UNIVERSIDADE FEDERAL DE SANTA CATARINA
CAMPUS UNIVERSITÁRIO REITOR JOÃO DAVID FERREIRA LIMA
PROGRAMA DE PÓS-GRADUAÇÃO EM ECOLOGIA

Eric Zettermann Dias de Azevedo

Ecologia e manejo pesqueiro em uma perspectiva da teoria dos jogos

Florianópolis
2022

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Tese submetida ao Programa de Pós-graduação em Ecologia da Universidade Federal de Santa Catarina para a obtenção do título de doutor em Ecologia

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Florianópolis
2022

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de Azevedo, Eric Zettermann Dias de
Ecologia e manejo pesqueiro em uma perspectiva da teoria dos jogos / Eric Zettermann Dias de de Azevedo ; orientador, Fábio Gonçalves Daura-Jorge, coorientador, David Valença Dantas, 2022.
169 p.

Tese (doutorado) - Universidade Federal de Santa Catarina, Centro de Ciências Biológicas, Programa de Pós Graduação em Ecologia, Florianópolis, 2022.

Inclui referências.

1. Ecologia. 2. ecologia pesqueira. 3. teoria dos jogos. 4. modelos bioeconômicos. 5. gestão pesqueira. I. Daura-Jorge, Fábio Gonçalves. II. Dantas, David Valença. III. Universidade Federal de Santa Catarina. Programa de Pós-Graduação em Ecologia. IV. Título.

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O presente trabalho em nível de doutorado foi avaliado e aprovado por banca examinadora composta pelos seguintes membros:

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Prof. Dr. Fábio Gonçalves Daura Jorge
Orientador

Florianópolis, 2022.

Para minha mãe, meu pai, minha companheira e meus filhos.

AGRADECIMENTOS

Minha formação em matemática—considerando a graduação e o mestrado—não tiveram nenhum incentivo a pesquisa. Não fui incentivado a contribuir com a comunidade científica ou a escrever manuscritos científicos, com a exceção dos trabalhos de conclusão. Por isso, tinha bastante receio de encarar o desafio de um doutorado. Ainda por cima um doutorado em uma área bem diferente da minha. Dessa forma, sem querer parecer narcisista, já sendo, queria fazer o primeiro agradecimento a mim mesmo, por ter acreditado em mim e por ter me permitido embarcar nessa experiência que trouxe descobertas muito importantes para minha vida profissional e pessoal: Obrigado eu!

Quem somos nós senão um experimento vivo dos nossos pais? Obrigado aos meus pais — Ana e Alex — pela oportunidade da vida. Por se preocuparem em sempre proporcionar todas as condições para meu desenvolvimento. Por se esforçarem ao máximo para que eu tivesse o melhor possível. Por contribuírem com a formação do meu caráter sendo simplesmente humanos. Pela força e pelo cuidado da minha mãe. Pelo comprometimento e pela dedicação do meu pai. Ao meu irmão Alan, agradeço pela companhia e pela parceira que transborda bons exemplos e bons ensinamentos sobre a vida. Agradeço aos meus também irmãos Alexander e Rodrigo por terem em suas lindas famílias, exemplos de vida.

Depois que saímos do seio familiar nos aventuramos em desafios próprios em um mundo que se mostra cheio de oportunidades e desafios. Nessa jornada, não poderia desejar parceria melhor do que a da minha companheira Luiza. Após quase 18 anos ainda fazemos sentido juntos, mesmo longe, mesmo perto, mesmo perdidos, mesmo loucos. Obrigado pela preocupação, pelas perguntas certas nas horas certas, pelo abraço e pela força. Te amo mais que te amo.

Dessa parceria nasceram Theo e Lara. Como seres tão pequenos conseguem promover mudanças tão imensas? Talvez um ecólogo não devesse se impressionar com essa pergunta... O fato é que tanto o Theo quanto a Lara são ambientes vulneráveis à invasão do meu amor, facilitando a entrada e a reprodução a taxas exponenciais de amor até a dominação total. Obrigado Theo pela alegria, pelo jeito único de ser e estar, e também pelo abraço quebra-miolos em vezes que o Papai subia para trabalhar. Obrigado Lara pela carinhosa maneira de cultuar o momento presente como quem não conhece o amanhã. Obrigado também às estrelinhas da família: Isabela, Otto e Lia, que mesmo com pouco tempo trouxeram grandes ensinamentos e valiosas oportunidades de crescimento.

Depois de iniciado um doutorado, a pergunta que mais se houve é “E aí? Como anda o doutorado?”. Por mais “cutucante” que essa pergunta possa parecer, mostra que a pessoa se preocupa e quer saber sobre essa etapa da nossa vida. Mas tem pessoas que vão mais fundo, que querem saber sobre o tema, sobre o orientador, sobre as experiências, sobre as disciplinas, e sobre tudo que é possível saber. Chamaremos isso de amizade e nesse momento agradeço a todas essas pessoas. Obrigado Aster, amigo desde a graduação, por todo apoio em forma de discussões profundas (e as vezes nem tão profundas) sobre a vida, por estar sempre a disposição para tudo e também por apresentar um nova ideia sobre como ver os problemas do mundo, ou talvez a ideia que vai apresentar um novo mundo. Obrigado Laise por compartilhar as experiências do seu doutorado, um ano a frente do meu. Com certeza me poupou de vários perrengues além de dar aquela sensação de ter alguém junto.

Mas tem aquelas pessoas que estão sempre lá pra você, independente do seu doutorado. Que dão apoio e se preocupam. Obrigado Fê por sempre estar por perto, do lado e comigo. Nando, obrigado pelas conversas que abraçam, que cuidam e que alegram. Shibuka obrigado por estar sempre a disposição em ouvir e em estar junto.

E sempre tem as galeras... Um grupo de pessoas em que cada um tem uma presença importante, diferente e complementar. Obrigado aos "amigos do escoteiro" que dividem experiências de vida desde a infância, compartilhando o crescimento e dando apoio também nos desafios atuais com aquela intimidade, humor e respeito de sempre. Obrigado à galera do Lamaq que sempre me recebeu bem, apesar de eu nunca ter tocado em nenhum bicho daqueles. As contribuições, as ideias, os desabafos, as besteiras e os consolos: todos me fizeram muito bem, sempre. Ao pessoal da UDESC que me apoiou para que eu conseguisse me afastar das salas de aulas e me dedicar e esse doutorado de maneira exclusiva. Com certeza é um privilégio trabalhar em um centro tão agradável de se estar. Em particular agradeço à professora Micheli Thomas, minha vizinha de sala, pelas fagulhas de motivação em formas de conversas. Ao professor Pedro Castilho pelo apoio no desenvolvimento do trabalho e da carreira. Ao professor Eduardo Gentil pelas contribuições e por compartilhar sua experiência nos temas de pesca. Obrigado.

O processo de orientação do professor Fábio Daura começou muito antes de ele de fato ser meu orientador de doutorado. Como colega da UDESC, vizinho de mesa, compartilhando de sua paixão pela ecologia e pela matemática, foi me contaminando com a semente da pesquisa e de fazer um doutorado. Foi só uma questão de tempo até amadurecermos as ideias e se encontrar novamente para iniciar essa jornada juntos. Agradeço muito por essa experiencia com você Fábio, pelos ensinamentos, insights, conselhos, "viagens", dedicação e comprometimento com o trabalho e comigo.

Obrigado professor David Dantas, colega de UDESC, pela coorientação. Me senti muito seguro em me aventurar nos temas da pesca e da gestão pesqueira tendo você e sua experiência sempre por perto. Obrigado pelas conversas e pelo constante apoio em todas as etapas desse doutorado.

No início do terceiro ano de doutorado—também início da pandemia de COVID-19—fiz um sanduíche para Portugal junto com toda a família. Estava muito ansioso para essa experiência pois não conhecia ainda o professor Pedro Pintassilgo, que viria a ser meu supervisor internacional. Eu tinha encontrado o nome dele nas referências dos trabalhos que eu estava lendo e resolvi mandar um e-mail sobre uma possível colaboração. Estava receoso pela resposta, pois foi minha primeira tentativa. A resposta ao e-mail assim como toda a experiência foi muito positiva. Além de ser muito bem recebido pela Universidade do Algarve, o professor Pedro foi muito atencioso e dedicado. Aprendi muito nos nossos encontros em frente ao projetor e quadro branco, trocando experiências e discutindo o segundo capítulo da tese. A experiência foi tão boa que o professor Pedro colaborou também no terceiro capítulo e também em outros projetos. Obrigado professor Pedro. Agradeço também a CAPES pelo financiamento do meu sanduíche através do edital PRINT-CAPES.

Agradeço ao programa de pós-graduação em Ecologia da UFSC pela excelência e por zelar por um ambiente saudável e de colaboração entre os laboratórios e entre os acadêmicos. Obrigado a todos os professores que, por intermédio desse programa, contribuíram com esse trabalho. Professora Andrea Freire na qualificação; professor Eduardo Luis Giehl na qualificação; professor Luis Gustavo Cardoso na pré-banca e banca da defesa pública; professor Maurício Petrucio na entrevista de seleção; Professora Natalia Hanazaki na defesa de projeto, avaliação SAPECO, na qualificação, na pré-banca e banca da defesa pública, professor Nivaldo Peroni na entrevista de seleção; professor Paulo Simões-Lopes na entrevista de seleção; Priscila Lopes na avaliação da SAPECO; professor Renato Silvano na banca da defesa pública; professor Rodrigo Medeiros na defesa do projeto, na qualificação e na pré-banca; professor Sérgio Floeter na qualificação. Muito obrigado por todas as colaborações.

Do jogo de xadrez aprendemos 5 coisas importantes na vida: previsão, prudência, cautela, o hábito de não se deixar abater por mais difícil que aparente ser a situação e finalmente a esperança por uma oportunidade favorável que existe sempre em qualquer situação.

Benjamin Franklin

RESUMO

Comunidades de pesca, frotas industriais, empresas, órgãos de fiscalização e gestão pública. Cada agente de uma pescaria tem uma realidade diferente, percebe o sistema de uma maneira diferente, tem interesses diferentes—conflitantes, as vezes—e maneiras diferentes de compreender e lidar com os problemas. Visto que a relação entre essas pessoas afeta diretamente a gestão da pescaria e que as mudanças no ecossistema refletem em toda o sistema, é evidente que qualquer estratégia de manejo deva ser pensada considerando o sistema pesqueiro como um todo. Essa tese de doutorado busca trazer uma perspectiva da teoria dos jogos acerca da gestão pesqueira e das relações ecológicas que a permeiam. O objetivo é entender como os fatores ecológicos, econômicos e sociais interagem no sistema socioecológico de uma pescaria e como essa interação pode contribuir para o fortalecimento da governança desse sistema. Em três capítulos, diferentes sistemas de pesca, com diferentes graus de complexidade são explorados. O primeiro capítulo faz uma análise bioeconômica da pesca do camarão (*Farfantepenaeus paulensis e Farfantepenaeus brasiliensis*) com o aviãozinho—petrecho de pesca local com atrativo luminoso em formato de avião—em Laguna, Santa Catarina. Nesse capítulo usamos um modelo bioeconômico aliado a um jogo evolutivo para discutir como que a percepção da fiscalização e a tolerância ao risco das pessoas que pescam, pode influenciar na decisão dessas pessoas de cooperar com uma restrição no esforço de pesca imposta por um plano de manejo. O cenário com alta percepção de fiscalização e alta tolerância ao risco facilitou o comportamento cooperativo. Esse mesmo cenário criou condições para a invasão e dominância do comportamento cooperativo. No segundo capítulo, um modelo bioeconômico foi desenvolvido e aplicado para pesca da tainha (*Mugil liza*) no Sul-Sudeste do Brasil. A complexidade aumenta com a escala da pescaria e com as modalidades de pesca consideradas, que passam a ser quatro petrechos: a pesca de cerco industrial, a pesca artesanal de emalhe de superfície, a pesca artesanal de cerco de praia e a pesca artesanal de emalhe anilhado. Nesse sistema—em que coexistem modalidades industriais e artesanais—fizemos cenários baseados em jogos não-cooperativos para analisar como uma restrição no esforço de pesca pode impactar o sistema considerando aspectos biológicos (estado final do estoque) e socioeconômicos (renda *per capita* das pessoas que pescam). Enquanto no cenário não-cooperativo o cerco de praia foi excluído da pesca, no cenário não-cooperativo restritivo todas as artes permaneceram no sistema obtendo um melhor estado de estoque e renda per capita. No último capítulo consideramos um modelo bioeconômico para um sistema multiespecífico com petrechos variados: um recorte na pesca artesanal do complexo lagunar de Laguna, Santa Catarina. Consideramos os botos-da-tainha (*Tursiops truncatus gephyreus*), as tainhas (*Mugil liza*) e os camarões (*Farfantepenaeus paulensis* e *Farfantepenaeus brasiliensis*). Os petrechos considerados foram a pesca com tarrafa, as redes de emalhe e o aviãozinho. Esse capítulo generaliza o modelo do capítulo dois com espécies do capítulo um e dois tentando analisar, em três cenários diferentes, as consequências socioeconômicas e ecológicas de um sistema considerando interações como a predação, o *bycatch* e respostas comportamentais na dinâmica dessas pescarias. A população de botos se mostrou ameaçada pela pesca acidental das redes de emalhe. Na solução do cenário de manejo ótimo as redes de emalhe foram excluídas, além disso o sistema perde um esforço equivalente ao de 994 pessoas. Por outro lado, no cenário de manejo, a renda *per capita* é maior e o estado final do estoque melhor do que nos demais cenários. Independente da complexidade do sistema, a relação entre as pessoas e os recursos envolve dimensões ecológicas, sociais e econômicas diretamente ligadas entre si e que interferem diretamente no comportamento dessas pessoas dentro do sistema. Logo, todas essas dimensões devem ser levadas em consideração em uma proposta de manejo.

