement – i.e., bycatch below PBR or ZMRG – and maintained

diminished levels. The number of bycaught porpoises was below PBR for only half of the years following HPTRP implementation (McDonald et al., 2016a). Subsequent monitoring and evaluation determined that this uptick in bycatch rates was driven by low compliance with plan measures and interannual changes in the distribution of harbor porpoises and fisheries (Orphanides and Palka, 2013).

There are two bodies (Directorate-General; DG) in the European Commission that issue legislation that purports to address cetacean bycatch. They are the DG ENV, which is responsible for implementing and managing programs of the Habitats Directive and MSFD, and DG MARE, which is responsible for regulations associated with the CFP. However, DG ENV and MARE rarely seem to coordinate across other policy departments and arguably struggle to achieve consistency within their suites of sectoral directives and regulations. The Commission also delegates some fisheries management authority and responsibilities to individual MS, understanding they will act together in the form of a regulatory framework. Joint recommendations have been challenging to achieve (Dolman et al., 2021) because they require unanimous consent from all nations involved. Further, European institutions and policy-makers are unlikely to favor independent bodies that challenge E.U. authority (Symes, 2009). This division of responsibility has led to inconsistent policy implementation and, consequently, a lack of necessary data and reporting to support effective bycatch management.

Annex XIII of Regulation N° 1241/2019 calls for MS to monitor the implementation of provisions, but there are few guidelines on how to develop such programs or capture métiers deployed by fishing vessels less than 12m in length (Dolman et al., 2021). Compliance with the requirements of Regulation N° 812/2004 to monitor E.U. fishing operations with onboard observers was already low (Peltier et al., 2020). Given the diversity of fishing fleets operating in E.U. waters and a top-down governance structure from the CFP to its various policy directives, it is not surprising that small-scale fisheries monitoring has been inadequate, especially across the Baltic Sea and Bay of Biscay. For the latter, Peltier et al. (2021) were unable to explain the dramatic increase in bycatch of common dolphins using E.U. and national-level data alone.

4.3.1.4.2 *Mitigation measures*

Generally, the E.U. follows the precautionary principle in its policy making, which is more protective than the approach in the U.S.; there, policy making is more reactive. For instance, the

U.S. Clean Water Act (CWA) of 1972 was passed after the Cuyahoga River caught on fire because it was heavily polluted. Similar to the national standards established by the CWA, the MMPA takes a reactive approach to unsustainable bycatch levels. For example, 691 stranded harbor porpoises were reported in varying numbers from Maine to North Carolina between 1994 and 1999 (Waring et al., 2001). The HPTRT responded by prescribing the use of acoustic alarms in certain areas and seasons (McDonald et al., 2016). The addition of time-area closures in the late 1990s was estimated to reduce annual bycatch in the western section of the Gulf of Maine by more than 500 animals (Palka et al., 2008). Bycatches were less than PBR for the first time in 1999, and this coincided with plan implementation and measures to reduce overfishing of groundfish (Geijer and Read, 2013). By the turn of the century, poor compliance with HPTRP mitigation measures, especially pinger requirements, likely influenced another spike in bycatch levels (Orphanides and Palka, 2013). As a possible explanation, Palka et al. (2008) found a steady decline in pinger usage following TRP inception. Since the mid-2000s, fishers in the U.S. Gulf of Maine have resisted alarms due to costs of maintenance, inspection, and the potential for devices to malfunction (Cox et al., 2007; Geijer and Read, 2013). Without financial or other incentives from the government to ensure compliance with pinger requirements, fishers are less likely to modify their fishing practices or risk damage to gears.

E.U. Regulation N° 1241/2019 (Annex XIII) lays out scant requirements for pingers in particular fishing areas and gears, notably on bottom-set gillnets or entangling nets in the Baltic Sea. The 2019 technical measures retain similar vague language that likely hindered bycatch mitigation efforts under the previous Regulation N° 812/2004 (Dolman et al., 2021). The terminology and definitions within the latest technical measures exclude certain gear types and net lengths (Dolman et al., 2016), and some argue this is no accident. Additionally, vessel size monitoring and pinger limits have been shown to exclude the majority of E.U. fishing fleets from the provisions of the regulation, including fisheries with a higher risk of bycatch. For example, problematic gear types for cetaceans such as midwater fixed nets and trammel nets are not subject to the exact pinger requirements as bottom-set gillnets. Also, trawls with high vertical openings, net lengths greater than 400m, and other impactful fisheries can circumvent the rules (Dolman et al., 2016; Peltier et al., 2021). Similar to the U.S. example, ensuring compliance with pinger requirements is challenged by intra- and inter-annual changes in certain species-fishery interactions, and the need to maintain and monitor these devices. Enforcement is low because

this represents a substantial economic cost to the MS (STECF, 2019). In addition, bycatch mitigation recommendations from expert bodies such as ASCOBANS and ICES Bycatch Working Group (ICES WGBYC) have not been explicitly incorporated into policies underneath Regulation N° 1241/2019 (Dolman et al., 2021). The recent call by several NGOs for implementation of Fisheries Emergency Measures to reduce dolphin bycatch in the Bay ultimately led to the Commission imposing some new requirements for France and Spain. However, these actions fall short of what some consider “emergency measures” and not all have been accepted by the MS. Even if MS decline to act, all emergency measures implemented under Article 12 of Regulation N° 1380/2013 can only be applied for six months, plus a possible six-month extension (EU, 2013).

4.4 DISCUSSION

The E.U. lacks an equivalent to the regulatory framework established under the U.S. MMPA to assess and, where necessary, effectively protect marine mammals from bycatch and other anthropogenic threats. The result is two systems with different approaches to monitoring bycaught animals and requirements to respond following the detection of high levels of bycatch in listed species and strategic stocks. By implementing well-defined, quantitative objectives and targeted measures to reduce bycatch within a specified period, the U.S. system is reactive and arguably more effective. Under the precautionary principle, the goal is to stay ahead of the curve, and most agreements, scientific advice, and even E.U. policy takes this approach. For example, the legal requirements to support the implementation of management measures contained within the Habitats Directive and MSFD are intended to be a key instrument for marine conservation in E.U. waters and across its administrative boundaries (Bellas, 2014; Santos and Pierce, 2015; Laran et al., 2017). Despite lofty goals, the E.U. is generally poor at implementing existing regulations because there are few mechanisms in place to ensure MS compliance with obligations for regular monitoring and mitigating bycatch (Carlén et al., 2021). The paucity of data is a convenient cover for inaction, especially in cases where multiple MS are involved. Yet the root cause for such failures to act is simply the lack of political will (Rogan et al., 2021).

The E.U. and its constituents know the steps they need to take to address the issue of bycatch. They need to set clear, quantitative management objectives into law that can be implemented and enforced at the regional and MS level, similar to the regulatory framework

established by the U.S. MMPA. For monitoring bycatch, E.U. policy directives are clear for organizing species and habitat monitoring networks, providing guidelines for MS regarding Good Environmental Status and protection of at-risk species from anthropogenic threats such as bycatch. These are obligations not memorialized in law like the CFP, but in theory, should be transposed into legislation at the MS level. The Habitats Directive has difficulties organizing comprehensive species monitoring networks at the national and E.U. scales, as highlighted by the transnational fisheries operating in the Bay of Biscay and Baltic Proper. Such monitoring measures are the responsibility of the MS. Consequently, cetacean conservation and management efforts struggle to align with commitments under international agreements such as ASCOBANS, European environmental law, and fisheries policy (Carlén et al., 2021). Further, the renewal of lapsed procedures since the adoption of Regulation N° 2019/1241 has further eroded any requirements to accommodate on-board observers.

The U.S. regulates fisheries through a combination of competent governance and organizational resources to monitor cetacean stocks and address unsustainable bycatch rates. Notably, the legal requirements to respond to high levels of bycatch are implemented systematically and using targeted measures to reduce bycatch within a specified period. The U.S. also has dedicated funding, possibly with fewer strings attached than the E.U., to conduct regular assessments and generate an appropriate management structure with adequate resources for enforcement (Read, 2013; Rogan et al., 2021). While flawed, the Take Reduction Plan initiated by the MMPA for harbor porpoises of the U.S. Gulf of Maine and the broader Mid-Atlantic region was found by many stakeholders to align policy outcomes with ecological outcomes (McDonald et al., 2016b). Moreover, the combination of comprehensive requirements for harbor porpoise monitoring, available data on historical change in species distribution and abundance, and the potential for scaling (i.e., merging the Gulf of Maine and Mid-Atlantic into one plan) suggest that the HPTRP process is a modest success story.

Unless they are amended, the current E.U. governance structure is unlikely to achieve the broad conservation objectives of the CFP, MSFD, and Habitats Directive. Fisheries policy should implement coherent laws that support socio-economic incentives and, at the same time, consistently enforce the regulations (Keane et al., 2008; Da Rocha et al., 2012). The European Commission has not adequately exercised its authority to punish MS for noncompliance. There are “tensions between those who favor a loosening of the bonds of central management and those

who fear its consequences (Symes, 2009, p. 102)”. A recent letter to Brussels from E.U. Commissioner, Virginijus Sinkevičius, highlights the critically endangered Baltic harbor porpoise subpopulation and reiterates the scientific advice for management action (HELCOM, 2020). It underscores a systematic failure by the European Commission to enforce regulations relevant to bycatch or follow recommendations from ICES, SCTEF, OSPAR, HELCOM, and other scientific bodies. Ultimately, consistent implementation of policies by MS, and enforcement by the Commission, is needed to leverage and integrate existing data and systems across national boundaries so that investments in bycatch monitoring and mitigation align with policy mandates, stakeholder feedback, and scientific advice (Dolman et al., 2016).

4.4.1 Necessary steps to make E.U. measures comparable to the U.S. MMPA

The legislative requirements of the Habitats Directive and MSFD are clear that cetacean monitoring and bycatch mitigation needs to adequately protect marine resources for current and future generations. For example, Article 17 of the Habitats Directive requires E.U. MS to report on the conservation status of listed species. In addition, many expert working groups (e.g., NAMMCO, ICES, HELCOM, ASCOBANS) provide specific recommendations for managing small cetacean bycatch in the Baltic Proper and Bay of Biscay. They emphasize that monitoring should estimate the annual cetacean mortality rate across all fisheries of bycatch concern (see **Table 12**). Yet, most scientific advice lacks the legal status to ensure that recommendations are adopted. Cetaceans are transnational species, and ICES (2020b) recommends that MS assess the distribution, abundance, and mortality rates at the population level, not nationally as required by E.U. policy directives. To do this assessment, MS would need to implement bycatch monitoring programs that utilize dedicated studies, with mandatory at-sea observers or remote electronic monitoring, regardless of vessel size (Dolman et al., 2016; Course, 2021). Absolute abundance estimates can improve the accuracy of quantitative analyses for setting bycatch removal limits (Saavedra et al., 2018) and, at the same time, fulfill MSFD requirements. This level of observation and assessment would require a substantial commitment from fishers and the MS to fund the abundance surveys, as effectively monitoring bycatch can only be achieved through their direct involvement to identify and implement strategies that are likely to be adopted (Brownell et al., 2019).

International cooperation is essential to achieve conservation objectives via the MSFD

and Habitats Directive of Good Environmental Status (GES) and Favorable Conservation Status (FCS). Monitoring should be more collaborative and focus initially on species at risk of losing GES/FCS in a particular region; for example, common dolphins in the Bay of Biscay and the endangered Baltic Proper porpoise. Based on a regional review of threats to marine mammals (ICES, 2019), bycatch threat levels are considered high for common dolphins in the Bay of Biscay. Yet, E.U. conservation objectives are not sufficiently specific and it is unclear exactly where or how to implement appropriate management measures (Read, 2021). More frequent surveys to detect mortality events and stricter rules for reporting bycatch and fishing effort are necessary to improve bycatch mitigation (Saavedra et al., 2018; Wade et al., 2021).

For both E.U. case studies analyzed here, the ongoing work to measure fishing effort and set mortality thresholds in a meaningful and consistent manner should be prioritized and completed. Fishing effort is now a mandatory field within the Regional Database and Estimation System exchange format and reported in the ICES database as the number of trips and days at sea (NAMMCO-IMR, 2019). To be as effective as the U.S. MMPA, removal limits need to be specific about timescale for recovery – e.g., reducing levels of bycatch should allow the population to either recover to, maintain at, or stay above 50% of PBR – and use a method that explicitly takes uncertainty into account and is robust to common biases with the estimates (Taylor et al., 2000; Wade et al., 2021). OSPAR suggests using three generations as a timescale for recovery but this can imply a very slow recovery, reserved for larger cetaceans (Taylor et al., 2007), and would be difficult to measure given the six-year periodicity for FCS assessment in the Habitats Directive.

The Technical Measures of E.U. Regulation N° 2019/1241 are tools to support the implementation of the CFP, a flawed legacy from the previous Regulation N° 812/2004 (Dolman et al., 2021; Peltier et al., 2021). Measures to mitigate cetacean bycatch should be guided by expert knowledge of the local environment and fisheries operational factors that influence bycatch rates (Dolman et al., 2016). The E.U. should identify and adopt mitigation measures greater in coverage (area and gear types) and use definitions that are difficult for fishers to circumvent. For example, the requirement of pingers on vessels with nets less than 400 m in length can be dodged by extending nets (Dolman et al., 2016). While acoustic alarms can significantly reduce cetacean bycatch rates, as observed in U.S. gillnet fisheries (Carretta and Barlow, 2011), their efficacy varies by species (Nelms et al., 2021), and modifications to most

fishing practices have economic costs (Carlén et al., 2021). In addition, devices can malfunction and, in the case of the U.S. Gulf of Maine, fisher compliance with the requirements was tenuous (Palka et al., 2008). To increase the effectiveness of technical measures, the E.U. should adapt its governance structure so that MS, the fishing industry, and other stakeholders are obligated to negotiate through science-policy bottlenecks and reach consensus on locally-supported interventions. Such a partnership could be modeled after take reduction planning in the U.S., which specifies the agreed-upon management steps and by when. In parallel, consultations with fishers' organizations to support trials, education campaigns, and monitoring programs to harness market initiatives that incentivize bycatch reduction via certification schemes (MSC, 2018; SFW, 2020) would enhance community support and responsibility.

4.4.2 Advancing bycatch management through risk assessment

Assessing the impacts of bycatch requires an understanding of the conditions under which animals are captured that can vary based on changes in the demographics and seasonal distribution of resident cetacean populations and active fisheries (Learmonth et al., 2014; Brown et al., 2015). In many cases, bycatch assessment suggests the necessary steps for systematic monitoring that detects species-fishery interactions where and when risk is most severe. For example, to estimate the relative risk of bycatch for vulnerable cetaceans of Northern Europe, Evans et al. (2021) combined density maps of AIS fishing pressure and species distribution, albeit at the regional scale. There are now calls for localized risk assessment (see Dolman et al., 2016; ICES, 2020b) that also draw on cetacean strandings data, although this approach has both supporters and detractors in the E.U. Given the dynamic changes in cetacean distributions and inconsistent measures of fishing effort across the E.U., spatially explicit assessment of bycatch risks can assist managers in three distinct ways. First, it pinpoints where bycatch exposure to cetaceans is highest across a range of problematic fisheries, enabling managers to identify information gaps and prioritize future monitoring, research, and engagement. It also compares the impacts of likely bycatch events based on species' sensitivity to specific gears, their overall resilience, and demographic characteristics over space and time. Finally, based on the contribution of exposure and consequence to risk across subregions and seasons, managers can translate these findings into specific action plans that enumerate the necessary steps for effectively monitoring and minimizing bycatch. Holistically, the approach focuses limited

capacity towards monitoring potentially harmful interactions to facilitate a more timely response to unsustainable bycatch levels.

4.4.2.1 Bycatch monitoring and reporting

E.U. MS are obligated by the Habitats Directive to report on the conservation status of listed cetaceans every six years. This requires assessments using data on their range and habitats, which depends on monitoring changes in distribution and abundance at the population level (SAMBAH, 2016; Carlén et al., 2018). Because small cetaceans are highly mobile and regularly cross international boundaries, multinational cooperation is needed to achieve accurate reporting. During the reproduction period (May to October), harbor porpoises were present in the vicinity of offshore banks, along the border region of the central Baltic Proper, in what appears to be a previously unknown breeding ground for this subpopulation (Carlén et al., 2018). For small subpopulations such as the Baltic Proper harbor porpoise, Curtis and Caretta (2020) caution that species interactions are difficult to capture with fishery observer programs and can be anticipated through a complimentary risk assessment approach. As only a few hundred porpoises remain in the area, it will be critical to identify the summer extent of Baltic Proper breeding grounds and further define the management border that separates the Belt Sea subpopulation (Sveegaard et al., 2015).

For common dolphins of the Bay of Biscay, where both abundance and bycatch numbers per year are higher than porpoises of the Baltic, remote electronic monitoring, supported by a random sampling strategy, is crucial for adding to existing knowledge of high-risk fishery interactions (Dolman et al., 2021). Dedicated cetacean bycatch observer and remote monitoring programs should focus on métiers and areas with the strongest evidence of mortality, as is the case under the U.S. MMPA for certain commercial fisheries interacting with strategic stocks of marine mammals. For example, the Northeast Fisheries Observer Program places at-sea observers on a tiny number of fishing trips (4%) that sample the U.S. Gulf of Maine representatively to estimate bycatch for the entire fishery and monitor progress towards management goals (Orphanides and Palka, 2013). Monitoring the effectiveness of bycatch management strategies in the U.S is only possible because observers collect detailed information on the trips, vessels, gears, functionality of mitigation devices, and bycatch mortality (Orphanides and Palka, 2013). To reduce the coverage requirements of costly monitoring

schemes in the E.U., bycatch risk assessment can guide monitoring efforts and produce data to complement existing bycatch estimation databases. Armed with these insights and more explicit conservation targets, E.U. MS – supported by the scientific community – could develop sampling procedures, establish standard formats for data storage and reporting, and design techniques for setting mortality thresholds compatible with E.U. legislation (ICES, 2020b).

4.4.2.2 Spatio-temporal patterns of bycatch risk

Across all three cases, cetacean exposure to bycatch risk is driven by local fishing practices (i.e., gear type usage and density), prey and species distribution, and compliance with legal mandates. Bottom-set gillnets, trammel nets, and pursue seines or midwater/bottom trawlers with high vertical heights and opening, were identified as fishing gears of greatest bycatch concern to the small cetaceans discussed in this study (Read, 2013; Brownell et al., 2019; Peltier et al., 2020). The management of harbor porpoise bycatch is furthest along in the U.S. Gulf of Maine due to clear conservation goals (reference points/thresholds), adequate information, greater involvement of stakeholders, and monitoring since HPTRP inception. Dynamic ocean management techniques that account for changes in the distribution of species and fisheries, seasonal closures, and compliance with technical measures could support efforts to monitor these bycatch risk factors in real-time (Hazen et al., 2018), including relevant oceanographic variables such as sea-surface temperature and the winter North Atlantic Oscillation index value (Orphanides and Palka, 2013), which show wide interannual variation in the U.S. Gulf of Maine and Mid-Atlantic.

For the fisheries positively correlated with the recent surge in common dolphin mortality in the Bay of Biscay, Peltier et al. (2021) concluded that change in the fishing effort was likely a factor. However, this trend was undetected based on current data collection and research methodologies deployed by the E.U. and its scientific community. Despite these information gaps and the diversity of fisheries operating in the Bay, this should not hinder new data collection and assessments of the feasibility of management strategies to minimize bycatch. For example, 500,000 Euros have been allocated to aerial observation programs for surveying the distribution and abundance of common dolphins during the winters of 2020 and 2021 (Ministry of the Sea, 2021). Researchers could leverage these surveys to build seasonal habitat models that account for changes in environmental conditions that influence prey abundance (Verutes et al., 2021). Bay of Biscay fishers are willing to engage with scientists and contribute to the data

collection process (e.g, self-reports of fishing effort and gear use), but also question the statistics regarding problematic fisheries and métiers (M. Authier, personal communication, February 23, 2021). Currently, and without further discussion among fishers and government officials, the time-area closures recommended by ICES appear to be the only strategy to meet E.U. requirements for bycatch reduction (ICES, 2020a; Peltier et al., 2021).

Bycatch remains one of the main threats to the harbor porpoises of the Baltic Proper population, along with impacts from noise and marine pollution (SAMBAH, 2016; NAAMCO-IMR, 2019). Spatio-temporal risk assessment has previously examined the overlap between harbor porpoises and static net fishing activities (Kindt-Larsen et al., 2016). Monitoring and evaluation should focus on the Swedish EEZ to ensure swift action to protect Baltic Proper porpoises, as most summer detections of this subpopulation occurred within this area (Carlén et al., 2021). Carlén et al. (2018) identified two main areas with a high probability of porpoise detection in the Baltic Proper during the reproductive season. As additional high-risk areas are identified, targeted bycatch mitigation measures could include replacing gillnets with less impactful gears and seasonal fisheries closures in critical habitat areas (Carlén et al., 2018). Further, an acoustic alert device (Porpoise ALarm or “PAL”) that produces synthetic communication signals is a promising technology to mitigate harbor porpoise bycatch (Culik et al., 2015). Tests in operational gillnet fisheries indicate a 65% reduction in bycatches in the western Baltic (Chladek et al., 2020). Nevertheless, the situation has become complicated by the Swedish Navy with the support from other navies and Baltic MS governments. They insist that introducing pingers as a mitigation measure interferes with active sonar’s submarine detection capabilities (P. Evans, personal communication, January 5, 2022). It is unclear if evidence about this potential interference will be presented at high-level meetings with acousticians.