Palavras-chave: Teoria dos jogos. Ecologia pesqueira. Manejo pesqueiro. Modelo bioeconômico. Pescaria de pequena escala. Sistema socioecológico. Camarão. Tainha. Boto nariz de garrafa.

ABSTRACT

Fishing communities, industrial fleets, enforcement institutions, management decision makers. Each stakeholder in a fishery has a different reality, perceives the system with a different point of view, with different interests — sometimes conflicting — and has different ways of dealing and understand the problems. As the stakeholders' interactions directly affect the fishery management and the changes in the ecosystem reflect in the system, it is a fact that every management strategy must account for the whole system. This thesis aims to access fishery management and associated ecological relations in a game-theoretic perspective. The main goal is to understand how ecologic, economic, and social factors interacts within the socioecological system of a fishery and how this interaction could affect positively the governance of the system. In three chapters, different fishery systems, with distinct complexities were explored. The first chapter presents a bioeconomic analysis of the shrimp fishery (*Farfantepenaeus paulensis* and *Farfantepenaeus brasiliensis*) with the shrimp fyke net in Laguna, Santa Catarina. In this chapter we combine a bioeconomic model with an evolutionary game to discuss how control perception and risk tolerance of the fishers could intervene in their decision to cooperate with a fishing effort restriction imposed by a management plan. The scenario with both high control perception and high risk tolerance facilitated the cooperative behavior. This same scenario created conditions for the cooperative strategy invasion. In the second chapter, a bioeconomic model was built and implemented for the mullet fishery (*Mugil liza*) in Southern-Southeastern Brazil. The complexity increases with the fishery scale and with the number fishing gears considered, four: the industrial purse seine, the artisanal gillnets, the artisanal beach seine, and the artisanal drift net. In this system — where small- and large-scale fisheries coexist — we considered scenarios based in non-cooperative games to analyze how a fishing effort restriction could impact the system biologic (stock health) and socioeconomically (per capita labor income). In the non-cooperative scenario, the beach seine fishing gear was excluded of the fishery, while in the constrained non-cooperative scenario all the fishing gears stayed in the system with a better stock status and a better *per capita* labor income. In the last chapter we considered a bioeconomic model for a multispecies and a multigear system: the artisanal fishery in the Lagoon complex of Santa Catarina. Species was the Lahille's bottlenose dolphin (*Tursiops truncatus gephyreus*), the mullet (*Mugil liza*) and the pink shrimp (*Farfantepenaeus paulensis* and *Farfantepenaeus brasiliensis*). Fishing gears was the casting net, the gillnets, and the shrimp fyke net. This chapter is a generalization of bioeconomic model presented in chapter two with the species from the first two chapters analyzing socioeconomic and ecologic implications from a system with interactions such as predation, bycatch and behavioral feedbacks. Bottlenose population was threatened by gillnet's bycatch. The optimal management solution excluded the gillnets. In addition, the system lost fishing effort equivalent of 994 people. On the other hand, optimal management scenario had the highest *per capita* labor income and better final stock status, in comparison with all other scenarios. Regardless system's complexity, the relationship between resources and people involves ecological, social, and economic dimensions directly linked to each other with directly intervention in people's behavior within the system. Therefore, all these dimensions must be considered in a management proposal.

Keywords: Game theory. Fishery ecology. Fishery management. Bioeconomic model. Small-scale fishery. Socioecological system. Shrimp. Lebranch mullet. Lahille's bottlenose dolphin.

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CONCLUSÃO GERAL

LISTA DE ABREVIATURAS E SIGLAS

ABS – Artisanal Beach Seine
ADN – Artisanal Drift Nets
AG – Artisanal Gillnets
AMP – Áreas Marinhas Protegidas
BS – Base Scenario
CDPF – Cobb-Douglas Production Function
CNCG – Constrained Non-Cooperative Game
FAO – Organização das Nações Unidas para Alimentação e Agricultura
IPS – Industrial Purse Seine
LCSC – Southern Lagoon Complex of Santa Catarina
LE – Labor Effort
LSF – Large-Scale Fishery
NCG – Non-Cooperative Game
NPV – Net Present Value
OA – Open Access
OM – Optimal Management
PCLI – *Per Capita* Labor Income
RSSF – Restricted Fishing Effort Small-Scale Fishery
SSF – Small-Scale Fishery
TLI – Total Labor Income
ZEE – Zona Economicamente Exclusiva

LISTA DE SÍMBOLOS

INTRODUÇÃO

H – harvest / captura

q – catchability / capturabilidade

E – fishing effort / esforço de pesca

X – stock size / tamanho do estoque

t – time / tempo

π – profit / lucro

p – price / preço

c – cost of fishing effort unit / custo da unidade de esforço de pesca

F – growth function / função de crescimento

θ – cooperative weight / peso da cooperação

PV – present value / valor presente

s – number of species / número de espécies

g – number of fishing gears / número de petrechos de pesca

v – number of vessels / número de embarcações

CAPÍTULO 1

K – carrying capacity

B – stock size

r – growth rate

f – fishing effort

q – catchability

δ – tendency to cooperate

P – fish market price

c – fishing unit cost

α – fishers' control perception

b – fishers' risk tolerance

H – harvest

t – time

F – fishing mortality

M – natural mortality

C – cooperators

NC – non-cooperators

π – profit

fit – fitness value

x – frequency

CAPÍTULO 2

P – set of players

N – number of players

T – number of periods

E – fishing effort

r – intrinsic rate

E_{2019} – fishing effort in 2019

X – stock size

H – harvest

X_0 – initial stock size

q – catchability

X_{25} – stock size in year 25

c – cost of a unit of fishing effort

NPV – net present value

l – laborers' percentage

k – carrying capacity

o – other costs percentage

m – shaping parameter

di – directly involved laborers per fishing effort unit

B_{MSY} – biomass level in the maximum sustainable yield

TC – total cost

Π – profit

δ – discount rate

TR – total revenue

p – fish price

PV – present value of the profit

R$ – reais (Brazil's currency)

CAPÍTULO 3

G – set of fishing gears
g – fishing gear
S – set of species
s – species
T – number of periods
E – fishing effort
r – intrinsic rate
X – stock size
H – harvest
X_0 – initial stock size
q – catchability
c – cost of a unit of fishing effort
NPV – net present value
l – laborers' percentage
k – carrying capacity
o – other costs percentage
m – shaping parameter
fd – fishers per fishing days ratio
B_{MSY} – biomass level in the maximum sustainable yield
TC – total cost
Π – profit
δ – discount rate
TR – total revenue
p – fish price
PV – present value of the profit
R$ – reais (Brazil's currency)
SD – standard deviation
μ – random variable

SUMÁRIO

1 INTRODUÇÃO GERAL

1.1 GESTÃO PESQUEIRA

Devido a vastidão dos oceanos, o recurso pesqueiro foi por muito tempo considerado inesgotável. Em 1883, por exemplo, Thomas Henry Huxley afirmava que com os métodos de pesca existentes, era inconcebível que grandes pescarias como o bacalhau, o arenque e a cavala, poderiam se extinguir (Shepherd, 1997). No entanto, com o avanço tecnológico das embarcações— que passaram da vela para o vapor—, das artes de pesca e do comércio, a pressão nos estoques começou a ser notada (Sims & Southward, 2006). Entre o final de 1960 e o início de 1970— a partir das evidências dos declínios de importantes estoques como o bacalhau, a anchoveta peruana, e arenque — a possibilidade de colapsos biológicos e econômicos de pescarias intensificou a necessidade de se discutir gestão pesqueira (Buckworth, 1998; Hilborn et al., 2020). Nessa época, considerando os grandes estoques, gerir uma pescaria consistia em tentar descobrir quanto deveria ser pescado para garantir o melhor custo-benefício, ou seja, o maior lucro possível sem que o recurso se esgotasse (Berkes et al., 2001). Entretanto, considerando os modelos de gestão com a política das capturas máximas sustentáveis—em que modelos populacionais aplicados à espécies alvo determinam limites de captura que garantem a sobrevivência do estoque e da atividade econômica da pesca—, os estoques continuaram em declínio e/ou colapsando, demonstrando que ter somente essa estratégia de gestão pode não ser um caminho sempre efetivo (Hilborn, 2010). Em meio a alguns sucessos isolados (Melnychuk et al., 2017) e dentre insucessos recorrentes—em que o foco do manejo era somente o estoque ou somente o lucro— a busca de ferramentas adicionais que pudessem contribuir para a sobrevivência das pescarias, abrangendo novas perspectivas voltadas para dimensão social da pesca começaram a fazer parte das discussões de gestão pesqueira (Jentoft & Chuenpagdee, 2015).

Em 1995, a FAO publicou o código de conduta para pescarias responsáveis. Nesse código, a gestão ou manejo pesqueiro é apresentado como um conjunto de medidas— inseridas em uma política com instrumentos e estrutura legal adequados—para a conservação a longo prazo e para o uso sustentável dos recursos pesqueiros. Essas medidas devem ser baseadas nas melhores evidências científicas disponíveis, garantindo a utilização otimizada do recurso pesqueiro, mantendo a disponibilidade para gerações presentes e futuras (FAO, 1995). Nesse mesmo documento são listadas as seguintes orientações, como parte dos objetivos de uma gestão pesqueira voltada à pesca responsável: (1) evitar exceder a capacidade da pescaria e manter a exploração dos estoques em níveis economicamente viáveis; (2) promover uma pesca sustentável nas condições econômicas com as quais as indústrias pesqueiras operam; (3) considerar os interesses de todas as pessoas envolvidas na pesca de subsistência, de pequena-escala e artesanal; (4) proteger a biodiversidade das espécies aquáticas ameaçadas; (5) permitir que estoques colapsados se recuperem, ou sejam ativamente restaurados; (6) avaliar — e corrigir, quando apropriado — os impactos ambientais adversos provindos da atividade pesqueira e (7) minimizar a poluição, o desperdício, os descartes, as capturas por petrechos abandonados ou perdidos, a captura de peixes e de outras espécies diferentes da espécie alvo e os impactos nas espécies associadas ou dependentes, utilizando medidas que incluam, na medida do praticável, o desenvolvimento e o uso de técnicas e petrechos seletivos, ambientalmente seguros e econômicos.

Mesmo considerando a grande diversidade de ferramentas, abordagens e orientações para a gestão pesqueira, seu objetivo central parece universal: garantir um fluxo razoavelmente estável e sustentável de benefícios provindos dos recursos pesqueiros para essa e para as próximas gerações da espécie humana (Berkes et al., 2001). No entanto, para atingir esse objetivo é necessário clareza em dois pontos fundamentais: (1) Quais são e para quem vai esses benefícios provindos dos recursos pesqueiros para a sociedade e (2) o que seria um fluxo estável e sustentável desses benefícios? Visto que a gestão ou manejo pesqueiro é o conjunto de ações, ferramentas e medidas utilizadas para conduzir a pesca a um objetivo previamente estipulado (Cochrane & Garcia, 2009), é necessário definir o contexto teórico da pesca, para então definir os objetivos e as ferramentas adequadas. Isto é, para que a gestão pesqueira atinja os objetivos traçados, todo o sistema precisa se articular em conjunto. Porém, para que o sistema se articule em conjunto é preciso que ele tenha uma boa governança.

1.2 GOVERNANÇA E OS PROBLEMAS PERVERSOS

Considere uma pescaria como um grande sistema composto por dois subsistemas: o sistema a ser governado e o sistema que governa. O sistema a ser governado é a pescaria e todo seu entorno — populações dos recursos pesqueiros explorados, famílias, empresas, comércio e outras instituições envolvidas na atividade pesqueira. O sistema que governa inclui agentes responsáveis pela gestão da pescaria — órgãos governamentais ou não-governamentais ou ainda formados pelas pessoas da própria comunidade, de fiscalização, de gestão e de legislação, por exemplo. Se considerarmos ainda as interações entre esses dois sistemas descritos anteriormente temos a estrutura da governança de uma pescaria na visão de Jentoft e Chuenpagdee (2015). Como indica a Figura 1.1, a governança de uma pescaria não diz respeito somente ao sistema que governa, mas também ao sistema a ser governado e às interações entre eles.