Table 12. Existing information from international policies, agreements, scientific advice, and the literature for the three case studies mapped to certain bycatch risk exposure and consequence attributes as introduced by Verutes et al. (2020).

Risk Attribute	Common dolphins (Bay of Biscay)	Harbor porpoises (Baltic Proper)	Harbor porpoises (U.S. Gulf of Maine)
<p>Spatial-temporal overlap</p> <p>(Likelihood of interaction between species and fishery)</p>	<ul style="list-style-type: none"> Regional abundance monitoring by SCANS surveys; decadal interval; smaller-scale, national surveys in France/Spain complete or in progress Fishing distribution/intensity of effort tracked by VMS for certain gear groupings and vessels >12 m; potential AIS data source in fishing vessels >15 m At least three-quarters of stranded common dolphins on the French Atlantic coast with evidence of bycatch originated along the continental shelf of the Bay of Biscay Recent increase in strandings mostly likely originated from mortality in ICES fishing subareas 27.8.a and 27.8 	<ul style="list-style-type: none"> SAMBAH project estimates porpoise densities and abundance in 5-80 m depth range of the Baltic Sea Baltic Proper subpopulation is spatially-distinct from Belt Sea subpopulation during the breeding season (May to October); probable mixing in the SW Baltic during winter months Relative to the Belt subpopulation, Baltic Proper porpoises are adapted to forage in deeper waters High degree of overlap observed between static net fisheries in Natura 2000 sites and within the seasonal distribution ranges of the Baltic Proper subpopulation 	<ul style="list-style-type: none"> Harbor porpoise abundance and removals by Category I/II commercial vessels (e.g., sink gillnet and midwater/bottom trawls) available in stock assessment and mortality reports Changes in two environmental variables (sea-surface temperature and the winter North Atlantic Oscillation index value) have been identified as likely drivers of overlap between high-risk fishing gears and harbor porpoise distribution
<p>Likelihood of capture by fishing gear</p> <p>(Net length, soak time, set height, mesh strength, etc.)</p>	<ul style="list-style-type: none"> Gears with high vertical heights (gillnet, purse seines) or openings (trawls) Fisheries targeting predatory fishes in winter such as cod and hake Static nets (gillnets and trammel nets) accounted for 50% of incidental catches between 2016 and 2018 	<ul style="list-style-type: none"> Static nets, especially gillnets and trammel nets, are gears used by fishing vessels with the highest reported removals of harbor porpoises 	<ul style="list-style-type: none"> Static nets are considered to have the highest likelihood of harbor porpoise capture as compared to other operational gears Gillnets are 90 m in length (strings of up to 20 nets) and can soak for 24 hours; Due to differences in the currents, Gulf of Maine arrays of nets are much longer than those used in the Bay of Fundy

Management identified, implemented, or enforced

Identified

- Pingers on midwater and bottom pair trawlers when temporal closures are not in effect and assuming they perform well in trials
- Temporal closures in Subarea 8 for métiers of greatest concern (pair and otter trawls, gillnets)
- Bycatch reduction scenarios of individual and combined closures and acoustic alarms for high-risk gears and seasons
- Dedicated bycatch observers and/or REM of all fishing vessels that experience year-round common dolphin bycatch

Implemented

- Mandatory reporting all accidental captures in French EEZ since 2011; not enforced until 2019
- Infringement procedures by the European Commission (EC) against France and Spain, following emergency measures requested by NGOs

Identified

- Closure of gillnet fisheries in the rest of the Natura 2000 area “Hoburgs bank och Midsjöbankarna” and other Natura 2000 areas east of 13.5° E
- Mandatory use of acoustic alarms in all commercial gillnet fisheries outside Natura 2000 areas within seasonal distribution of the species
- HELCOM adopted Recommendation 17/2 on the Protection of harbor porpoise in the Baltic Sea Area in 1996
- The ASCOBANS Recovery Plan for Baltic Harbor Porpoises (Jastarnia) was adopted in 2003

Implemented

- Natura 2000 sites within Baltic Proper population range were designated in 2001-2002 by Poland, in 2004 and 2007 by Germany, 2009 by Denmark, and 2016 by Sweden
- EC started infringement procedures against Sweden

Implemented

- TRT formed when mortality rates exceed PBR (HPTRP first implemented in 1998)
- Vessels of a Category I or II fishery must accommodate observers on board upon request
- Modified/authorized based on TRT/TRP. For example, closure of the Northern Midsea Bank to all fisheries, with the exception of passive gears proven not to bycatch harbor porpoise (this includes pots, traps, and longlines, but excludes static nets equipped with pingers or other acoustic devices)

Enforced

- NOAA Fisheries administers the provisions on cetaceans
 - The monitoring of the application of the MMPA, TRT, TRPs and its enforcement is the competence of the U.S. Federal Government
-

Local conservation status of species	<ul style="list-style-type: none"> • According to Article 11 of Habitats Directive: “species of community interest in need of strict protection” • In 2019, MS reporting for Article 17 requirements of the Habitats Directive, classified the conservation status of Northeast Atlantic common dolphins as either “Unknown” or “Unfavourable-Inadequate”; only one E.U. MS reported its status as “favourable” within their national waters • No baselines or reference levels for population abundance or bycatch mortalities established by MS against which the conservation status of population can be assessed; ICES and OSPAR are offering proposals 	<ul style="list-style-type: none"> • In 1992, listed in Annexes II and IV of the Habitats Directive (priority species and animal species of Community interest whose conservation requires the designation of special areas of conservation) • In 2008, the Baltic harbor porpoise was listed as Critically Endangered by the IUCN and decreasing population trend • All E.U. MS assessments and the E.U. biogeographical assessment of conservation status of harbor porpoise in the Baltic Marine Region classified the Baltic Proper HP as “Unfavourable-Bad” 	<ul style="list-style-type: none"> • Not considered endangered or threatened and, therefore, not listed under the Endangered Species Act • Designated as a strategic stock by the U.S. MMPA
---	---	---	---

4.4.2.3 Management and action plans

A more straightforward strategy for E.U. MS to take immediate action in the monitoring and mitigation of small cetacean bycatch is needed. For instance, MS can leverage the resources of Regional Fisheries Management Organizations (RFMO) to improve bycatch management through expanded at-sea observer programs, standardized data collection, and mitigation trials. However, RFMOs depend on technical capacity and political will to address unsustainable bycatch (Lewison et al., 2011), and pathways towards stakeholder engagement in the E.U. can be obscured by red tape and political distrust. For example, in the Bay of Biscay, two independent seasonal trends of increasing cetacean strandings and fishing effort were incorrectly conflated, leading to a 2002 ban on the driftnet fishery (Authier et al., 2021). Notably, ICES has identified anthropogenic mortality limits for both E.U. cases discussed in this paper. Across most management scenarios analyzed, the current mortality levels exceed PBR. Seasonal fishing closures in the Bay of Biscay could achieve the E.U. requirements for bycatch reduction (Peltier et al., 2021), especially if they are required as a routine solution. However, any emergency measures closure does not represent a long-term solution and, if implemented, would last for

only 6 to 12 months. The Commission could close fisheries under the authority of Article 26(4) of Council Regulation N° 2371/2002 and withhold funding as a last resort.

Given the dire status of the Baltic Proper harbor porpoise (NAAMCO-IMR, 2019), urgent action is needed to implement management strategies and scientific advice as guided by multisectoral engagement and bycatch risk mapping. Low abundance levels and persistent anthropogenic threats to this subpopulation (SAMBAH, 2016) underscore the need for the Baltic Range States to provide strict protections that effectively minimize porpoise mortality and conserve critical habitats. Despite the identification of multiple Natura 2000 sites, no conservation measures or management plans have been implemented within or in the vicinity of these sites (Carlén et al., 2021). The Habitats Directive requires Special Areas of Conservation (SACs) for harbor porpoises. Although a substantial proportion of the Baltic Proper has been designated for protection, it is the SACs coupled with appropriate management plans that represent the best hope for improving the conservation status of the Baltic harbor porpoise (Carlén et al., 2021). Even as the European Commission begins to implement emergency fishing closures, the German Federal Ministry of Food and Agriculture has failed to recognize Baltic Proper porpoises as a separate subpopulation unit. Failure to acknowledge this has effectively blocked its listing in the Convention on Migratory Species, Appendix I. The German Ministry is also unwilling to completely ban static nets within protected areas because it could jeopardize traditional net fisheries (Carlén et al., 2021). Low observer coverage (<1%), scant knowledge on species distribution, and patchy availability of information on operational small-scale fisheries also limit conservation action in the region (F. Ritter, personal communication, March 24, 2021).

Regardless of regional factors or regulations, fishers will participate in finding solutions if given the right approach. Back the industry into a corner or depict them as the enemy and they will resist, especially if the monitoring and mitigation solutions are unduly burdensome and expensive (Read, 2013). Overall, fisheries need to be economically profitable in the short term, while sustainable and viable over the longer term (Read, 2021). A more durable solution to unsustainable cetacean bycatch without jeopardizing fisher livelihoods is the development of efficient and inexpensive fishing gears to replace static nets (Leaper and Calderan, 2018). For example, to minimize the depredation of gillnets, the Baltic inshore cod fishery switched from nets to pots during part of the year (Königson et al., 2015). Gear switching and modifications are also likely to be met with resistance, especially in traditional fisheries where techniques often

date back generations. Action plans on cetacean bycatch should include wide-ranging and credible cost-benefit analysis (Dolman et al., 2016), since fishers will not embrace solutions which reduce their income and well-being. In the U.S. example, GIS analysis estimated the cost of closing an area to fishing. Economic information, available on a monthly basis and presented to stakeholders in terms of lost fish landings, was used to explore potential time-area closures to address the bycatch of harbor porpoises in the Gulf of Maine (Read, 2013). Benefits can also be improved via market initiatives that link cooperation on incidental bycatch with incentives and seafood certification schemes (e.g., MSC, 2018; SFW, 2020). Until measures to effectively minimize bycatch are embraced by fisheries organizations, stricter enforcement of the regulations – such as gillnet bans or other restrictions even at the cost of efficiency – may be the only way to save endangered species from extinction in the near term (Brownell et al., 2019).

4.5 CONCLUSION

Regulatory measures to manage cetacean bycatch in the E.U. and U.S. are challenged by the need to reconcile ecological, economic, and political objectives that are often in conflict. This paper analyzes how current legal instruments are performing with regard to addressing unsustainable mortality levels and summarizes existing knowledge about small cetacean bycatch risk factors in three comparative case studies. While the overall trend is alarming, especially in the E.U., there are encouraging signs of transnational and cross-sectoral cooperation to balance competing objectives. Our analysis revealed that successful bycatch reduction plans were the product of straightforward legal mandates that support the implementation of policies and international agreements. In the U.S., this is achieved with quantifiable conservation goals under the MMPA. Progress is tracked based on established biological reference points and adequate scientific information. The U.S. Harbor Porpoise Take Reduction Plan leveraged stakeholder engagement, early and often, and included a post-implementation monitoring program.

The regulated community constantly adapts to policy by changing its practices. Therefore, environmental regulations need to evolve to more effectively protect vital resources. It is unclear how the E.U. will respond to the new import rule that requires countries exporting seafood to the U.S. to demonstrate that their approach to managing marine mammal bycatch is equivalent to that mandated by the MMPA (Williams et al., 2016). This reporting process has focused attention on the shortcomings of the European system and whether or not the E.U. can

convince NOAA that the CFP is no different than the MMPA. The recent call for Fishery Emergency Measures to address unsustainable levels of small cetacean bycatch provides an example of how things currently work (or do not) under the regulatory framework of the E.U. The current deficiencies result from E.U. fisheries legislation having a poor habit of stating the goal but not the means to achieve it; perhaps to avoid responsibilities for Member States in applying and enforcing policies they do not want to implement. Nevertheless, the Bay of Biscay and Baltic Proper are suitable areas for localized bycatch risk assessment because robust spatial information on the distribution of problematic fisheries already exists. Additionally, the increasing rates of cetacean bycatch are likely the result of changes in fishing practices not currently monitored by the E.U. or its Member States.

Change takes time, and getting data to advance policy implementation and initiate management action is no exception. On its face, bycatch may appear to be a technical problem, but it is mainly political. Politics can drive progressive reform, especially in conservation issues. From this perspective, effective bycatch management needs to stay ahead of any negative curve – by turning existing information into action – rather than waiting for science or public opinion to catch up. The whole point of the precautionary principle is to implement policies that are conservative enough that they do not allow stocks to collapse. Yet, there are few E.U. regulatory mechanisms to translate vague and non-binding policy directives into action. Even with overwhelming evidence collected via drift modeling in the Bay of Biscay or acoustic monitoring in the Baltic Sea, systematic bycatch monitoring, assessment, and reporting is an afterthought.

There is a genuine willingness, at least in some parts of the fishing sector, to tackle the bycatch problem. Nevertheless, industry lobbying – and the default position that fisheries ministries are there to serve fisheries and not conservation – has arguably been why the Member States rejected some of the measures that the Commission required them to implement. The recently proposed management strategies to save the critically endangered Baltic harbor porpoise from extinction may be effective. However, if governments do not act and comply with the regulations and international commitments, will it be too late? The hope is that political leaders, stakeholders, and decision-makers decide to prioritize the fight so that successful forms of negotiation, persuasion, and innovation can take root.

4.6 REFERENCES

- Anderson, R. C., Herrera, M., Ilangakoon, A. D., Koya, K. M., Moazzam, M., Mustika, P. L., & Sutaria, D. N. (2020). Cetacean bycatch in Indian Ocean tuna gillnet fisheries. *Endangered Species Research*, 41, 39-53.
- ASCOBANS. (2019). Species Action Plan for the North-East Atlantic Common Dolphin (*Delphinus delphis*), Available at: https://www.ascobans.org/sites/default/files/document/ascobans_common-dolphin-sap_aug2019_0.pdf
- Authier, M., Peltier, H., Dorémus, G., Dabin, W., Van Canneyt, O., & Ridoux, V. (2014). How much are stranding records affected by variation in reporting rates? A case study of small delphinids in the Bay of Biscay. *Biodiversity and conservation*, 23(10), 2591-2612.
- Authier, M., Rouby, E., & Macleod, K. (2021). Estimating cetacean bycatch from non-representative samples (I): a simulation study with regularized multilevel regression and post-stratification. *Frontiers in Marine Science*, 1459.
- Bærum, K. M., Anker-Nilssen, T., Christensen-Dalsgaard, S., Fangel, K., Williams, T., & Vølstad, J. H. (2019). Spatial and temporal variations in seabird bycatch: Incidental bycatch in the Norwegian coastal gillnet-fishery. *PloS one*, 14(3), e0212786
- Baltic Marine Environment Protection Commission (HELCOM). (2019). HELCOM Recommendation 17/2: Protection of Harbour Porpoise in the Baltic Sea Area. Available at: <https://www.helcom.fi/wp-content/uploads/2019/06/Rec-17-2.pdf>
- Baltic Marine Environment Protection Commission (HELCOM). (2020). Letter from the EU Commissioner addressing by-catch in EU waters. Available at: <https://portal.helcom.fi/meetings/FISH%2011-2020-687/MeetingDocuments/8-2%20Letter%20from%20the%20EU%20Commissioner%20addressing%20by-catch%20in%20EU%20waters.pdf>
- Barratclough, A., Smith, C. R., Gomez, F. M., Photopoulou, T., Takeshita, R., Pirota, E., et al. (2021). Accurate Epigenetic Aging in Bottlenose Dolphins (*Tursiops truncatus*), an Essential Step in the Conservation of at-Risk Dolphins. *Journal of Zoological and Botanical Gardens*, 2(3), 416-420.
- Bartholomew, D. C., Mangel, J. C., Alfaro-Shigueto, J., Pingo, S., Jimenez, A., & Godley, B. J. (2018). Remote electronic monitoring as a potential alternative to on-board observers in small-scale fisheries. *Biological Conservation*, 219, 35-45.
- Bellas, J. (2014). The implementation of the Marine Strategy Framework Directive: Shortcomings and limitations from the Spanish point of view. *Marine Policy*, 50, 10-17.
- Benaka, L. R., & Dobrzynski, T. J. (2004). The national marine fisheries service's national bycatch strategy. *Marine Fisheries Review*, 66(2), 1-8.
- Benke, H., Bräger, S., Dähne, M., Gallus, A., Hansen, S., Honnef, C. G., et al. (2014). Baltic Sea harbour porpoise populations: status and conservation needs derived from recent survey results. *Marine Ecology Progress Series*, 495, 275-290.
- Berggren, P., Wade, P. R., Carlström, J., & Read, A. J. (2002). Potential limits to anthropogenic mortality for harbour porpoises in the Baltic region. *Biological Conservation*, 103, 313-322.
- Berkes, F. (2007). Community-based conservation in a globalized world. *Proceedings of the National academy of sciences*, 104(39), 15188-15193.
- Brown, S.L., Reid, D. and Rogan, E. 2015. Spatial and temporal assessment of potential risk to cetaceans from static fishing gears. *Marine Policy*, 51: 267-280.
- Brownell, R. L., Reeves, R. R., Read, A. J., Smith, B. D., Thomas, P. O., Ralls, K., et al. (2019). Bycatch in gillnet fisheries threatens Critically Endangered small cetaceans and other aquatic megafauna. *Endangered Species Research*, 40, 285-296.
- Baltic Sea Advisory Council (BSAC). (2021). News for BSAC member organisations for November-December 2021. Available at: http://www.bsac.dk/getattachment/Home/Message9Nov_DecfinalREVREV.pdf.aspx?lang=en-GB

- Calderan, S., & Leaper, R. (2019). Review of harbour porpoise Bycatch in UK Waters and Recommendations for Management. Nairobi: United Nations Environment Programme. Available at: https://d2ouvy59p0dg6k.cloudfront.net/downloads/cms_report_042918_web_pages.pdf.
- Campbell, L. M., Cornwell, M. L. (2008). Human dimensions of bycatch reduction technology: current assumptions and directions for future research. *Endangered Species Research*, 5:325-334.
- Cañadas, A., Donovan, G. P., Desportes, G., & Borchers, D. L. (2009). A short review of the distribution of short-beaked common dolphins (*Delphinus delphis*) in the central and eastern North Atlantic with an abundance estimate for part of this area. *NAMMCO Scientific Publications*, 7, 201-220.
- Cardoso, P., 2012. Habitats Directive species lists: urgent need of revision. *Insect Conserv. Div.* 5, 169–174.
- Carretta, J. V., & Barlow, J. (2011). Long-term effectiveness, failure rates, and “dinner bell” properties of acoustic pingers in a gillnet fishery. *Marine Technology Society Journal*, 45(5), 7-19.
- Carlén, I., Thomas, L., Carlström, J., Amundin, M., Teilmann, J., Tregenza, N., et al. (2018). Basin-scale distribution of harbour porpoises in the Baltic Sea provides basis for effective conservation actions. *Biological Conservation*, 226, 42-53.
- Carlén, I., Nunny, L., & Simmonds, M. P. (2021). Out of sight, out of mind: how conservation is failing European porpoises. *Frontiers in Marine Science*, 8, 13.
- Chladek, J., Culik, B., Kindt-Larsen, L., Albertsen, C. M., & von Dorrien, C. (2020). Synthetic harbour porpoise (*Phocoena phocoena*) communication signals emitted by acoustic alerting device (Porpoise ALert, PAL) significantly reduce their bycatch in western Baltic gillnet fisheries. *Fisheries Research*, 232, 105732.
- Christiansen, F., Vivier, F., Charlton, C., Ward, R., Amerson, A., Burnell, S., & Bejder, L. (2018). Maternal body size and condition determine calf growth rates in southern right whales. *Marine Ecology Progress Series*, 592, 267-281.
- Course, G. P. (2021). Monitoring Cetacean Bycatch: An Analysis of Different Methods Aboard Commercial Fishing Vessels. ASCOBANS Secretariat, Bonn, Germany. ASCOBANS Technical Series No.1. Available at: https://www.ascobans.org/sites/default/files/document/ascobans_ac26_inf2.5b_bycatch-monitoring-methods-analysis.pdf
- Cox, T. M., Lewison, R. L., Žydelis, R., Crowder, L. B., Safina, C., & Read, A. J. (2007). Comparing effectiveness of experimental and implemented bycatch reduction measures: the ideal and the real. *Conservation Biology*, 21(5), 1155-1164.
- Culik, B., Dorrien, C., & Conrad, M. (2015). Porpoise Alerting Device (PAL): Synthetic harbour porpoise (*Phocoena phocoena*) communication signals influence behaviour and reduce by-catch. Von Nordheim & Wollny-Goerke (Hrsg.): *Progress in marine conservation in Europe*, 150-156.
- Curtis, K. A., & Carretta, J. V. (2020). ObsCovgTools: Assessing observer coverage needed to document and estimate rare event bycatch. *Fisheries Research*, 225, 105493.
- D’Agrosa, C., Lennert-Cody, C. E., Vidal, O. (2000). Vaquita bycatch in Mexico’s artisanal gillnet fisheries: driving a small population to extinction. *Conservation Biology*, 14:1110–1119.
- Da Rocha, J. M., Cerviño, S., & Villasante, S. (2012). The common fisheries policy: an enforcement problem. *Marine Policy*, 36(6), 1309-1314.
- Dawson, S., Fletcher, D., & Slooten, E. (2013). Habitat use and conservation of an Endangered dolphin. *Endangered Species Research*, 21(1), 45-54.
- Deporte, N., Ulrich, C., Mahévas, S., Demanèche, S., & Bastardie, F. (2012). Regional métier definition: a comparative investigation of statistical methods using a workflow applied to international otter trawl fisheries in the North Sea. *ICES Journal of Marine Science*, 69(2), 331-342.
- Dolman, S., Baulch, S., Evans, P. G., Read, F., & Ritter, F. (2016). Towards an EU action plan on cetacean bycatch. *Marine Policy*, 72, 67-75.
- Dolman, S. J., Evans, P. G. H., Ritter, F., Simmonds, M. P., & Swabe, J. (2021). Implications of new technical measures regulation for cetacean bycatch in European waters. *Marine Policy*, 124, 104320.
- European Commission (2008). 56/EC of the European Parliament and of the Council: Establishing a