Em 1973, Rittel e Webber, (1973) definiram, em um contexto de planejamento e de políticas sociais, os "*wicked problems*" (problemas perversos, em uma tradução livre) e listaram dez características para esse tipo de problema: (1) o problema não pode ser definido de maneira completa, pois não é possível entendê-lo em sua completude; (2) o problema não tem um critério definido para quando o ele termina; (3) não existem soluções verdadeiras ou falsas, apenas soluções boas ou ruins; (4) não existe uma maneira rápida de testar uma solução, qualquer tentativa pode comprometer o problema; (5) cada solução é uma tentativa única, não é possível utilizar o método de tentativa e erro pois na segunda tentativa o problema já não é mais o mesmo; (6) não existe uma lista definida de regras ou de ações possíveis para lidar com o problema; (7) cada problema é único; (8) cada problema tem origem em um outro problema; (9) o problema pode ser entendido de diferentes formas dependendo da realidade de quem está analisando; (10) cada solução deve ser pensada com responsabilidade pois pode modificar o sistema negativamente.

Figura 1.1. Esquema da governança de um sistema socioecológico formada pelo sistema que governa, pelos sistema a ser governado e pelas interações de governança.

Em 2009, Jentoft e Chuenpagdee (2009) utilizaram o conceito de "*wicked problems*" para estudar os conflitos de governança em pescarias e sistemas costeiros, mostrando que as características listadas acima também se encaixam nos problemas das pescarias. Muitas vezes o problema a ser resolvido num sistema pesqueiro não está totalmente claro. Se pensarmos na explicação para a degradação de um recurso pesqueiro de uma determinada pescaria, não teríamos clareza se o problema teria origem na dinâmica da espécie ou se seria uma resposta a algum comportamento da espécie humana, ou ainda, se seria uma combinação desses dois fatores, por exemplo. Na maioria dos casos não existe uma única variável—seja ela social ou biológica—que explique completamente a situação (Jentoft & Chuenpagdee, 2009).

A partir daí, Jentoft e Chuenpagdee (2009) discutem a diferença entre gerenciamento e governança de uma pescaria, questionando as diferentes maneiras de entender a gestão pesqueira. O gerenciamento busca soluções técnicas, com ferramentas próprias, baseados em métodos e protocolos pré-estabelecidos, para tarefas determinadas e com objetivos claros e resultados mensuráveis. Já a governança é mais ampla e se preocupa com os valores de cada objetivo, com as implicações e com as prioridades. A governança geralmente requer conhecimentos práticos, éticos, filosóficos, baseados em experiência para interagir com os conflitos do sistema.

Dentre as caraterísticas de uma pescaria que faz com que a governança nesse sistema seja considerada um "*wicked problem*", podemos listar a diversidade, complexidade, dinamicidade e a heterogeneidade de escala (Jentoft & Chuenpagdee, 2015). A diversidade acontece devido a variabilidade e as diferenças entre os agentes da pescaria, que podem ter interesses e necessidades distintos e possivelmente distantes, ou ainda, contrários. A complexidade aparece no alto nível de interdependência, interrelação e intersecção entre os agentes e entre as interações que ocorrem no sistema. Ao intervir no sistema, por exemplo, todas as relações serão afetadas resultando em um efeito sistêmico difícil de prever ou contabilizar. A dinamicidade é devido a variabilidade das condições do sistema em relação ao tempo. As vezes essa variação é linear, mas na maioria dos casos é imprevisível e inesperada. A heterogeneidade de escala ocorre nas diferenças das escalas temporais e espaciais nas quais os agentes do sistema socioecológico e do sistema que governa funcionam e interagem entre si (múltiplas jurisdições no sistema que governa, por exemplo).

O desafio da governança em uma pescaria deve, portanto, ser considerado de um ponto de vista amplo e sistêmico. Cada sistema estudado, deve ser considerado parte de um conjunto diverso, complexo, dinâmico e estruturado em múltiplas escalas, como é o caso de uma pescaria (Chuenpagdee & Jentoft, 2019).

1.3A PESCA COMO UM SISTEMA SOCIOECÓLOGICO

Para refinar a caracterização e funcionamento do sistema a ser governado, Berkes et al. (2001) apresentam o termo sistema socioecológico. Esse termo reforça o conceito de que, em se tratando de sistemas que exploram recursos naturais, a dimensão ecológica e socioeconômica estão ligadas de maneira intrínseca e indissociável. Em se tratando de uma pescaria, a dimensão socioeconômica seria composta pelas famílias, empresas, pessoas que trabalham, organizações comunitárias, organizações religiosas e todas as demais parcelas da sociedade que interagem com a pesca (Berkes et al., 2003). A dimensão ecológica englobaria todo o ecossistema associado aos recursos pesqueiros explorados pela pescaria.

Então, ao gerir uma pescaria como sistema socioecológico deve-se incorporar à discussão — além do recurso pesqueiro explorado — os agentes que, de fato, decidem e agem sobre o recurso (Berkes et al., 2001). Em 1974, a porcentagem de estoques pesqueiros explorados em níveis sustentáveis era de 90,0 %, enquanto em 2017 esta porcentagem caiu para 65,8 %, sugerindo a sobrepesca como um problema central para a discussão da gestão pesqueira, tanto em escala local quanto global (FAO, 2020). Assumindo a pesca como um sistema socioecológico, a frase "*Todos sabem que o problema básico é a sobrepesca, no entanto, ninguém concorda em como esse problema deve ser resolvido*", dita por Ostrom (2009), aponta que o problema da gestão pesqueira é na realidade sobre como lidar com a natureza humana, para a partir daí reavaliar como lidamos com nossos recursos.

Sabendo que os recursos pesqueiros são renováveis e que esta renovação ocorre a uma taxa proporcional ao tamanho do estoque, a pergunta natural seria: "*quanto do estoque deve ser capturado e quanto deve ser preservado para garantir a persistência de uma pescaria?*" (Sumaila, 2013). A pergunta parece simples e a resposta, em alguns casos, não é impossível quando aplica-se modelos clássicos de avaliação de estoque emprestados da Ecologia Pesqueira (King, 2007). O problema está na hora de traduzir as predições dos modelos teóricos que emergem nos corredores da academia—ou nas agências destinadas a este fim—, em estratégias de manejo alinhadas com o mundo real. O desafio é maior do que entender e resolver os problemas de cada subsistema isoladamente—o sistema ecológico e o sistema socioeconômico—pois almeja-se entender como estes subsistemas funcionam em conjunto, em constante interação e de forma dinâmica. O desafio é ainda maior se consideramos sistemas pouco estudados, marginalizados em relação às políticas públicas, com problemas relacionados à pobreza e a segurança alimentar, por exemplo, como é o caso de muitas pescarias de pequena escala (Jentoft & Eide, 2011; Cinner et al., 2009).

1.4 AS PESCARIAS DE PEQUENA ESCALA

Até o final do século passado o futuro do desenvolvimento global da pesca era atribuído à pesca industrial de grande escala. Isso motivou o desenvolvimento de tecnologias com fins a maximizar o esforço de pesca dessa modalidade. Nesse contexto, os governos e suas políticas públicas ignoravam a pesca de pequena escala devido a sua ineficiência econômica. Acreditava-se que o único meio de expandir o setor de pequena escala era através da modernização, adotando tecnologias de larga escala ou prestando serviços para o setor da pesca industrial (Panayotou, 1982).

Com a crise global da pesca—incentivada pela supercapacidade do setor de grande escala—o modo de desenvolvimento industrial, baseado no aumento constante da capturabilidade, foi questionado. Depois de décadas colocando a economia e a eficiência como prioridade, entre 1990 e 2000, preservar as pescarias tradicionais e de pequena escala se tornou ainda mais fundamental (Schuhbauer & Sumaila, 2016). O grande potencial social, cultural e econômico das comunidades pesqueiras locais em termos de geração de emprego, distribuição de renda, nutrição, segurança alimentar, utilização sustentável dos recursos pesqueiros e economia de energia, começou a ser notado e valorizado (Chuenpagdee & Jentoft, 2015; Coronado et al., 2020; FAO, 2015; Jentoft & Eide, 2011)

A pesca de pequena escala concentra mais de 90% das pessoas diretamente envolvidas na pesca de captura em todo mundo (Chuenpagdee & Jentoft, 2015). Devido à imensa heterogeneidade entre os tipos de embarcação, os tipos de petrechos, a distância da costa e a cadeia produtiva do recurso pesqueiro, não é possível definir o setor de maneira objetiva (FAO, 2015). Geralmente as pescarias de pequena escala, incluem as pescarias tradicionais, artesanais, de subsistência, geralmente utilizando pequenas embarcações, com diversidade de espécies-alvo e baixa biomassa de captura que se concentram em regiões relativamente próximas a costa (Jentoft et al., 2017; Smith & Basurto, 2019). As pescarias de pequena escala são, em sua maioria, associadas culturalmente à comunidade local; e o recurso capturado é escoado principalmente para o consumo direto das famílias e para o comércio local. No entanto, essas definições dependem muito do contexto: uma mesma pescaria pode ser de pequena escala em uma localidade e de grande escala em outra. As pescarias de pequena escala recebem muito menos subsídios quando comparadas a pesca de grande escala, o que sugere uma falta de visibilidade para o setor, e uma marginalização do ponto de vista do reconhecimento perante às políticas públicas (Schuhbauer et al., 2017).

Em 2014 a ONU, através da FAO, publicou as “Diretrizes Voluntárias para Garantir a Pesca de Pequena Escala Sustentável”, documento que marca uma mudança a histórica quanto a visibilidade da pesca de pequena escala para as políticas públicas, levantando questões de direitos humanos e desenvolvimento sustentável. Os principais problemas enfrentados pelas pescarias de pequena escala podem ser de origem global, como as mudanças climáticas e a pressão econômica vinda do mercado global de pescado. Em escala local, a pobreza, a desigualdade de gênero, a poluição, a baixa governança, a falta de representatividade nas tomadas de decisão, a competição com pescas industriais e a sobrepesca, por exemplo, também podem ameaçar a existência dessas pescarias (FAO, 2015). Outro grande desafio enfrentado pela pesca de pequena escala é a falta de informações sistematizadas sobre a pesca, sobre a situação dos recursos explorados e sobre o sistema socioeconômico associado, dificultando ainda mais a representatividade e a relevância desse setor nas tomadas de decisões (Schuhbauer et al., 2017).

De maneira ampla, os efeitos da pesca de pequena escala ao sistema socioecológico associado são discutidos em torno de questões como: (1) o co-manejo ou conservação de seus habitats (Gelcich et al., 2019); (2) o risco que algumas práticas impõem ao ambiente natural e às espécies não-alvo (Shester & Micheli, 2011); (3) à valorização do conhecimento tradicional para o manejo (Begossi, 2008); e (4) os valores da diversidade cultural armazenada em muitas comunidades e tradições pesqueiras (Pellowe & Leslie, 2021). De maneira local—considerando as pescas de pequena escala específicas espalhadas pela mundo—as informações disponíveis são geralmente fragmentadas no tempo e no espaço, com dificuldades de padronização, dificultando a implementação de estratégias locais de manejo. A informação biológica e socioeconômica acerca desse setor é muito importante, e depende de incentivos e esforços contínuos dos governos e das organizações responsáveis pelo manejo pesqueiro.

1.5 MODELOS BIOECONÔMICOS

Ao desenvolver um modelo para uma pescaria, em geral busca-se descrever a dinâmica das espécies exploradas. Dessa forma, os cenários gerados pelo modelo seriam focados em procurar condições que garantam a sustentabilidade do estoque. No entanto, ao considerar esse único eixo—a dinâmica do estoque—deixa-se de lado fatores importantes como os impactos da pesca na renda das famílias, na geração de empregos ou na segurança alimentar. Por outro lado, ao considerar no desenvolvimento do modelo apenas aspectos socioeconômicos da pescaria, tende-se a gerar elementos para uma proposta de manejo que podem prejudicar a sustentabilidade do estoque. Portanto, para descrever a pescaria de modo a gerar elementos para a consolidação de um manejo que contemple o sistema socioecológico como um todo, é necessário que o modelo utilizado leve em consideração tanto aspectos biológicos quanto socioeconômicos.

Um modelo bioeconômico de uma pescaria reúne informações biológicas (e.g. taxa de crescimento e capacidade suporte) e econômicas (e.g. custos e preços de venda) para descrever o sistema (Clark & Munro, 1975). Dessa forma, esse modelo pode ser utilizado para investigar a dinâmica de uma pescaria considerando o sistema socioecológico associado a ela, facilitando a identificação de soluções que possam manejar o sistema natural em sincronia com o sistema socioeconômico. Ou seja, um modelo bioeconômico pode servir para analisar as consequências de cenários de manejo hipotéticos—como a restrição do esforço de pesca, a implementação de um sistema de quotas, ou até mesmo a proibição total da atividade pesqueira—no sistema socioecológico, e vice-versa.