- framework for community action in the field of marine environmental policy. Official Journal of the European Union, 51, 19-40.
- European Commission (2020). July infringement package: key decisions. Infringement decisions, 2 July 2020. Available at: https://ec.europa.eu/commission/presscorner/detail/en/INF_20_1212
- European Union (EU). (2013). Regulation (EU) No 1380/2013 of the European Parliament and of the Council of 11 December 2013 on the Common Fisheries Policy, amending Council Regulations (EC) No 1954/2003 and (EC) No 1224/2009 and repealing Council Regulations (EC) No 2371/2002 and (EC) No 639/2004 and Council Decision 2004/585/EC. Official Journal of the European Communities, No. L 354: 22–61. Available at: <http://data.europa.eu/eli/reg/2013/1380/oj>
- Evans, P. G. H., & Baines, M. E. (2013). A methodology to assess the sensitivity of marine mammals to different fishing activities and intensities (No. 12/6). CCW Policy Research Report.
- Evans, P. G., & Similä, T. (2018). Progress report on the Jastarnia Plan: The recovery plan for the harbour porpoise in the Baltic proper. In 24th ASCOBANS Advisory Committee Meeting AC24/Doc (Vol. 3).
- Evans, P. G. H., Carrington, C. A., & Waggitt, J. J. (2021) Risk Mapping of Bycatch of Protected Species in Fishing Activities. Sea Watch Foundation & Bangor University, UK. European Commission Contract No. 09029901/2021/844548 ENV.D.3.
- Fernández-Contreras, M. M., Cardona, L., Lockyer, C. H., & Aguilar, A. (2010). Incidental bycatch of short-beaked common dolphins (*Delphinus delphis*) by pairtrawlers off northwestern Spain. ICES Journal of Marine Science, 67(8), 1732-1738.
- Geijer, C. K., & Read, A. J. (2013). Mitigation of marine mammal bycatch in US fisheries since 1994. Biological Conservation, 159, 54-60.
- Glemarec, G., Königson, S., & Kindt-Larsen, L. (2021). Bycatch in Baltic Sea commercial fisheries: High-risk areas and evaluation of measures to reduce bycatch. Available at: <https://portal.helcom.fi/workspaces/ACTION-164/ACTION%20reports%20final%20review/Work%20package%201%20-%20Bycatch/Bycatch%20in%20Baltic%20Sea%20commercial%20fisheries.pdf>
- Goetz, S., Read, F. L., Santos, M. B., Pita, C., & Pierce, G. J. (2014). Cetacean–fishery interactions in Galicia (NW Spain): results and management implications of a face-to-face interview survey of local fishers. ICES Journal of Marine Science, 71(3), 604-617.
- Hamer, D. J., Childerhouse, S. J., & Gales, N. J. (2012). Odontocete bycatch and depredation in longline fisheries: a review of available literature and of potential solutions. Marine Mammal Science, 28(4), E345-E374.
- Hamilton, S., & Baker, G. B. (2019). Technical mitigation to reduce marine mammal bycatch and entanglement in commercial fishing gear: lessons learnt and future directions. Reviews in Fish Biology and Fisheries, 29(2), 223-247.
- Hammond, P. S., Bearzi, G., Bjørge, A., Forney, K., Karczmarski, L., Kasuya, T., et al. (2008). *Phocoena phocoena*. The IUCN Red List of Threatened Species 2008: e. T17027A6734992.
- Hammond, P. S., Macleod, K., Berggren, P., Borchers, D. L., Burt, L., Cañadas, A., et al. (2013). Cetacean abundance and distribution in European Atlantic shelf waters to inform conservation and management. Biological Conservation, 164, 107-122.
- Hammond, P. S., Lacey, C., Gilles, A., Viquerat, S., Boerjesson, P., Herr, H., et al. (2017). Estimates of cetacean abundance in European Atlantic waters in summer 2016 from the SCANS-III aerial and shipboard surveys. Wageningen Marine Research.
- Hastie, G., Merchant, N. D., Götz, T., Russell, D. J., Thompson, P., & Janik, V. M. (2019). Effects of impulsive noise on marine mammals: investigating range-dependent risk. Ecological Applications, 29(5), e01906.
- Hazen, E. L., Scales, K. L., Maxwell, S. M., Briscoe, D. K., Welch, H., Bograd, S. J., et al. (2018). A dynamic ocean management tool to reduce bycatch and support sustainable fisheries. Science advances, 4(5), eaar3001.
- Hines, E., Ponnampalam, L. S., Junchompoo, C., Peter, C., Vu, L., Huynh, T., et al. (2020). Getting to the bottom of bycatch: a GIS-based toolbox to assess the risk of marine mammal bycatch. Endangered

- Species Research, 42, 37-57.
- Hordyk, A. R., & Carruthers, T. R. (2018). A quantitative evaluation of a qualitative risk assessment framework: Examining the assumptions and predictions of the Productivity Susceptibility Analysis (PSA). *PLoS one*, 13(6), e0198298.
- ICES. (2017). Report of the Working Group on Bycatch of Protected Species (WGBYC), 12–15 June 2017, Woods Hole, Massachusetts, USA. ICES CM 2017/ACOM:24, 82. Available online at: <https://doi.org/A10.17895/ices.pub.3053>
- ICES Working Group on Bycatch of Protected Species, WGBYC. (2019). ICES Scientific Reports, 1:51, 163 pp. <https://doi.org/10.17895/ices.pub.5563>
- ICES. (2020a). EU Request on Emergency Measures to Prevent bycatch of Common Dolphin (*Delphinus delphis*) and Baltic Proper Harbour Porpoise (*Phocoena phocoena*) in the Northeast Atlantic. ICES Special Request Advice, 2020, Available online at: https://www.ices.dk/sites/pub/Publication%20Reports/Advice/2020/Special_Requests/eu.2020.04.pdf
- ICES. (2020b). Road map for ICES bycatch advice on protected, endangered, and threatened species. In Report of the ICES Advisory Committee, 2020. Available at: <https://doi.org/10.17895/ices.advice.6022>
- ICES. (2020c). Workshop on fisheries Emergency Measures to minimize BYCatch of short-beaked common dolphins in the Bay of Biscay and harbour porpoise in the Baltic Sea (WKEMBYC). ICES Scientific Reports. 2:43. 354 pp. <http://doi.org/10.17895/ices.pub.7472>
- ICES. (2021). Gear Type Vocabularies. Available at: <https://vocab.ices.dk/?ref=1498>
- IWC (International Whaling Commission) (2017) Report of the Scientific Committee. *Journal of Cetacean Research Management*, 18, 1–671.
- James, M., Mendo, T., Jones, E. L., Orr, K., McKnight, A., & Thompson, J. (2018). AIS data to inform small scale fisheries management and marine spatial planning. *Marine Policy*, 91, 113-121.
- Jüssi, M., Ahola, M., Verevkin, M., & Loisa, O. (2016). Marine mammals. The Gulf of Finland assessment/Eds. Mika Raateoja and Outi Setälä.
- Kastelein, R. A., van der Heul, S., van der Veen, J., Verboom, W. C., Jennings, N., de Haan, D., & Reijnders, P. J. (2007). Effects of acoustic alarms, designed to reduce small cetacean bycatch in gillnet fisheries, on the behaviour of North Sea fish species in a large tank. *Marine Environmental Research*, 64(2), 160-180.
- Keane, A., Jones, J. P., Edwards-Jones, G., & Milner-Gulland, E. J. (2008). The sleeping policeman: understanding issues of enforcement and compliance in conservation. *Animal conservation*, 11(2), 75-82.
- Kelleher, K. (2005). Discards in the world's marine fisheries: an update (Vol. 470). FAO.
- Kesselring, T., Viquerat, S., Brehm, R., & Siebert, U. (2017). Coming of age:-Do female harbour porpoises (*Phocoena phocoena*) from the North Sea and Baltic Sea have sufficient time to reproduce in a human influenced environment? *PLoS One*, 12(10), e0186951.
- Khalilian, S., Froese, R., Proelss, A., & Requate, T. (2010). Designed for failure: a critique of the Common Fisheries Policy of the European Union. *Marine Policy*, 34(6), 1178-118.
- Kindt-Larsen, L., Berg, C. W., Tougaard, J., Sørensen, T. K., Geitner, K., Northridge, S., et al. (2016). Identification of high-risk areas for harbour porpoise *Phocoena phocoena* bycatch using remote electronic monitoring and satellite telemetry data. *Marine Ecology Progress Series*, 555, 261-271.
- Königson, S. J., Fredriksson, R. E., Lunneryd, S. G., Strömberg, P., & Bergström, U. M. (2015). Cod pots in a Baltic fishery: are they efficient and what affects their efficiency? *ICES Journal of Marine Science*, 72(5), 1545-1554.
- Koschinski, S. u. N. Wolff (2013). *Lebendige Ostsee: Beispiele für vorbildliche Fangmethoden und ihre Anwendbarkeit auf den Ostseeraum*. Berlin: Deutsche Umwelthilfe.
- Kroodsma, D. A., Mayorga, J., Hochberg, T., Miller, N. A., Boerder, K., Ferretti, F., et al. (2018). Tracking the global footprint of fisheries. *Science*, 359(6378), 904-908.
- Lah, L., Trense, D., Benke, H., Berggren, P., Gunnlaugsson, P., Lockyer, C., et al. (2016). Spatially explicit analysis of genome-wide SNPs detects subtle population structure in a mobile marine