Os modelos bioeconômicos podem considerar uma (Sumaila, 1997b) ou mais espécies (Lai et al., 2021), podem avaliar um (Trisak, 2005) ou mais petrechos (proposta do capítulo 2 dessa tese, Azevedo et al., 2021) e podem ser organizados para um local específico dentro de um país (proposta do capítulo 1 dessa tese, Azevedo et al., 2020) ou para uma pescaria entre países (Ulrich et al., 2002). Podem incluir interações biológicas (e.g. predação), interações econômicas (e.g. competição entre petrechos) ou mesmo interações tecnológicas (e.g. pesca de fauna acompanhante) (Kasperski, 2016), permitindo sua aplicabilidade para uma ampla diversidade de sistemas, e elaboração de múltiplos cenários hipotéticos para se projetar as consequências das mais diversas soluções.

A base de um modelo bioeconômico é a relação entre a dinâmica das populações das espécies pescadas (estoques pesqueiros), as capturas e as receitas. As informações de capturabilidade—característica técnica do petrecho que representa sua eficiência em capturar recursos—transformam os dados dos estoques em capturas. As informações sobre preços e custos transformam as capturas em receitas e lucros. As informações biológicas e as capturas atualizam o tamanho dos estoques para o próximo evento de pesca. Assim podemos modelar a dinâmica dessa pescaria ao longo de sucessivos eventos (e.g. anos, meses, temporadas).

A seguir uma versão simples e clássica de um modelo bioeconômico aplicado à pesca é apresentado (Grønbæk et al., 2020a). Considerando uma espécie explorada por um petrecho de capturabilidade q, com esforço de pesca no período t dado por E_t, a captura dessa espécie no instante t é dada por:

$$H_t = q \cdot E_t \cdot X_t$$

em que X_t é o tamanho do estoque no instante t.

Se o petrecho tem um custo c por unidade de esforço de pesca e o recurso é vendido a um preço p, o lucro dessa atividade—considerado como sendo a diferença entre a receita e o custo—no instante t será:

$$\pi_t = H_t \cdot p - c \cdot E_t$$

Se o estoque cresce naturalmente $F(X_t)$ no instante t, então o tamanho do estoque no próximo período é dado por:

$$X_{t+1} = X_t + F(X_t) - H_t$$

isto é, o tamanho do estoque mais o que ele cresce naturalmente em determinado período t, descontado de tudo que foi capturado nesse mesmo período, será o tamanho do estoque no próximo período.

A partir dessa estrutura básica, é possível incluir novas complexidades como mais espécies, outros petrechos e novas interações (ecológicas, tecnológicas ou socioeconômica), por exemplo. Utilizando as informações da dinâmica de um sistema pesqueiro, podemos utilizar um modelo bioeconômico como ponto de partida para outras análises, como por exemplo, associá-lo a uma abordagem da teoria dos jogos para investigar nuances comportamentais das pessoas envolvidas na pescaria dentro do sistema.

1.6 A TEORIA DOS JOGOS

A teoria dos jogos é uma abordagem matemática da interação entre agentes independentes com interesses próprios (Leyton-Brown & Shoham, 2008). A teoria é atribuída a John Von Neumann e Oskar Morgenstern e nasceu buscando estudar problemas de comportamento humano em economia (Von Neumann & Morgenstern, 1944). De modo geral, como vemos na Figura 1.2, para se definir um jogo é necessário que saibamos: (1) quem está jogando; (2) quais são as ações/estratégias possíveis; e (3) qual é a recompensa de cada agente para cada conjunto de ações/estratégias (Dugatkin & Reeve, 1988).

Figura 1.2. Esquema gráfico mostrando o que é necessário para se definir um jogo: definir quem joga, definir as regras e as escolhas possíveis, definir as recompensas.

Cada participante do jogo é considerado como agente racional que toma sua decisão baseado na análise das possibilidades de ações dos demais participantes, buscando maximizar recompensas e ganhos (*payoffs*). Pode haver um acordo prévio ou não, caracterizando um jogo cooperativo ou não-cooperativo, respectivamente (Leyton-Brown & Shoham, 2008).

Um jogo não-cooperativo clássico, organizado por Tucker (1983), é conhecido como o dilema dos prisioneiros. Dois prisioneiros A e B, suspeitos, são mantidos em celas separadas e sem comunicação. Para cada um deles é proposto exatamente o mesmo acordo: 1) se você confessar e seu parceiro também confessar cada um fica com cinco anos de prisão; 2) se um confessar e o outro não confessar, quem confessou saiu impune e quem não confessou fica com dez anos de prisão e 3) se ninguém confessar os dois ficam com um ano de prisão cada. A resposta deve ser dada simultaneamente sem saber o que o outro respondeu. Podemos apresentar os jogadores, as estratégias e os ganhos de forma gráfica, utilizando uma matriz de recompensas (matriz de *payoffs*; Figura 1.3).

Figura 1.3. Representação de uma matriz de recompensas para o dilema dos prisioneiros apresentado nessa seção. Para cada combinação de estratégias, é mostrado o ganho do prisioneiro A e o do prisioneiro B. Esse jogo pode ser apresentado com outros valores de recompensas.

Uma solução para um jogo é um cenário em que todos os jogadores ficam “satisfeitos” ao mesmo tempo, ou seja, em que todos os jogadores jogam sua melhor estratégia baseado nas possibilidades de ações dos adversários (Dugatkin et al., 1992). Os conceitos de Equilíbrio de Nash (Nash, 1950a) e de Pareto dominância (Pareto, 1909) são as ferramentas mais utilizadas para análise das soluções dos jogos. Ambos os conceitos envolvem estruturas comparativas que nos permitem dizer quais cenários são “melhores” do que os outros (Leyton-Brown & Shoham, 2008). Quando não for possível “melhorar” mais o resultado final para os jogadores, é porque o jogo chega em um Equilíbrio de Nash que, —em um contexto de uma população de jogadores—seria uma Estratégia Evolutivamente Estável (Nowak, 2006b). Ou seja, em uma solução de equilíbrio, nenhum jogador tem motivações para se desviar da estratégia escolhida. No caso do dilema dos prisioneiros a solução do jogo é a estratégia “(confessar, confessar)”. Por mais que o cenário “(não confessar, não confessar)” seja mais vantajoso para os prisioneiros em uma perspectiva coletiva, —o que definiria um Ótimo de Pareto—uma análise racional e individual das opções de modo a otimizar o desempenho individual acaba conduzindo-os para a estratégia de confessar. O prisioneiro A pensaria: “*Se meu parceiro confessar, eu ganho mais confessando também. Se meu parceiro não confessar, eu também ganho mais confessando*”. O prisioneiro B pensaria da mesma forma, o que conduz o jogo a solução (confessar, confessar) pois, independente do que o "oponente" fizer, confessar será sempre a melhor escolha.

Várias áreas como Ciências Políticas, Biologia, Psicologia, Linguística, Sociologia e Ciências da Computação utilizam os conceitos da teoria dos jogos em suas produções (Leyton-Brown & Shoham, 2008). Na Biologia, a teoria dos jogos foi generalizada para um contexto populacional, e reorganizada na teoria dos jogos evolutivos (Nowak, 2006a). Como a maioria dos recursos pesqueiros se comporta como de livre acesso na natureza—por falhas na gestão e na fiscalização—envolvendo conflitos entre diferentes entidades, a teoria dos jogos é frequentemente aplicada na gestão dos recursos pesqueiros, para analisar os sistemas de manejo existentes—ou não existentes (Sumaila, 1997a). Esta aplicação da teoria dos jogos para a pesca requer uma abordagem multidisciplinar, combinando questões e conceitos da Ecologia Humana, Economia, Ecologia de Populações e, especialmente, da própria Ecologia Pesqueira (Grønbæk et al., 2020b).

1.7 TEORIA DOS JOGOS APLICADA À PESCA

Segundo Munro (1979) um estoque compartilhado entre dois países em suas respectivas ZEE — zona economicamente exclusiva — deveria ser manejado de forma conjunta. Munro (1979) considera um País 1 e um País 2 compartilhando uma pescaria e sua conclusão foi embasada em simulações de jogos cooperativos e não-cooperativos utilizando a teoria da barganha—que valora as recompensas de cada jogador em um contexto cooperativo (Nash, 1950b). O jogo não-cooperativo se resume em encontrar a estratégia ótima de exploração dos recursos para os países 1 (PV_1) e 2 (PV_2) separadamente. A abordagem cooperativa otimiza as estratégias de maneira conjunta ($\theta \cdot PV_1 + (1-\theta) \cdot PV_2$), em que θ é o peso que mede o quanto cada país "cede" dos seus ganhos individuais para otimizar o ganho conjunto). Esse estudo aborda os jogadores de uma forma assimétrica, isto é, cada jogador tem custos e ganhos personalizados de acordo com seu contexto. Esse trabalho é o marco inicial da aplicação da teoria dos jogos na pesca. Note que a conclusão de Munro (1979) não diz que a pesca deve ser cooperativa entre os países, mas que o manejo deve ser discutido em conjunto entre eles.

Em 1980, o trabalho de Colin Clark foi publicado denotando que em um jogo teórico de dois jogadores explorando uma área de acesso restrito, o cenário não-cooperativo conduz a sobrepesca (Clark, 1981). A maioria dos trabalhos até 2000, modelam a exploração dos recursos pesqueiros por jogos de dois jogadores (Bailey et al., 2010). Mesmo quando a pesca envolve mais de duas entidades, o modelo pode agrupar os agentes envolvidos em dois grupos que compartilham estratégias, facilitando a construção e o tratamento computacional do modelo e transformando-o em um jogo de dois jogadores. Modelos da teoria dos jogos com dois jogadores—agrupando agentes em torno de estratégias—também analisaram a eficiência do manejo pesqueiro envolvendo áreas marinha protegidas (AMP) a partir dos anos 2000. Neste caso o jogo avalia as condições para que os agentes (pessoas que pescam) cooperem com a AMP e suas normativas legais (Sumaila & Armstrong, 2003).

Ao invés de mostrar os efeitos positivos da cooperação no manejo dos recursos pesqueiros, como a maioria dos trabalhos, Trisak (2005) focou em fatores que estimulam a cooperação ou a não-cooperação entre os jogadores. O autor conclui que fatores biológicos como a taxa intrínseca de crescimento populacional, bem como o tamanho do estoque — considerando uma população com crescimento denso-dependente —, são instintivamente perceptíveis pelos pescadores e influenciam na decisão deles de cooperar ou não (Trisak, 2005). Ou seja, em cenários em que os pescadores percebem um alto risco para o estoque — baseado na percepção empírica de questões ecológicas como taxa de crescimento populacional, aspectos reprodutivos e crescimento individual — os mesmos tendem a não cooperar com uma estratégia de manejo que busca a redução de capturas para o Rendimento Máximo Sustentável (Dunkelt, 1970).

Outro tipo de modelo envolvendo pescarias e a teoria dos jogos utiliza um jogo sequencial. Nesse tipo de jogo, o primeiro jogador faz sua jogada. Analisando a jogada realizada, o segundo jogador age após a decisão do primeiro jogador (Dugatkin et al., 1992). As jogadas não ocorrem simultaneamente, elas ocorrem uma depois da outra como em uma partida de xadrez. No trabalho de Laukkanen, (2003) um estoque que se desloca entre duas áreas diferentes é analisado. Na área 1 o estoque se alimenta e é explorado pelo jogador 1, na área 2 o estoque faz a desova e é explorado pelo jogador 2. Antes do jogador 2 escolher o esforço de captura a ser empregado para otimizar seu lucro, ele observa o esforço empregado pelo jogador 1 que explora a espécie primeiro. Nesse contexto a solução cooperativa só foi suportada à níveis moderados de incerteza de disponibilidade do estoque (Laukkanen, 2003).