- mammal, the harbor porpoise. *PloS one*, 11(10), e0162792.
- Laran, S., Authier, M., Blanck, A., Doremus, G., Falchetto, H., Monestiez, P., et al. (2017). Seasonal distribution and abundance of cetaceans within French waters-Part II: The Bay of Biscay and the English Channel. *Deep Sea Research Part II: Topical Studies in Oceanography*, 141, 31-40.
- Learmonth, J. A., Murphy, S., Luque, P. L., Reid, R. J., Patterson, I. A. P., Brownlow, A., et al. (2014). Life history of harbor porpoises (*Phocoena phocoena*) in Scottish (UK) waters. *Marine Mammal Science*, 30(4), 1427-1455.
- Lens, S. & Diaz, P. (2009). Annual Report of Spain to the European Commission on the Implementation of Council Regulation 812/2004 on Cetacean Bycatch. Instituto Español de Oceanografía. Available at: <http://www.repositorio.ieo.es/e-ieo/handle/10508/8812>
- Lewison, R. L., Soykan, C. U., Cox, T., Peckham, H., Pilcher, N., LeBoeuf, N., et al. (2011). Ingredients for addressing the challenges of fisheries bycatch. *Bulletin of Marine Science*, 87(2), 235-250.
- Lewison, R. L., Johnson, A. F., & Verutes, G. M. (2018). Embracing complexity and complexity-awareness in marine megafauna conservation and research. *Frontiers in Marine Science*, 5, 207.
- Lukoschek, V., Funahashi, N., Lavery, S., Dalebout, M. L., Cipriano, F., & Baker, C. S. (2009). High proportion of protected minke whales sold on Japanese markets is due to illegal, unreported or unregulated exploitation. *Animal Conservation*, 12(5), 385-395.
- Martin, S. L., Stohs, S. M., & Moore, J. E. (2015). Bayesian inference and assessment for rare-event bycatch in marine fisheries: a drift gillnet fishery case study. *Ecological Applications*, 25(2), 416-429.
- McDonald, S. L., & Rigling-Gallagher, D. (2015). Participant perceptions of consensus-based, marine mammal take reduction planning. *Marine Policy*, 61, 216-226.
- McDonald, S. L., Lewison R. L., & Read A. J. (2016a). Evaluating the efficacy of environmental legislation: A case study from the US marine mammal Take Reduction Planning process. *Global Ecology and Conservation*, 5, 1-11.
- McDonald, S. L., Lewison, R. L., Roady, S. E., Kramer, R. A., Rigling-Gallagher, D., & Read, A. J. (2016b). Comparing stakeholder perceptions with empirical outcomes from negotiated rulemaking policies: Is participant satisfaction a proxy for policy success? *Marine Policy*, 73, 224-230.
- Mehtälä, J., & Vuorisalo, T. (2007). Conservation policy and the EU Habitats Directive: favourable conservation status as a measure of conservation success. *European Environment*, 17(6), 363-375.
- Meynier, L., Pusineri, C., Spitz, J., Santos, M. B., Pierce, G. J., & Ridoux, V. (2008). Intraspecific dietary variation in the short-beaked common dolphin *Delphinus delphis* in the Bay of Biscay: importance of fat fish. *Marine Ecology Progress Series*, 354, 277-287.
- Michelin, M., Elliott, M., Bucher, M., Zimring, M., & Sweeney, M. (2018). Catalyzing the growth of electronic monitoring in fisheries. Available at: <https://oursharedseas.com/wp-content/uploads/2019/10/Catalyzing-the-Growth-of-Electronic-Monitoring-in-Fisheries-CEA.pdf>
- Ministry of the Sea. (2021). The Fight Against Accidental Capture of Small Cetaceans in the Atlantic. Available at: https://www.mer.gouv.fr/sites/default/files/2021-05/20183_infog_capture_cetaces_site_1234567_english.pdf
- Moore, J. E., Wallace, B. P., Lewison, R. L., Żydelis, R., Cox, T. M., & Crowder, L. B. (2009). A review of marine mammal, sea turtle and seabird bycatch in USA fisheries and the role of policy in shaping management. *Marine Policy*, 33(3), 435-451.
- Morizur, Y., Berrow, S. D., Tregenza, N. J. C., Couperus, A. S., & Pouvreau, S. (1999). Incidental catches of marine-mammals in pelagic trawl fisheries of the northeast Atlantic. *Fisheries Research*, 41(3), 297-307.
- Marine Stewardship Council (MSC). (2018). MSC Fisheries Standard Version 2.01. Available at: https://www.msc.org/docs/default-source/default-document-library/for-business/program-documents/fisheries-program-documents/msc-fisheries-standard-v2-01.pdf?sfvrsn=8ecb3272_9
- Murphy, S., Evans, P. G., Pinn, E., & Pierce, G. J. (2021). Conservation management of common dolphins: Lessons learned from the North-East Atlantic. *Aquatic Conservation: Marine and Freshwater Ecosystems*, 31, 137-166.
- Murray, K. T., Read, A. J., & SoLow, A. R. (2000). The use of time/area closures to reduce bycatches of

- harbour porpoises: lessons from the Gulf of Maine sink gillnet fishery. *Journal of Cetacean Research and Management*, 2(2), 135-141.
- Nabe-Nielsen, J., Sibly, R. M., Tougaard, J., Teilmann, J., & Sveegaard, S. (2014). Effects of noise and by-catch on a Danish harbour porpoise population. *Ecological Modelling*, 272, 242-251.
- National Oceanic and Atmospheric Administration (NOAA) (2021a). Marine Mammal Protection Act List of Fisheries. Available at: <https://www.fisheries.noaa.gov/national/marine-mammal-protection/marine-mammal-protection-act-list-fisheries>
- National Oceanic and Atmospheric Administration (NOAA) (2021b). Stock Assessment Reports. Available at: <https://www.nmfs.noaa.gov/pr/sars/species.htm>
- National Oceanic and Atmospheric Administration (NOAA) (2021c). Marine Mammal Mortality and Serious Injury Reports. Available at: <https://www.fisheries.noaa.gov/resource/publication-database/marine-mammal-mortality-and-serious-injury-reports>
- Nelms, S. E., Alfaro-Shigueto, J., Arnould, J. P., Avila, I. C., Nash, S. B., Campbell, E., et al. (2021). Marine mammal conservation: over the horizon. *Endangered Species Research*, 44, 291-325.
- North Atlantic Marine Mammal Commission and the Norwegian Institute of Marine Research (NAMMCO-IMR). (2019). Report of Joint IMR/NAMMCO International Workshop on the Status of Harbour Porpoises in the North Atlantic. Tromsø, Norway.
- Northridge, S., Kingston, A., & Thomas, L. (2015). Annual report on the implementation of council regulation (EC) No 812/2004 during 2014. Available at: https://research-repository.st-andrews.ac.uk/bitstream/handle/10023/6855/12530_UK812Report2015on2014Final.pdf?sequence=1
- Northridge, S. P., Morizur, Y., Souami, Y., and Van Canneyt, O. (2006). PETRACET: Project EC/FISH/2003/09 Final Report to the European Commission 1735R07D. Lymington: MacAliser Elliott and Partners Ltd.
- Orphanides, C. D. (2009). Protected species bycatch estimating approaches: estimating harbor porpoise bycatch in US northwestern Atlantic gillnet fisheries. *Journal of Northwest Atlantic Fishery Science*, 42.
- Orphanides, C. D., & Palka, D. L. (2013). Analysis of harbor porpoise gillnet bycatch, compliance, and enforcement trends in the US northwestern Atlantic, January 1999 to May 2010. *Endangered Species Research*, 20(3), 251-269.
- Palka, D. L., Rossman, M. C., Vanatten, A., & Orphanides, C. D. (2008). 217 Effect of pingers on harbour porpoise (*Phocoena phocoena*) bycatch in the US Northeast gillnet fishery. *J. Cetacean Res. Manage*, 10(3), 217-226.
- Palka, D. L. (2012). Cetacean abundance estimates in US northwestern Atlantic Ocean waters from summer 2011 line transect survey.
- Pauly, D., & Zeller, D. (2016). Catch reconstructions reveal that global marine fisheries catches are higher than reported and declining. *Nature communications*, 7(1), 1-9.
- Peltier, H., Dabin, W., Daniel, P., Van Canneyt, O., Dorémus, G., Huon, M., & Ridoux, V. (2012). The significance of stranding data as indicators of cetacean populations at sea: modelling the drift of cetacean carcasses. *Ecological Indicators*, 18, 278-290.
- Peltier, H., Authier, M., Deaville, R., Dabin, W., Jepson, P. D., van Canneyt, O., et al. (2016). Small cetacean bycatch as estimated from stranding schemes: the common dolphin case in the northeast Atlantic. *Environmental Science & Policy*, 63, 7-18.
- Peltier, H., Authier, M., Dabin, W., Dars, C., Demaret, F., Doremus, G., et al. (2020). Can modelling the drift of bycaught dolphin stranded carcasses help identify involved fisheries? An exploratory study. *Global Ecology and Conservation*, 21, e00843.
- Peltier, H., Authier, M., Caurant, F., Dabin, W., Daniel, P., Dars, C., et al. (2021). In the Wrong Place at the Wrong Time: Identifying Spatiotemporal Co-occurrence of Bycaught Common Dolphins and Fisheries in the Bay of Biscay (NE Atlantic) From 2010 to 2019. *Frontiers in Marine Science*, 8(617342).
- Pilcher, N. J., Adulyanukosol, K., Das, H., Davis, P., Hines, E., Kwan, D., et al. (2017). A low-cost solution for documenting distribution and abundance of endangered marine fauna and impacts from