Os modelos que envolvem—ou são adaptados para—jogos de dois jogadores são mais fáceis de trabalhar. No entanto, o desafio do manejo de estoques trasfronteiriços, estoques tranzonais e estoques de alto mar requerem jogos com mais jogadores devido ao interesse de múltiplas entidades (frotas ou países) em explorar esse tipo de estoque. Uma grande quantidade de esforço científico se dedicou à análise desses estoques expandindo a teoria de jogos com a possibilidade de alianças entre os jogadores (Bailey et al., 2010). Um cenário de aliança é quando um número de jogadores (menor que o total de jogadores) age cooperativamente (Lindroos et al., 2007). Uma pergunta que surge em um jogo com alianças é: "*quanto cada jogador deve receber* *de recompensa se um cenário de aliança ocorrer?*". Os métodos para responder essas perguntas envolvem: (a) o valor de Shapley (Shapley, 1953)—que dá pesos aos jogadores envolvidos com base nas contribuições marginais de cada um deles; (b) o núcleo—uma solução única que resulta da maximização dos benefícios da menor aliança aceitável (Schmeidler, 1969); e (c) a solução de barganha de Nash—que consiste em uma abordagem igualitária visto que sem qualquer dos jogadores aliados, a aliança não existiria (Nash, 1950b). Outro problema que envolve a abordagem das alianças é a estabilidade. Nada em uma análise da teoria dos jogos garante que os jogadores (países, na maioria das vezes) vão manter uma aliança estável. Pintassilgo (2003) diz que uma aliança é estável quando ela apresenta estabilidade interna—nenhum jogador da aliança ficaria melhor fora dela—e estabilidade externa—ninguém que está fora da aliança gostaria de entrar nela.

As externalidades associadas a um modelo são as consequências do modelo não previstas inicialmente por ele. No caso dos jogos com alianças, a análise das externalidades se volta em analisar os efeitos positivos e/ou negativos que a aliança pode causar nos demais envolvidos (Yi, 1997). Uma análise dessas externalidades pode ser feita ao se observar a mudança nas recompensas dos jogadores não aliados antes e depois da formação da aliança (Lindroos et al., 2007). Outras externalidades também podem ser exploradas: (a) a externalidade dinâmica é a perda bioeconômica gerada pela pescaria de um estoque com um número finito de agentes, ou seja, é a consequência das escolhas dos jogadores no estoque e nos próprios jogadores (b) a externalidade de mercado se refere as interações no mercado influenciadas pelo modelo e (c) as externalidades de interação entre espécies envolvem a relações entre as espécies exploradas com outras espécies (Sumaila, 1997a).

Para evitar as externalidades, um modelo pode tentar absorvê-las. É o caso dos modelos multiespecíficos, que já contam com as interações entre as espécies exploradas dentro do próprio modelo. Kasperski (2015) estuda o problema de maximizar os lucros de uma pescaria de s espécies, com g tipos diferentes de petrechos, manejados por v embarcações. Nesse modelo podem ser incorporadas interações ecológicas entre as espécies, interações econômicas na escolha dos petrechos e das espécies alvo de cada embarcação e interações tecnológicas derivadas da natureza de cada petrecho (Kasperski, 2015). Já o trabalho de Lai et al. (2021) estuda uma rede trófica entre o arenque (*Clupea harengus*), o salmão (*Salmo salar*) e a foca cinzenta (*Halichoerus grypus*) para explorar as possíveis consequências da pescaria dessas espécies em diferentes cenários de variação populacional. A incorporação da dinâmica entre as espécies em uma análise de manejo pesqueiro via teoria de jogos é um desafio complexo e atual em termos de pesquisa científica e também como problema de gestão pesqueira (Grønbæk et al., 2020a).

Portanto, a aplicação da teoria dos jogos em um contexto de manejo pesqueiro inclui diferentes abordagens como as alianças (Lindroos et al., 2007; Pintassilgo, 2003; Pintassilgo et al., 2015), os modelos multiespecíficos (Kasperski, 2015; Salenius, 2018), a gestão baseada no ecossistema (Cisneros-Montemayor et al., 2020; Miller et al., 2013), os jogos evolutivos (proposta do capítulo 1, Azevedo et al., 2020), e os jogos sequenciais (Laukkanen, 2003; Punt, 2018), por exemplo. Em geral, essa literatura é massivamente focada nas pescarias internacionais, onde países competem por um ou mais estoques compartilhados. Portanto, a aplicação da teoria dos jogos em pescarias locais e nacionais é considerada um campo pouco explorado, uma nova fronteira na pesquisa dos sistemas pesqueiros (Grønbæk et al., 2018).

1.8 OBJETIVOS

1.8.1 Objetivo geral e hipótese

Essa tese de doutorado busca trazer uma perspectiva da teoria dos jogos acerca da gestão pesqueira e das relações ecológicas que a permeiam. O objetivo é entender como os fatores ecológicos, econômicos e sociais interagem no sistema socioecológico de uma pescaria e como essa interação pode contribuir para o fortalecimento da governança desse sistema. A nossa hipótese geral é de que os modelos bioeconômicos aliados à teoria dos jogos, considerando as interações entre os fatores ecológicos, sociais e econômicos inseridos no sistema socioecológico de uma pescaria, podem orientar cenários de manejo sustentáveis para o sistema.

1.8.2 Objetivos específicos

a. Descrever diferentes sistemas pesqueiros através de modelos bioeconômicos;
b. Utilizar a teoria de jogos para explorar como os modelos bioeconômicos interagem com os fatores ecológicos, econômicos e sociais da pescaria;
c. Identificar, em cada sistema pesqueiro, fatores que possam ser decisivos para a sustentabilidade e governança do sistema socioecológico associado;
d. Entender como a percepção da fiscalização e a tolerância ao risco podem influenciar em um comportamento cooperativo de um sistema pesqueiro local com restrição de esforço de pesca (referente ao capítulo 1);
e. Analisar as implicações sociais e biológicas de diferentes cenários bioeconômicos em pescarias onde ocorre a coexistência de pesca de pequena e de grande escala (referente ao capítulo 2);
f. Investigar a pertinência dos modelos bioeconômicos aliado à teoria dos jogos para analisar mecanismos sociais e ecológicos em um sistema pesqueiro multiespecífico (referente ao capítulo 3);

1.9 ESTRUTURA DA TESE

Esse documento de tese explora a hipótese geral em três capítulos. Os capítulos trazem sistemas de pesca diferentes, com diferentes graus de complexidade (Figura 1.4). O primeiro capítulo faz uma análise bioeconômica da pesca do camarão rosa (*Farfantepenaeus paulensis* e *Farfantepenaeus brasiliensis*) com o aviãozinho em Laguna, Santa Catarina — aviãozinho é um petrecho passivo com redes de saco e com um atrativo luminoso organizados em um formato que lembra um pequeno avião. Nesse capítulo usamos um modelo bioeconômico aliado a um jogo evolutivo para discutir como que a percepção da fiscalização e a tolerância ao risco das pessoas que pescam (agente pesqueiro), pode influenciar na decisão dessas pessoas em cooperar com uma restrição no esforço de pesca imposta por um plano de manejo (objetivo d). Nesse capítulo o jogo é centrado em uma população que pesca com somente um único tipo petrecho, explorando um único recurso pesqueiro.

No segundo capítulo, apresentamos um sistema com quatro petrechos diferentes explorando concomitantemente um único estoque. O modelo bioeconômico desse capítulo foi aplicado à pesca da tainha (*Mugil liza*) no Sul-Sudeste do Brasil. A complexidade aumenta com a escala da pescaria e com a variedade de modalidades de pesca consideradas: a pesca de cerco industrial, a pesca artesanal de emalhe de superfície, a pesca artesanal de cerco de praia e a pesca artesanal de emalhe anilhado. Nesse sistema—em que coexistem modalidades de grande e de pequena escala—fizemos cenários baseados em jogos não-cooperativos para analisar como uma restrição no esforço de pesca pode impactar o sistema considerando aspectos biológicos (saúde do estoque) e socioeconômicos (renda *per capita*) (objetivo e).

No capítulo final, tanto o camarão rosa quanto a tainha — considerados isoladamente nos capítulos iniciais — coexistem em um sistema multiespecífico e multipetrecho. Nesse capítulo, generalizamos o modelo do capítulo dois apresentando um modelo bioeconômico para um subsistema da pesca artesanal do complexo lagunar em Laguna, Santa Catarina. Consideramos os botos-da-tainha (*Tursiops truncatus gephyreus*), as tainhas (*Mugil liza*) e os camarões (*Farfantepenaeus paulensis* e *Farfantepenaeus brasiliensis*). Os petrechos considerados foram a pesca com tarrafas, as redes de emalhe e o aviãozinho. Esse capítulo busca analisar o impacto socioeconômico e ecológico das interações biológicas (predação) e tecnológicas (bycatch) nesse sistema (objetivo f).

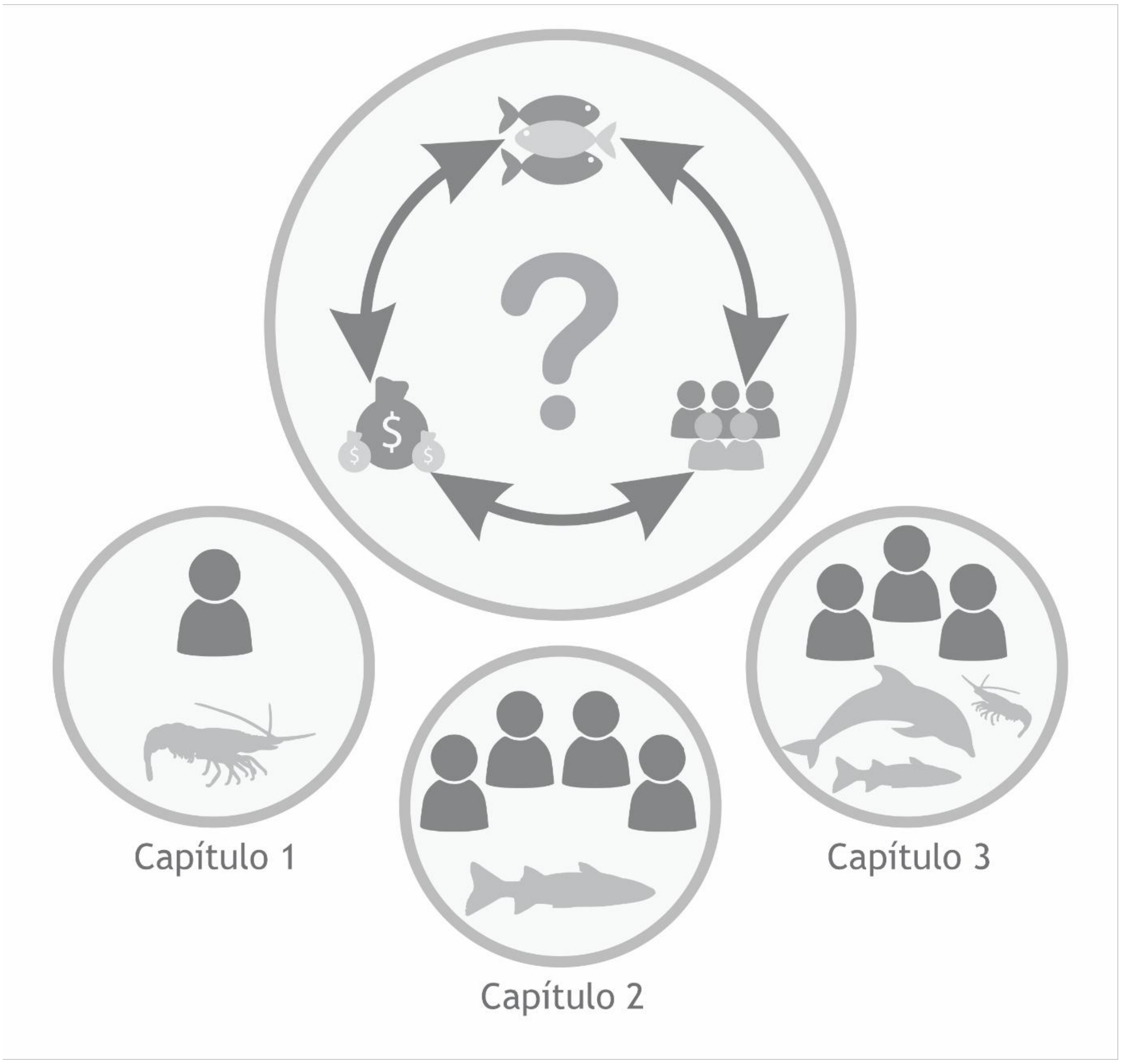

Figura 1.4. Resumo gráfico da tese mostrando a hipótese geral relacionando fatores sociais, ecológicos e econômicos. Cada capítulo também é ilustrado referente ao número de jogadores considerados (indivíduos ou petrechos) e de espécies consideradas em cada modelo.

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2 CAPÍTULO 1: RISK TOLERANCE AND CONTROL PERCEPTION IN A GAME-THEORETIC BIOECONOMIC MODEL FOR SMALL-SCALE FISHERIES.