- fisheries. *PloS one*, 12(12), e0190021.
- Pusineri, C., Magnin, V., Meynier, L., Spitz, J., Hassani, S., & Ridoux, V. (2007). Food and feeding ecology of the common dolphin (*Delphinus delphis*) in the oceanic Northeast Atlantic and comparison with its diet in neritic areas. *Marine Mammal Science*, 23(1), 30-47.
- Read, A. J., Drinker, P., & Northridge, S. (2006). Bycatch of marine mammals in US and global fisheries. *Conservation biology*, 20(1), 163-169.
- Read, A. J. (2013). Development of conservation strategies to mitigate the bycatch of harbor porpoises in the Gulf of Maine. *Endangered Species Research*, 20(3), 235-250.
- Reeves, R. R., McClellan, K., & Werner, T. B. (2013). Marine mammal bycatch in gillnet and other entangling net fisheries, 1990 to 2011. *Endangered Species Research*, 20(1), 71-97.
- Rogan, E., Read, A. J., & Berggren, P. (2021). Empty promises: The European Union is failing to protect dolphins and porpoises from fisheries by-catch. *Fish and Fisheries*, 22(4), 865-869.
- Rouby, E., Ridoux, V., & Authier, M. (2021). Flexible parametric modeling of survival from age at death data: A mixed linear regression framework. *Population Ecology*, 63(1), 108-122.
- Rimaud, T., Authier, M., Mehault, S., Peltier, H., and Van Canneyt, O. 2019. RAPPORT Final du projet PIC. Pêcheurs de Bretagne.
- Saavedra C, Gerrodette T, Louzao M, Valeiras J, Garcia S, Cervino S, et al. (2018). Assessing the environmental status of the short-beaked common dolphin (*Delphinus delphis*) in North-western Spanish waters using abundance trends and safe removal limits. *Progress in Ocean*, 166, 66-75.
- SAMBAH. (2016). Final report for LIFE+ project SAMBAH LIFE08 NAT/S/000261 covering the project activities from 01/01/2010 to 30/09/2015. Reporting date 29/02/2016. Available at: <http://www.sambah.org/Nysida-11.htm>
- Scheidat, M., Couperus, B., & Siemensma, M. (2018). Electronic monitoring of incidental bycatch of harbour porpoise (*Phocoena phocoena*) in the Dutch bottom set gillnet fishery (September 2013 to March 2017) (No. C102/18). Wageningen Marine Research.
- Scientific, Technical and Economic Committee for Fisheries (STECF). (2019). Review of the implementation of the EU regulation on the incidental catches of cetaceans (STECF-19-07). Publications Office of the European Union, Luxembourg. Available at: <https://op.europa.eu/en/publication-detail/-/publication/e889de8c-e8fd-11e9-9c4e-01aa75ed71a1>
- Scientific, Technical and Economic Committee for Fisheries (STECF). (2021). 66th Plenary Report (PLEN-21-01). Publications Office of the European Union, Luxembourg. Available at: <https://op.europa.eu/en/publication-detail/-/publication/90a5c87f-a7cd-11eb-9585-01aa75ed71a1/language-en>
- SEC. (2002). Report of the second meeting of the Subgroup on Fishery and Environment (SGFEN) of the Scientific, Technical and Economic Committee for Fisheries (STECF) Incidental Catches of Small Cetaceans Brussels, 11–14 June 2002. Commission Staff Working Paper, Commission of the European Communities. SEC (2002)1134.
- Seafood Watch (SFW). (2020). Seafood Watch Fisheries Standards v4. Available at: <https://www.seafoodwatch.org/globalassets/sfw/pdf/standards/fisheries/seafood-watch-fisheries-standard-version-f4.pdf>
- Sonntag, N., Schwemmer, H., Fock, H. O., Bellebaum, J., & Garthe, S. (2012). Seabirds, set-nets, and conservation management: assessment of conflict potential and vulnerability of birds to bycatch in gillnets. *ICES Journal of Marine Science*, 69(4), 578-589.
- Soykan, C. U., Moore, J. E., Zydalis, R., Crowder, L. B., Safina, C., & Lewison, R. L. (2008). Why study bycatch? An introduction to the Theme Section on fisheries bycatch. *Endangered Species Research*, 5(2-3), 91-102.
- Stobutzki, I. C., Miller, M. J., Heales, D. S., & Brewer, D. T. (2002). Sustainability of elasmobranchs caught as bycatch in a tropical prawn (shrimp) trawl fishery. *Fishery Bulletin*, 100(4), 800-821.
- Sveegaard, S., Galatius, A., Dietz, R., Kyhn, L., Koblitz, J. C., Amundin, M., et al. (2015). Defining management units for cetaceans by combining genetics, morphology, acoustics and satellite tracking. *Global Ecology and Conservation*, 3, 839-850.

- Symes, D. (2009). Reform of the European Union's Common Fisheries Policy: making fisheries management work. *Fisheries Research*, 100(2), 99-102
- Taylor, B. L., Wade, P. R., De Master, D. P., & Barlow, J. (2000). Incorporating uncertainty into management models for marine mammals. *Conservation Biology*, 14(5), 1243-1252.
- Taylor, B., Chivers, S. J., Larese, J. & Perrin, B. (2007). Generation length and percent mature estimates for IUCN assessments of cetaceans. Southwest Fisheries Science Center. Administrative report LJ-07-01.
- Teh, L. S., Teh, L. C., Hines, E., Junchompoo, C., & Lewison, R. L. (2015). Contextualising the coupled socio-ecological conditions of marine megafauna bycatch. *Ocean & Coastal Management*, 116, 449-465.
- Trimble, M., & Berkes, F. (2013). Participatory research towards co-management: lessons from artisanal fisheries in coastal Uruguay. *Journal of environmental management*, 128, 768-778.
- Trippel, E. A., Strong, M. B., Terhune, J. M., & Conway, J. D. (1999). Mitigation of harbour porpoise (*Phocoena phocoena*) by-catch in the gillnet fishery in the lower Bay of Fundy. *Canadian Journal of Fisheries and Aquatic Sciences*, 56(1), 113-123.
- Verutes, G. M., Johnson, A. F., Caillat, M., Ponnampalam, L. S., Peter, C., Vu, L., et al. (2020). Using GIS and stakeholder involvement to innovate marine mammal bycatch risk assessment in data-limited fisheries. *PloS one*, 15(8), e0237835.
- Verutes, G. M., Tubbs, S. E., Selmes, N., Clark, D. R., Walker, P., & Clements, O. (2021). Modeling Seasonal Distribution of Irrawaddy Dolphins (*Orcaella brevirostris*) in a Transnational Important Marine Mammal Area. *Frontiers in Marine Science*.
- Vinther, M., & Larsen, F. I. N. N. (2004). Updated estimates of harbour porpoise (*Phocoena phocoena*) bycatch in the Danish North Sea bottom-set gillnet fishery. *Journal of Cetacean Research and Management*, 6(1), 19-24.
- Wade, P. R. (1998). Calculating limits to the allowable human-caused mortality of cetaceans and pinnipeds. *Marine Mammal Science*, 14(1), 1-37.
- Wade, P. R., Long, K. J., Francis, T. B., Punt, A. E., Hammond, P. S., Heinemann, D., et al. (2021) Best practices for assessing and managing bycatch of marine mammals. *Frontiers in Marine Science*, 8:757330.
- Waring, G. T., Quintal, J. M., Schwartz, S. L. (eds) (2001). US Atlantic and Gulf of Mexico marine mammal stock assessments—2001. NOAA Tech Memo NMFS NE 168, Northeast Fisheries Science Center, NOAA, Woods Hole, MA. Available at: <http://www.nefsc.noaa.gov/nefsc/publications/tm/tm168/>
- Waring, G.T., Josephson, E., Maze-Foley, K., Rosel, P.E. (Eds.), 2011. U.S. Atlantic and Gulf of Mexico Marine Mammal Stock Assessments – 2010. NOAA Technical Memorandum NMFS-NE-219, Woods Hole, MA, 598pp.
- Williams, R., Burgess, M. G., Ashe, E., Gaines, S. D., & Reeves, R. R. (2016). US seafood import restriction presents opportunity and risk. *Science*, 354(6318), 1372-1374.
- Wilson, S. M., Raby, G. D., Burnett, N. J., Hinch, S. G., & Cooke, S. J. (2014). Looking beyond the mortality of bycatch: sublethal effects of incidental capture on marine animals. *Biological Conservation*, 171, 61-72.
- Woodley, T. H., & Read, A. J. (1991). Potential rates of increase of a harbour porpoise (*Phocoena phocoena*) population subjected to incidental mortality in commercial fisheries. *Canadian Journal of Fisheries and Aquatic Sciences*, 48(12), 2429-2435.
- World Wild Fund for Nature (WWF). (2009). Factsheet on Bycatch. Available at: https://wwfint.awsassets.panda.org/downloads/bycatch_factsheet.pdf

4 Policy analysis: Case studies of cetacean bycatch

Chapter 5



5 CONCLUSIONS

In coastal fishing zones worldwide, resource managers struggle to balance multiple objectives, including identifying species most affected by bycatch, high-impact fishing gears, and areas in greatest need of protection. Pathways to address fisheries bycatch should seek to understand and carefully adjust human behavior, while not jeopardizing an industry that many rely on for food and their livelihood. Fundamental to this process is the need to integrate existing knowledge into managing fishing activities known to entangle, potentially kill, and strand marine mammals. The overarching aim of this thesis was to make better use of existing information in data-limited fisheries. To this end, I co-developed a management tool (ByRA) that draws on geospatial analysis and stakeholder involvement to pinpoint areas, seasons, and fishing gears of significant bycatch risk to marine mammals. I tested and shared the inner workings of the tool with local scientists, managers, students, and community stakeholders to identify effective strategies for monitoring bycatch and measured conservation action. To do so, I utilized interdisciplinary techniques that facilitated cross-sectoral engagement, participatory mapping, and quantitative analyses. These research methods acknowledged and accounted for data uncertainty in the estimates of marine mammal habitat suitability and bycatch risk.

5.1 RESULTS SYNTHESIS

There are spatio-temporal patterns in bycatch occurrence that can be identified, even in data-limited SSF. The first application of the ByRA tool (**Chapter 2**) leveraged existing data to estimate the risk of bycatch to dugongs and Irrawaddy dolphins in three field sites of Southeast Asia. Once these data were collected, estimates of bycatch risk and data input uncertainty could be validated and improved. Outputs highlighted emergent spatio-temporal risk patterns that could be validated by and communicated to stakeholders, including gears and seasons of most significant concern. The entire process served as a powerful example of how integrating and synthesizing available information in a simple and accessible format can support the

development of bycatch management plans. Because the tool guides monitoring efforts in data-limited fisheries, scientists could – for the first time in the region – established baselines and identified strategies for collecting data that filled critical knowledge gaps. Visual summaries of analytical results and associated uncertainties provided a durable roadmap for managers with limited resources and scientific capacity.

The first application of ByRA revealed areas of highest bycatch risk in the coastal waters of the Kep Archipelago, along the Cambodia-Vietnam border. Knowledge of cetacean species' geographic and seasonal distribution is crucial when designing marine protected areas and implementing management actions. However, limited data on animal sightings prevented accurate assessments of dolphin distribution in the region. **Chapter 3** documented the development of species distribution models for Irrawaddy dolphins inside the recently recognized Kien Giang-Kep Archipelago Important Marine Mammal Area (IMMA). Leveraging two years of species occurrence and oceanographic data, I built and validated temporally stratified models to estimate dolphin distribution and infer seasonal habitat importance. The availability of high resolution, remotely-sensed data describing monthly sea surface temperatures and chlorophyll-a concentrations were essential towards advancing analytical complexity in a data-limited field site. Results suggested when and where to refocus dolphin survey efforts as part of regular monitoring inside the Kep Marine Fisheries Management Area and the broader IMMA. This information is needed to assist researchers in Cambodia and Vietnam with the training of staff on emerging technologies to track the movement of species and fisheries, and develop robust risk assessments so that marine managers can effectively manage illegal fishing activities along a dynamic border region.