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Manuscrito publicado na revista ***Royal Society Open Science*** *em 22 de Julho de 2020.*

http://doi.org/10.1098/rsos.200621

Abstract

Cooperation is generally the most advantageous strategy for the group; however, on an individual level, cheating is frequently more attractive. In a fishery, one can choose to cooperate by fishing only the regulated amount or to not cooperate, by fishing to maximize profits. Top-down management can help to emulate a cooperative result in fisheries, but it is costly and not always a viable alternative for development states. Here, we investigate elements of a fishing system that can be strategically managed to encourage a cooperative behaviour. Using bioeconomic data, we modelled an evolutionary game between two populations of fishers that differ if they cooperate or do not cooperate with a fishing restriction. We penalized players including risk tolerance and control perception, two social parameters that might favour cooperation. We assessed the degrees to which risk tolerance and control perception affect the cooperative behaviours of fishers in a restricted fishing effort small-scale fishery (RSSF) in southern Brazil. We also assessed the likelihood of a scenario wherein a cooperative strategy can evolve and dominate the system. We identified dominance and coexistence outcomes for the RSSF. Sensitivity analyses suggested that both control perception and risk tolerance could facilitate a cooperative outcome for the fishery.

Keywords: cooperation; bioeconomic models; evolutionary game theory; small-scale fishery; fisher behaviour; compliance.

2.1 INTRODUCTION

It is widely accepted that the "tragedy of the commons" [1] or the "tragedy of free for all fishing" [2] is the core of the issue in a Malthusian overfishing perspective [3]. Combined with technological advances, globalization of the fishing industry, marginalization and inappropriate policies, such perspective can turn the open and unregulated access of Common-pool resources unsustainable [3]. Any successful solution, whether applied through governmental intervention or through organization of a concerned community, will depend upon cooperation [4].

Despite potential costs to individuals, cooperation is "good"—in terms of fitness—for the members of a group [5]. From the perspective of the group, the individual cost, if any, is rationally justified. However, for all individuals in a cooperative situation, there is a more attractive choice: cheating [6]. This paradox presents a dilemma for stakeholders in social-ecological systems: how to deal with cheaters? In fisheries, independent of the scale, this dilemma waylays fishers, decision-makers, researchers, and all of those concerned about building a sustainable way to fish [7,8]. Cooperative behaviour in this complex conflict, can be explored through evolutionary game theory to discern tendencies or produce predictions concerning each agent's choices [9].

Game theory is a mathematical approach to studying the strategic interaction of independent agents and their interests [10]. John Von Neumann and Oskar Morgenstern introduced the field to the scientific community in their studies on human behaviour in an economic context [11]. In biology, John Maynard Smith and George Price brought a game-theoretical framework to study evolution [12]. Evolutionary game theory considers populations of fixed strategies players interacting randomly with each other [13]. A population succeed when it reproduces its strategy for future generations. Payoffs for this game are interpreted as reproductive fitness.

In fisheries games, the payoffs combine economic relationships drawn from fisheries (e.g. revenue, costs, market price) and ecological information about the stock (e.g. growth rate, stock size, catchability), resulting in so-called bioeconomic models [14]. Game-theoretic models for fisheries have focuses on international waters, and applications of this framework on national/regional scale fisheries have yet to be sufficiently explored [9]. However, small-scale fisheries are crucial in the health of fishing ecosystems [15] albeit the present scarcity of data concerning has direct consequences upon management strategies [16]. Managing strategies for fishers involve harvesting quotas, fishing effort restrictions, individual transferable quotas, protected areas, and co-management [17–23], requiring cooperation from stakeholders both to implement and to maintain the system.

In a restricted fishing effort small-scale fishery (RSSF), there is regulation of the number of fishing units permitted to harvest. Social dilemmas appear when agents must decide whether to obey the restriction or to cheat and exceed the quota [24]. Key factors include both risk [25] and control [26] perceptions. A fisher's attitude toward risk (uncertainty) is an important issue to model decision making in fisheries [27]. Risk tolerance has been incorporated before in fisheries game theory models [28] and has being defined by theoretical and empirical studies as the ability to support uncertainty. In fishery, it is influenced by the sense of availability of the resource in the future, fisheries prices' changes and environmental instabilities [25,28,29]. On another side, compliance, in criminal literature, is basically associated with certainty and severity of a punishment [30]. The control perception, in our study, is the amount of certainty that the fisher has about being punished [31]. Authorities' control over fisheries can be frequent or infrequent depending on the system, and the perception among fishers of control initiatives also factors into fishers' compliance [32].

We constructed a bioeconomic model for an RSSF using game theory. There is an extensive literature on the application of game theory to fisheries, and different approaches have been used in the last decades: two-players games, sequential games and coalitions games, to cite a few [33]. The seminal paper that analysed fisheries in a two-players game context was based in the classical Prisoner's Dilemma, which assumes that cheating is an equilibrium solution [34]—although non-cooperation does not automatically means a negative outcome [33]. To remove the temptation to cheat, our model assumes a priori that both risk tolerance and control perception can interfere in fishers' behaviour. We sought to illuminate the interactions of social features with the bioeconomic aspects of this system, including the following: a) are there combinations of values of risk tolerance and control perception that neutralize the system's natural tendency toward cheating dynamics and, in consequence, facilitate cooperation? b) is there a scenario wherein cooperative strategies can evolve and dominate the fishery game? We set our model with parameters empirically adjusted to a case study focusing on an artisanal shrimp fyke net fishery in Southern Brazil. In the last decades, game theory in fisheries has overwhelmingly focused on larger fleets and relatively simpler dynamics compared to artisanal fisheries close to open access, as the case here explored. We expect that our model helps to shed light on the conditions to the emergence of cooperation in small scale fisheries, which is absolutely essential in developing countries that do not have the capacity for top down enforcement and requires alternative and strategic management plans [35].

2.2 METHODS

2.2.1 The Model

Let A and B be two populations of fishers in a RSSF. Each population has a fixed strategy: to cooperate and to fish within the restrictions placed by a regulatory agency (cooperators), or to not cooperate and to fish pursuing individual profit maximization (non-cooperators or cheaters). In this game, we assume that the fish stock is composed of only one species in logistic growth. Catchability, a gear efficiency parameter, is assumed to be constant. Generations will be the fishing seasons, as stages in repeated games. Additional parameters used in the model are listed in Table 2.1.

Table 2.1. Biological, economic, and social parameters used in the model.

Notation	Description	Unit
K	Carrying capacity	Kg (biomass)
B	Stock size	Kg (biomass)
r	Growth rate	Individual/time
f	Fishing effort	Fishing units (nets, fishers, vessels, etc.)
f^*	Fishing effort regulated by law	Fishing units (nets, fishers, vessels, etc.)
q	Catchability	Percentage
P	Fish Market price	Reais (Brazil's Currency)
c	Fishing unit cost	Reais (Brazil's Currency)
δ	Tendency to cooperate	Percentage

α	Fishers' control perception	Percentage
b	Fishers' risk tolerance	Percentage
H	Harvest	Kg (biomass)

A behaviour penalty (δ) is calculated using the risk profile (b), control perception (α), and the growth rate of the stock (r). This penalty varies from zero, when cooperators has the maximum penalty, to one, when cheaters have the maximum penalization. We calculated this parameter by:

$$\delta = \frac{\alpha}{1 + b \times r} \quad (E1)$$

The bottom expression shows the risk profile (b) and growth rate (r) in a negative relationship with the population penalty. High repositions of the stock (growth rate is high) will favour cheaters because stock will recover fast, reducing the sense of overharvesting and that a restriction is indeed necessary. Risk profiles vary from zero to one and show whether the fisher has a high $(b \gg 0)$ or low $(b \gg 1)$ risk tolerance. In this model, high risk tolerance will favour cooperators because, in this case, uncertainty will not drive fishers to fish more. Alternatively, behaviour penalty is directly proportional to control perception [30]. When perception of control is low (close to zero), for instance, the cheaters are favoured.

2.2.2 The Stock Dynamics

Gulland's harvest equation (Gulland, 1983) shows the relationship of harvest to stock size:

$$H = \frac{F}{F + M} \cdot B \cdot \left(1 - e^{-(F+M) \cdot t}\right)$$

In time t, H represents the amount harvested; M and F represents, respectively, stock mortalities by harvest and by natural causes and B captures the biomass of the stock. We considered $t = 1$ because of the short fishing season. As natural mortality is a biological characteristic, we are assuming it to be constant and to not play an essential role in the dynamics of the system. For that reason, we assigned the value of natural mortality to $M = 0$. We assume $F = q \cdot f$ because fishery mortality depends on fishing effort and catchability. So $H = B \cdot (1 - e^{-q \cdot f})$. Harvest equation was used to calculate payoff's matrix.

2.2.3 The game

We are playing a symmetric, simultaneous, deterministic, repeated evolutionary game. After set populations' strategies, each one receives their payoffs depending on the bioeconomic model. π_{CC} is the payoff for cooperators that meet each other. When a cooperator found a cheater, cooperators receive π_{CN} and cheaters receive π_{NC}. Cheaters encounters with themselves has a payoff measured by π_{NN}. The first payoff index indicates the individual that is receiving the payoff, either a cooperator or a noncooperator (cheater). The other index indicates who meet with the payoff receiver. C stands for "cooperator" and N for "non-cooperator". Table 2.2 shows all possible encounters with the respective payoffs.

Table 2.2. Cooperators and non-cooperators encounters. (π_{XY} is the pay-off for an individual from the population of X in an encounter with an individual of population of Y. C indicates cooperator and N non-cooperator.)

	Cooperators	**Non-cooperators**
Cooperators	π_{CC}	π_{CN}
Non-cooperators	π_{NC}	π_{NN}

Since risk tolerance and control perception intervene in the decisions of population i we multiplied its payoff by δ for cooperators or by $(1-\delta)$ for non-cooperators. For instance: $\pi'_{CN} = \delta \cdot \pi_{CN}$ and $\pi'_{NN} = (1-\delta) \cdot \pi_{NN}$. Individuals payoffs consist of all revenues minus all costs during the fishing season. The expected payoff for each population (fitness) was calculated using the frequency of the population and the payoffs for each individual meeting. Cooperators fish the resource respecting fishing effort restrictions. When a cooperator meets a cheater, she/he will fish with a regimented effort while the cheater will try to maximize her or his profit. When cheaters find each other, they will both try to maximize their profit at the same time, regardless of restrictions, generating rent dissipation due to fishing race [37]. Payoffs on each case are presented hereafter and detailed in the ESM S1.

$$\pi'_{CC} = \delta \cdot \left(B\left(1-e^{-q \cdot f^*}\right) \cdot P - c \cdot f^*\right)$$

$$\pi'_{CN} = \delta \cdot \left(\frac{(c - B \cdot P \cdot q) \cdot f^*}{\ln\left(\frac{c}{B \cdot P \cdot q}\right)} - c \cdot f^* \right)$$

$$\pi'_{NC} = (1 - \delta) \cdot \left(\frac{\ln\left(\frac{c}{B \cdot P \cdot q}\right) - q \cdot f^*}{\ln\left(\frac{c}{B \cdot P \cdot q}\right)} B\left(1 - \frac{c}{B \cdot P \cdot q}\right) \cdot P - c \cdot \left(- \frac{\ln\left(\frac{c}{B \cdot P \cdot q}\right)}{q} - f^* \right) \right)$$

$$\pi'_{NN} = (1 - \delta) \cdot 0 = 0$$

2.2.4 Manipulating the model

We manipulated the model to produce findings independent of stock size (B). We divided all payoffs by the carrying capacity (*K*) and introduced two new parameters. The parameter $B' = \frac{B}{K}$ measures the relative stock size and $c' = \frac{c}{K}$ measures the fishing cost of a unit of the stock when it reaches carrying capacity. Manipulated payoffs can be accessed in the ESM S2.

2.2.5 Replicator's equation

To repeat the game over generations with a fixed payoff matrix we used the replicator's equation:

$$\frac{dx_C}{dt} = x_C \cdot (1 - x_C) \cdot [fit_C(\vec{x}) - fit_N(\vec{x})]$$

Here, $\frac{dx_C}{dt}$ is the variation in cooperators' relative frequency and $\vec{x} = (x_C, x_N)$ is the population's composition with $x_C + x_N = 1$ within every time interval. $fit_C = x_A \cdot \pi_{CC} + x_B \cdot \pi_{CN}$ and $fit_N = x_A \cdot \pi_{NC} + x_B \cdot \pi_{NN}$ are fitness values for cooperative and non-cooperative individuals, respectively.

2.2.6 Solving the game

The outcomes for the game were: cooperative dominance, cooperative coexistence, non-cooperative coexistence, no fishing situation, bistability and non-cooperative dominance. Cooperative dominance was defined as when a cooperative strategy was dominant upon non-cooperative one (Nash equilibrium). The same applies for non-cooperative dominance. Coexistence occurred when both strategies (populations) equilibrated the system with different frequencies. When the frequency of the cooperative population was higher, we defined it as cooperative coexistence. When the opposite occurred, we defined non-cooperative coexistence. No fishing situation occurred when fishing costs were higher than fishing revenue, making it unviable to fish. Bistability is an instable scenario where both populations could dominate with an instable equilibrium point relies between the dominance's outcomes. To determine outcome in each simulation we used conditions described in Table 2.3.

Table 2.3. Conditions for the outputs of strategic dynamics for the game. (Here, π_{CC}, π_{NC}, π_{CN} and π_{NN} are values taken from the pay-off matrix.)

Conditions	Output
$\boldsymbol{\pi_{CC}} > \boldsymbol{\pi_{NC}}$ and $\boldsymbol{\pi_{CN}} > \boldsymbol{\pi_{NN}}$	Cooperative strategy dominates
$\boldsymbol{\pi_{CC}} < \boldsymbol{\pi_{NC}}$ and $\boldsymbol{\pi_{CN}} < \boldsymbol{\pi_{NN}}$	Noncooperative strategy dominates
$\boldsymbol{\pi_{CC}} > \boldsymbol{\pi_{NC}}$ and $\boldsymbol{\pi_{CN}} < \boldsymbol{\pi_{NN}}$	Bistability
$\boldsymbol{\pi_{CC}} < \boldsymbol{\pi_{NC}}$ and $\boldsymbol{\pi_{CN}} > \boldsymbol{\pi_{NN}}$	Coexistence

Algorithms are presented in ESM S3. The equilibrium frequency in all coexistence outcomes was calculated, as shown in [13] by:

$$\bar{x} = \frac{\pi'_{NN} - \pi'_{CN}}{\pi'_{CC} - \pi'_{CN} - \pi'_{CN} + \pi'_{NN}}$$

2.2.7 Playing the game

At the beginning, the game represents the situation in which one population of cooperative individuals are coexisting with a population of non-cooperative individuals. x_C and x_N are the frequencies of the respective populations. Random encounters occur between these individuals and, for all of them, payoffs for everyone are accounted. Using the frequencies, we calculate expected payoffs for each population. These payoffs represent the reproductive fitness and replicator's equation uses them to decide how would be populations' frequencies in the next generation. Population with better fitness will grow better, together with its behaviour strategy. As the game evolve, one population could dominate making the opponent's frequency to be null. Or, the two populations could coexist with a stabilized frequency for each of them. Based on the game conditions we could predict what would happen over the generations.

2.2.8 The system

We fitted the model to RSSF in Laguna, Southern Brazil. This fishery targets shrimp (*Farfantepenaeus paulensis* and *Farfantepenaeus brasiliensis*) in a lagoon complex using an unusual shrimp fyke net (used only in Southern Brazil) since the decade of 1980 [38]. This passive fishing apparatus has two sleeves, a conic tunnel, and a bagger, and attracts fish using a lighted sign. Using a unique LED lamp, six fyke nets can be combined in a circular layout (ESM S4), trapping shrimp from all directions [39]. This fishery, and particularly this resource, is very important for the surrounding communities, both economically and culturally [38]. Local ordinance n°32/1998 prescribes that only one location with six nets can be used for each licensed professional fisher [40]. The number of shrimp fyke nets found is more than the number of licensed fishers, indicating illegal harvesting [38]. Personal observations indicate that fishers indicated that the use of only one location restricts too much of the fishery, and relayed that without proper enforcement, some fishers utilize 70 or more locations. Concerned communities requested reviews of license regulation and for the approval of three fishing locations in a fishery agreement proposal, each spot with six nets. We applied our model to this system assuming the cooperation strategy, with fishers using only 18 nets, in accordance with the fishery agreement ($f^* = 18$). Some parameters were empirically determined using personal observations, technical reports, and investigations upon this fishery as shown in the ESM S5.

2.2.9 Sensitivity Analyses

In all simulations, we fixed the values for parameters P, q, c' and f^* ($P = 23$, $q = 0.023$, $c' = 2 \times 10^{-5}$ and $f^* = 18$). To build a scenario, we set values for α_1, α_2, b_1, and b_2 and the algorithm generated a game for each B' and r value from zero to one and between zero and two, respectively. In the coloured graphs, each colour identifies one of the possible outcomes. We set four different scenarios according to risk tolerance and control perception. For each of these scenarios, we analysed cooperative strategy frequency equilibria and how they evolve according to growth rate and to relative stock size. Finally, we present two scenarios in which cooperation invades a non-cooperative population as a strategy.

2.3 RESULTS

2.3.1 Risk tolerance and control perception scenarios

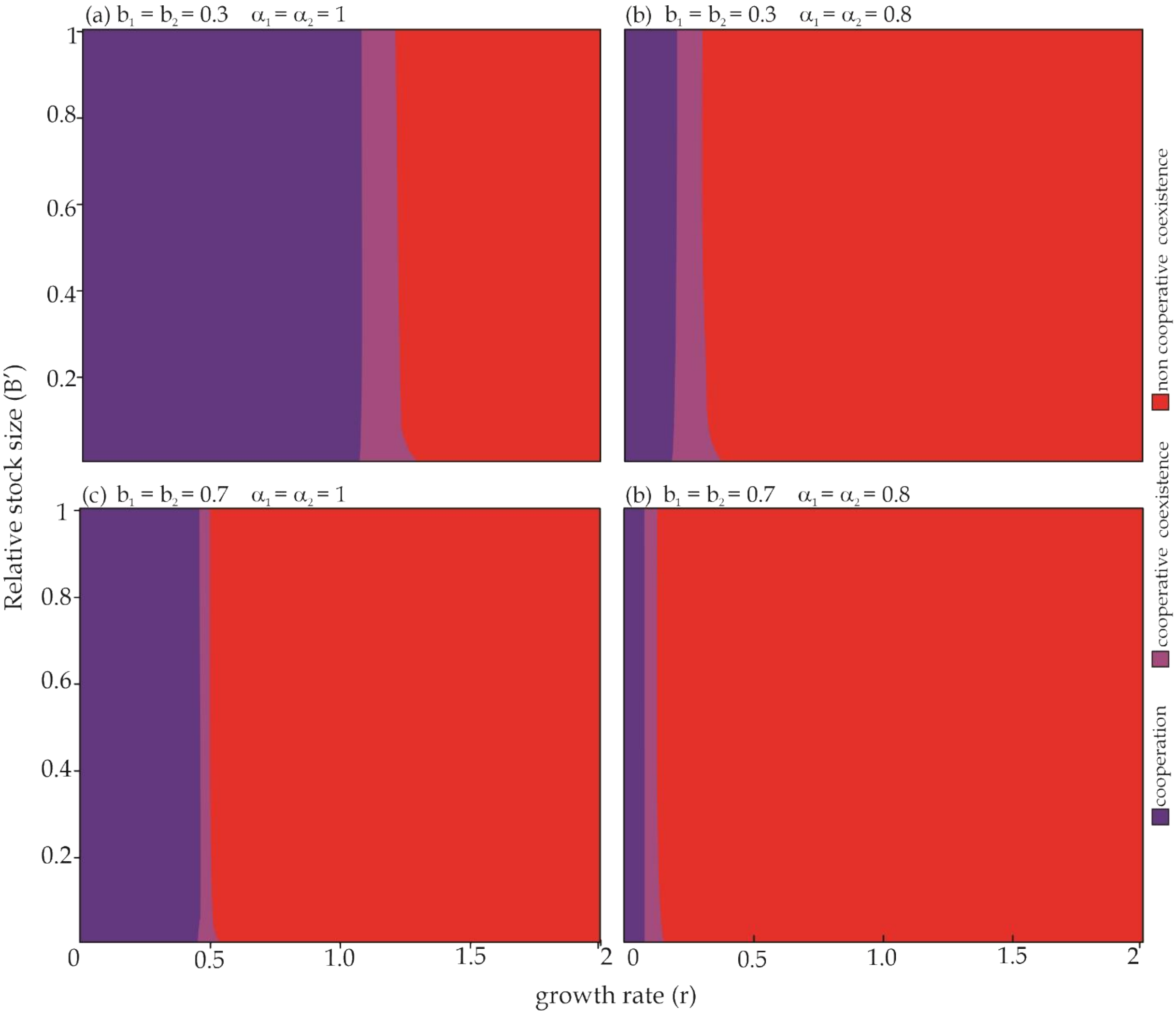

Figure 2.1. Cooperative dominance (blue), cooperative coexistence (pink) and non-cooperative coexistence (red) outcomes in two high risk tolerance ($b = 0.3$) scenarios (a) with a symmetric high perception of control ($\alpha = 1$) and (b) a symmetric low perception of control ($\alpha = 0.8$), and in two low risk tolerance ($b = 0.7$) scenarios (c) with a symmetric high perception of control ($\alpha = 1$) and (d) with a symmetric low perception of control ($\alpha = 0.8$). Every parameter beside α is the same in both scenarios ($b1 = b2 = 0.3, p = 23, q = 0.023, c' = (2 \times 10)^{-5}$).

When risk tolerance is high, there is an evident effect of control perception upon cooperative outcomes (Figure 2.1a-b). Desirable outcomes for the system include both cooperative dominance and cooperative coexistence, in opposition to an undesirable non-cooperative coexistence. The most frequent outcome in Figure 2.1a is the cooperation domination with some cooperative coexistence for growth rate (r) values between 1.1 and 1.3. For $r > 1.3$, we found non-cooperative coexistence outcomes. Figure 2.1b shows a very small cooperative dominance range $(0 < r < 0.2)$. Cooperative coexistence appeared in Figure 2.1b when $0.2 < r < 0.33$. Noncooperative coexistence appeared in Figure 2.1b for almost every game with $r > 0.33$.

For low-risk tolerance scenarios, the perception of control also had a positive effect on cooperative outcomes (Figure 2.1c-d). Cooperation strategy dominated when $0 \leq r \leq 0.46$ and when r increased, the frequency of the cooperative strategy decreased. On the other hand, Figure 2.1d shows primarily noncooperative coexistence outcomes. Cooperative domination and cooperative coexistence take place only when $r < 0.14$. For all scenarios, high values of growth rate discouraged cooperation.

High-risk tolerance with high control perception facilitates cooperation (Figure 2.1a) and low risk tolerance with low control perception discourages cooperative behaviour (Figure 2.1d). The sensitivity of the model was higher for control perception than it was for risk tolerance.

2.3.2 Growth rate as driver for the cooperative behaviour

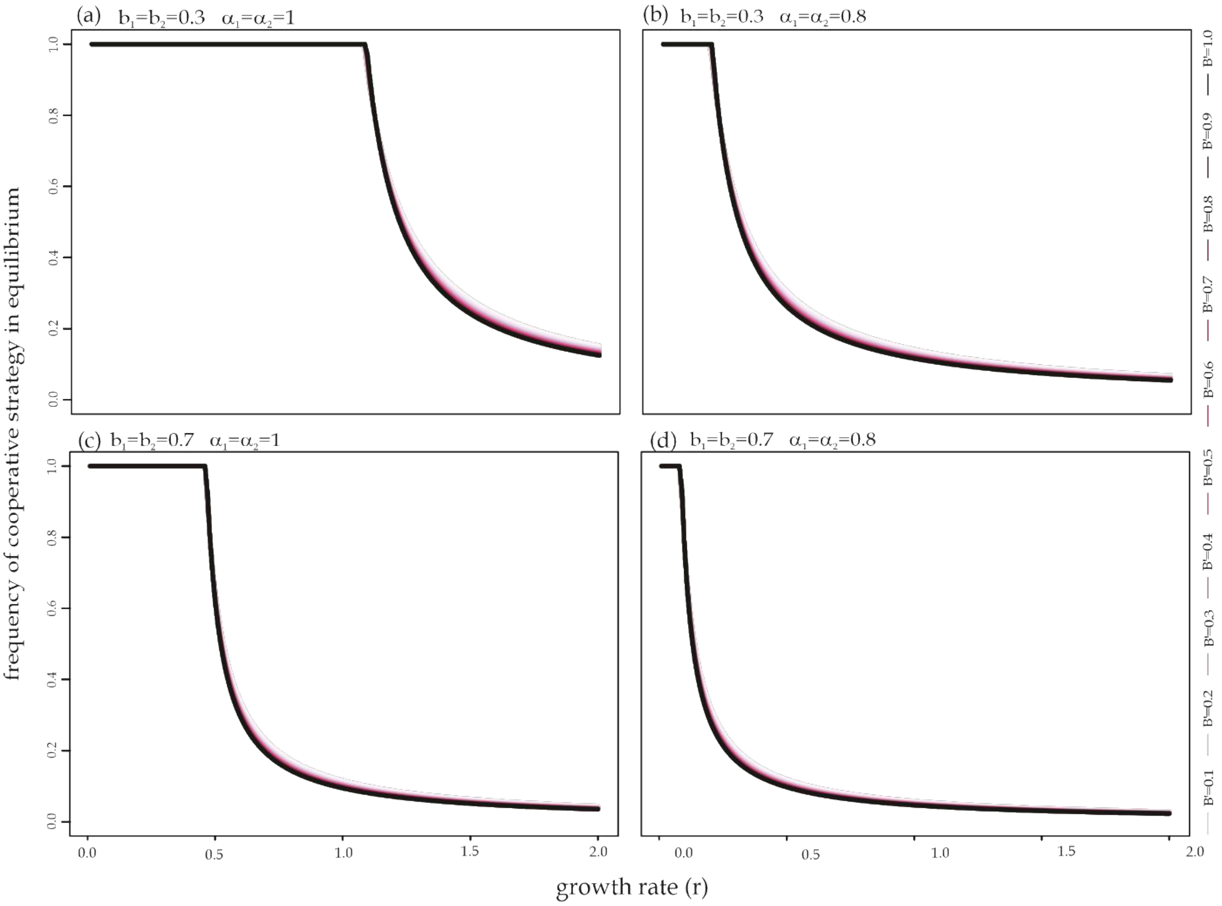

Figure 2.2. Interactions of cooperative strategy's frequency with growth rate in multiple scenarios: (a) with high risk tolerance and high perception of control, (b) with high risk tolerance and low perception of control, (c) with low risk tolerance and high perception of control, and (d) with low risk tolerance and low perception of control. Each colored line represents a different relative stock size (B') value. Besides risk tolerance and control perception, all parameters are constant ($p = 23, q = 0.023, c' = (2 \times 10)^{-5}$).