Relative to Southeast Asia, baseline data and legal instruments to address unsustainable bycatch are more prevalent in the European Union (E.U.) and the United States (U.S.). To understand a suite of factors that enable and limit effective bycatch management, I carried out three case studies in E.U. and the U.S. with high rates of small cetacean bycatch, and an endangered subpopulation of harbor porpoise in the Baltic Sea (**Chapter 4**). Findings suggested that if cetacean mortality numbers exceed safe removal limits, a more reactive approach, such as the mandatory Take Reduction Planning mandated by the U.S. Marine Mammal Protection Act, can reduce bycatch mortality rates. The E.U. and its Member States have struggled to demonstrate unified action with a similar effect because of a multi-tiered system of governance

with strong bureaucratic inertia, logistical problems, and a division of responsibility. While it is impossible to directly compare available resources for managing bycatch in E.U. and U.S. waters, there are stark differences in regional capacity and political will to implement marine mammal conservation policies. This policy analysis also concluded that a science-policy engagement process is often the missing link to advance the implementation of policies, regulations, and action plans for the protection of small cetaceans from bycatch.

5.2 CONTRIBUTION TO RESEARCH, POLICY, AND MANAGEMENT

This thesis advances marine mammal conservation research by leveraging emergent technologies for the acquisition of high-resolution environmental data and a stakeholder-friendly fisheries management tool. The ByRA is a timely option for managers and a fishing sector that is under increasing pressure to mitigate marine mammal bycatch. It was initially conceived and funded to meet the need for enhanced international transparency and compliance with a new U.S. MMPA rule. This U.S. trade regulation will take full effect in 2022 and ban imports of seafood caught in fisheries with high rates of marine mammal bycatch.

Following extensive fieldwork, with iterative engagement and design, ByRA was first applied in three field sites of Southeast Asia to characterize marine mammal distributions, fishing effort, and their interaction rates. The resulting bycatch risk estimates highlighted emergent patterns of interaction between high-impact fishing gears and marine mammals through a systematic screening of more than 10,000 square kilometers of coastal waters. Outputs pinpointed areas and seasons of greatest bycatch concern and suggested management actions that are likely to mitigate risk. For the first time, scientists and managers in the region could set management goals for compliance with international regulations and pursue more targeted monitoring that leads to data quality improvements.

As long as uncertainty is accurately characterized and accounted for, even low-resolution information can be useful to advance marine mammal conservation research. The clearest illustration of data limitations was along the Vietnam-Cambodia border where ByRA identified the Kep Archipelago as a location of high bycatch risk to the resident population of endangered Irrawaddy dolphins. To reduce data uncertainty for this understudied population, a habitat model was built, tested, and validated following the acquisition of remotely-sensed environmental data and dolphin sightings by the Cambodian Marine Mammal Conservation Project. In summary, the

preliminary ByRA communicated the need to collect, analyze, and apply additional data on Irrawaddy dolphin distribution and abundance based on an acute threat from illegal fishing. As these and other datasets became available, dolphin habitat models for the Kep Archipelago offered more spatially and temporally resolute estimates of habitat suitability, while controlling for sampling biases. These high-resolution habitat model outputs can now be combined with fishing intensity maps to further hone in on areas of greatest bycatch risk and identify management opportunities.

Recently, the ByRA framework was extended beyond the Southeast Asian field sites initially used to demonstrate its capabilities for participatory engagement in data-limited SSF. New research is underway to identify overlap between threatened marine megafauna species and high-risk fishing activities. Notably, the ByRA tool is open source and freely available to students, managers, and practitioners. The tool is part of the InVEST suite of ecoinformatics software modules maintained by the Natural Capital Project at Stanford University (naturalcapitalproject.stanford.edu/software/invest). Sample data and standard geospatial processing routines are codified as plugins to the QGIS mapping software. A user manual in English and Spanish is available on a dedicated website (mmbycatchtoolbox.org). To date, ByRA has been applied in six field sites of Malaysia, Thailand, Vietnam, Sri Lanka, and Peru.

There are additional opportunities to apply the ByRA in new decision contexts such as for multispecies assessment or evaluating bycatch risk in commercial fisheries of the U.S. or E.U., where there are well-documented challenges to advance policy implementation and compliance with bycatch mitigation measures. ByRA applied in these geographies can integrate new sources of data for characterizing animal distribution, population structure, fisheries effort, and interaction rates. Building on regional mapping efforts and calls from the international scientific community to conduct localized risk assessments, it is anticipated that bycatch mapping will support efforts in the E.U. to address critical monitoring deficiencies and engage new stakeholders. The hope is that by bringing these and other complexity-aware approaches into the fold, managers can overcome stalemates related to data scarcity, and identify locally-supported conservation strategies that both safeguard marine biodiversity and maintain fisher livelihoods.

5.3 PERSPECTIVES AND RECOMMENDATIONS

Governments and institutions establish environmental regulations to protect wildlife and productive ecosystems while managing conflicts between coupled human and natural systems. Yet, it is the participation of local stakeholders in disputes over the allocation and preservation of natural resources that is critical for conservation success. Stakeholder involvement offers a pragmatic perspective in the identification of more tenable solutions to addressing fisheries bycatch. Specific to the management of data-limited fisheries, community-driven research involving fishers is needed to access untapped knowledge and support the design and implementation of locally-supported strategies to monitor and mitigate bycatch. This type of engagement involves face-to-face meetings to co-develop assessment methods, iteratively fill knowledge gaps, and galvanize support for concrete management action. In this thesis, I used community involvement and participatory mapping as a tool to systematically augment data availability and complexity awareness in marine mammal bycatch research. Specific to the field sites of Southeast Asia, it was only after input and buy-in from fisher communities and other stakeholders that many of the most critical insights came to light. Undoubtedly, this community perspective enhanced the salience and quality of the research findings.

Given the poor status of marine mammal populations worldwide, urgent action is required on multiple fronts. In Southeast Asia and much of the developing world, bycatch monitoring programs and emerging technology to track fisheries, marine mammals, and their interactions are cost-prohibitive. The research in Malaysia, Vietnam, and Cambodia was greatly enhanced by data contributions from colleagues who identified the need for and the value of a participatory approach to evaluate bycatch risk. I leveraged existing data on animal sightings, fisher interviews, and environmental covariables through remote sensing techniques and by forging strategic partnerships. Given the scarcity of resources and capacity in the region, I conducted rapid assessments using available data to screen areas of coastal-estuarine waters that were previously unsurveyed. Initial outputs enabled managers to identify new research priorities through a characterization of data quality and uncertainty. Still, there were analytical limitations. For example, I could not conduct fisheries effort mapping because vessel monitoring systems and onboard observers do not reliably track these activities in Southeast Asia. Nevertheless, important insights about current knowledge gaps will provide a foundation for future assessments to address data insufficiencies and guide monitoring to regions and seasons of

conservation concern.

As highlighted by this thesis, context matters; that is, where in the world we are working will determine the available information, regulatory framework, and relevant strategies to address bycatch. In most cases, bycatch is the symptom of a more significant problem. For example, the current status of European fisheries is both an economic and political concern, so addressing bycatch is usually an afterthought. In addition, the E.U. system of governance lacks the legal and political mechanisms for Member States to take responsibility. Consequently, short-term decision-making is prioritized over long-term strategy. Further, no biological reference points are currently fixed into E.U. law or agreements binding on its Member States. The implementation of fisheries policy cannot halt because insufficient data or division of responsibility has eroded political will. Solutions to reduce unsustainable bycatch levels begin with government commitments to work with fisheries organizations and other sectors in a process that considers both marine fisheries and biodiversity conservation objectives. Multisectoral outreach is also crucial to identify ways to stop the decline of critical fish and marine mammal stocks, restore ocean health, and respect the intrinsic value of marine biodiversity.

In some situations, strong governance and fisheries management has effectively minimized the number of bycaught animals. The U.S. represents the gold standard for identifying and confronting unsustainable bycatch of marine mammals. The MMPA criteria to estimate impacts to marine mammal population from certain fisheries ensures that high-quality information is used to develop stakeholder-supported management strategies. Robust data on species abundance and mortality are essential for estimating safe removal limits and evaluating the effectiveness of mitigation measures. NOAA Fisheries is responsible for collecting and disseminating these data as annual stock assessment reports, dating back to 1987 for some strategic marine mammal stocks. Comparative studies on the effectiveness of U.S. take reduction planning processes indicate that increasing bycatch rates were not the result of policy implementation challenges, but a lack of compliance with specific management measures prescribed by these plans. Therefore, regulatory controls should be flexible enough to allow for changes in the relevant fisheries and environmental conditions, including enforcement of the new U.S. seafood import rule. Dynamic ocean management is also a promising tool for leveraging data with high spatial and temporal resolution. As it becomes cheaper to deploy technologies that

track fishing activities, species movements, and environmental variability, scientists and managers will have access to information about threats and opportunities for management in real-time.

Sustainable development in today's ocean economy relies on spatially explicit information to mitigate the mounting pressures on ecosystems from human activities and to safeguard marine biodiversity. The health of our oceans, environment, and people are all connected. Bycatch management is one piece of the puzzle to addressing a critical environmental need of our time: stewardship of global ocean resources and their habitats. Can we heal much of the harm that has been done, and treat marine ecosystems with the full respect they demand? Solutions to bycatch, such as the risk mapping demonstrated by this thesis, represent a low-cost, transparent, and transferrable solution to augment scientific knowledge through community involvement and complexity awareness. Notably, the approach ensures that data collection does not become an obstacle to bycatch research in data-scarce situations. Regardless of the conservation issue, we need to value information, including tacit knowledge from marginalized populations and impacted sectors; and then analyze the data we have while there is still time. This research contributes to an emerging suite of approaches and tools for monitoring data-limited fisheries and identifying locally-supported management strategies to reduce marine mammal bycatch.



Bycatch, the incidental capture of non-target species in active fishing gear, has been recognized as a threat to marine megafauna for decades. Is it possible to design and apply an assessment framework for evaluating harmful interactions between marine mammals and fisheries using existing information only? This is the main question I attempt to answer. More broadly, I investigate the ways in which international policies have, or have not, translated into effective management strategies for monitoring and mitigating marine mammal bycatch in data-limited fisheries.