Growth rate (r) and risk tolerance (b) are components that control fishers' behaviour in the model (E1). Relative stock size (B'), however, influenced outcomes indirectly, through the payoff functions. Figure 2.2 shows that the growth rate is a better driver of the frequency of cooperative strategy than relative stock size. While variations in growth rate (horizontal axis) shape the curve, variations in B' value (coloured scale) result in overlapping curves. When coexistence for both cooperative and non-cooperative strategies is the outcome for the game, the frequency of the former decreases as growth rate increases.

2.3.3 Invasion of the cooperative strategy

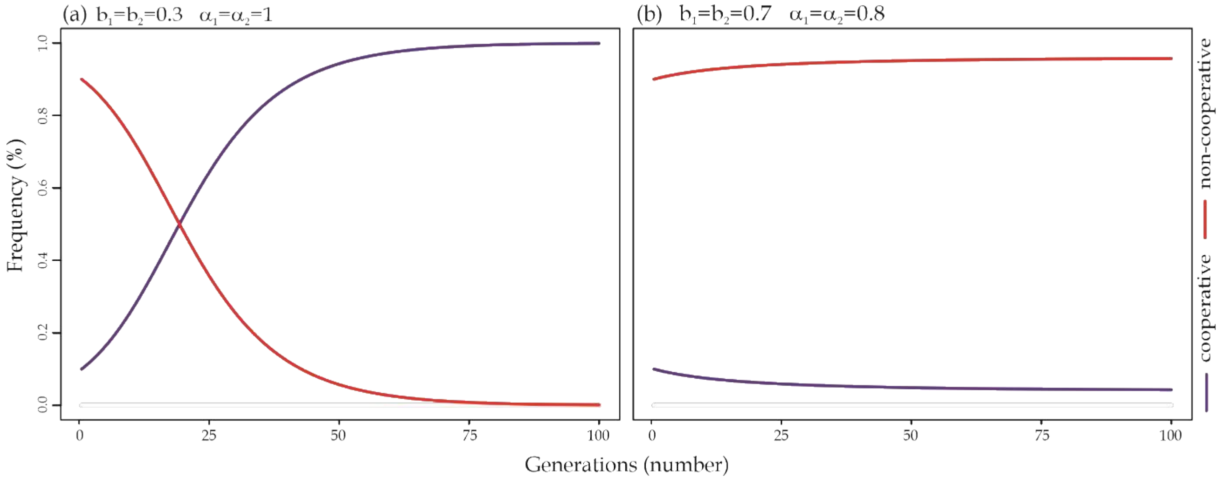

Figure 2.3. Dynamics of the strategic game between cooperative (blue) and non-cooperative (red) fishers in (a) high and (b) low risk tolerance and control perception scenarios using the replicator's equation. The initial population composition is 10% of cooperative individuals and 90% of non-cooperative individuals. Both scenarios have the same relative stock size (B') and growth rate (r) ($B' = 0.3$ and $r = 1.0$). Besides risk tolerance and control perception all parameters are constant ($p = 23, q = 0.023, c' = (2 \times 10)^{-5}$).

Figure 2.3 shows two different scenarios in which a population with 90% non-cooperative individuals (the residents) and 10% cooperative individuals (the invaders) is simulated. The first scenario (Figure 2.3a) has high-risk tolerance and high control perception and encourages the invasion of cooperation by increasing the fitness of that strategy and, consequently, increasing its frequency dominance. In contrast, low-risk tolerance and low perception of control scenarios do not allow cooperative behaviour to invade (Figure 2.3b) and after multiple generations, the fitness of the cooperative strategy does not increase sufficiently to overcome non-cooperative behaviour and stabilizes in 4%.

2.4 DISCUSSION

This study focused on the interactions of risk tolerance and control perception with the bioeconomic aspects of RSSF. If we remove control and risk effects from the model, noncooperative coexistences result for all combinations of r and B' values (an all-red graph). This indicates that the game at its base state does not inspire cooperation. Manipulating risk and control effects in the fishery could be a way to obtain cooperative strategy dominant scenarios.

Using empirical information from Laguna's shrimp fyke net fishery, we were able to produce scenarios where cooperation was the most frequent outcome. The panorama presented in Figure 2.1a is a "good" scenario: high-risk tolerance and high control perception overcame the temptation to cheat and lead to a dominance of cooperation in most of the outcomes, indicating that cooperation could exist for some combination of these social parameter values. When control perception became low, either with high (Figure 2.1b) or low (Figure 2.1d) risk tolerance, the domination of cooperative strategies almost vanished as an outcome indicating a stronger influence through control perception when compared with risk tolerance. In the "bad" scenario (Figure 2.1d) we saw 80% of the fishers harvesting as much as possible to achieve maximum profit (see Figure 2.2d) while, on the other side of the water, fish stock significantly decreases due to overexploitation, in a probable future collapse [41]. Here, fishers did not feel that restrictions were enforced sufficiently, and they would not tolerate the risk of stock uncertainty ($\alpha_1 = 0.8$ and $b = 0.7$). In a model with only risk tolerance and growth rate variables influencing the tendency to cooperate (an absence of control perception), analyses in [25] showed differences in cooperation behaviour from high risk tolerance scenario (most of the outcomes were cooperative) to low-risk tolerance scenarios (few cooperative outcomes). The "no fishing zone" appeared in all other scenarios presented in [25] but did not appear in either of ours.

Our results showed the growth rate of the stock (r) as a driver in the frequency of cooperative strategies (Figure 2.2). As individuals sense the stock's characteristics, it might be important for management to focus on fishers' relation to the future of their resource. It is important to note that from the perspective of the fishers, the first result of changing from competition to cooperation is a reduction in revenue [42] and fishers' perceptions of the stock can differ from each other and also from authorities or experts in a shifted baseline [43]. Trisak's model also presented growth rate (r) as a driver for cooperative behaviour, and relative stock size encouraged non-cooperative behaviour in high risk scenarios [25].

In visualizing the invasion of cooperative strategies in a non-cooperative population, our results indicated that both risk tolerance and control perception are essential to guaranteeing the domination of cooperation. If the scenario is not good (Figure 2.3b), the temptation to cheat will prevent cooperation from arising in the system. On the other hand, if one could produce desirable values for risk tolerance and control perception (Figure 2.3a), a cooperative strategy could invade and dominate the fishing system, producing a new equilibrium state for the game.

These conclusions raise a critical question: How could we strategically manipulate control perception and risk tolerance in real life? The simplistic answer is to control the fishery effectively and to guarantee that there will always be fish for everybody. Considering the difficulty of bringing these strategies to reality, especially in a developing state, we refer to examples of management in local fisheries. An Amazonian protection area of sustainable use called Mamirauá uses joint management to control their most economical fishery [44]. The Pirarucu's (Arapaima gigas) stock is monitored by both fishers and researchers, requiring active participation form local habitants. Fishers are organized in an association of producers and they fish with a compliance-based transferable quotas scheme [44]. The local community helps to protect the lakes against invasions and illegal fishing activities. This type of protection area permits local people to remain interacting with biodiversity (habitation and exploration), helping management to achieve sustainable use [45]. Through joint monitoring, local perception of fishing control could raise as fishers control and manage their fishery. In addition, this example indicates that stabilizing stock size could be a way to manage risk influence in the system as constant values of catch through time could facilitate fishers to perceive the real state of the stock.

Fishing teams in Yucatán, Mexico [29], transferable quotas in Dutch fisheries [46], reform on regulations rules in small pacific islands [35] are other initiatives that improved cooperation in fisheries management. Of course, these measures do not guarantee success for all the fishery systems [47]. Stability of the cooperative system, also a complex issue, should be an early concern for management agents to guarantee the viability of cooperation [48]. For our case study in Laguna, based on our results, we recommend a package of initial measures to better perceive the fishery's particular characteristics. Both fishers and authorities aim to resolve legislation problems in a way to benefit economic and ecological interests about the fishery, but information about the system (scientific researches and local knowledge of ecologic and social aspects) are not existent or transparent for all. Produce and organize this information transparently could be a first step to achieve better regulation's rules. Over time, transparency could also decrease cheating and empower local community [49]. Information and transparency could also diminish fishers' uncertainty felling and by consequence the risk effect on their behaviour, which favour cooperation. In addition, as aforementioned, effective top-down enforcement is costly [50,51] increasing the seek for other compliance alternatives such as fisher's self-management and social norms (raised by empowerment of local fishers) [46]. Our model suggest that such alternatives can motivate cooperation if it increases the control perception by fishers.

It is important to note that small-scale fisheries are more complex than our model could have captured in this study, leaving some challenges for future work. Food security and poverty are important social drivers that account for a portion of model fishers' cooperative behaviour [52]. Other types of payoffs that would not be evaluated directly by money terms (such as tradition, social status or religion) could also contribute to fishers' decisions [53]. An analysis in an ecosystem level could also bring important insights and capture more complexity even for an one-species fisheries [54]. However, even simplifying the system, our model offers some directions for a strategic management. There is no way to build a sustainable fishing scenario besides working together with all stakeholders in an interdisciplinary task. The temptation to overfish in regular fisheries is sufficiently high that induces fishers not to behave cooperatively. Top-down enforcement costs for developmental states claim for better alternatives. Strategically manipulate risk tolerance and control perception, then, could be very useful management tools to mitigate overexploitation problems in small-scale fisheries, facilitating cooperative decisions.

2.5 ACKNOWLEDGEMENTS

We thank Andrea Freire, Asteroide Santana, Eduardo Giehl, Eduardo G. de Farias, Micheli C. Thomas, Natália Hanazaki, Pedro Pintassilgo, Rodrigo P. Medeiros and Sergio Floeter for all the suggestions. We also thank the two anonymous referees for comments and insights about our work.

2.6 FUNDING

No funding was received for this research.

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2.8 SUPLLEMENTARY MATERIAL

2.8.1 Supplementary Material *S1* – The Payoffs equations.

Case 1 – Cooperator meets cooperator

In this case, both individuals are cooperators. For that reason, we can assume that fishing effort for each player is f^*, the maximum effort regulated by law. So, we can calculate how much each of these players will won. If c is the cost of a fishing effort unit for the whole season, the total cost for each fisher will be $\text{Cost} = c \cdot f^*$. The revenue for the cooperator is $\text{Revenue} = H \cdot P$. Here, H is the harvest and P is the market price of the prey.

Harvest equation tell us that

$$H = B(1\text{-}e^{-q \cdot f})$$

But $f = f^*$, so:

$$H = B(1\text{-}e^{-f^* \cdot q})$$

And then:

$$\pi_{CC} = \text{Revenue-Cost} = B\left(1\text{-}e^{-q \cdot f^*}\right) \cdot P\text{-}c \cdot f^*$$

Finally,

$$\pi'_{CC} = \delta \cdot \left(B\left(1\text{-}e^{-q \cdot f^*}\right) \cdot P\text{-}c \cdot f^*\right)$$

Case 2 – Cooperator meets cheater

Suppose that cooperator meet a cheater. While cooperator is fishing with the fishing effort regulated by law, cheater is using all the effort she/he can to maximize her/his profit, despite of the regulation.

Payoff for the cheater is

$$\pi_{NC} = B\left(1\text{-}e^{-q \cdot f}\right) \cdot P\text{-}c \cdot f$$

For maximize this equation, lets derivate this function by f and make it zero.

$$\frac{\partial \pi_{NC}}{\partial f} = B(0\text{-}\left(\text{-}q \cdot e^{-q \cdot f_{max}}\right) \cdot P\text{-}c = B \cdot P \cdot q \cdot e^{-q \cdot f_{max}}\text{-}c = 0$$

So,

$$e^{-q \cdot f_{max}} = \frac{c}{B \cdot P \cdot q}$$

And then,

$$\mathrm{f_{max}} = -\frac{\ln\left(\frac{c}{B \cdot P \cdot q}\right)}{q}$$

With the maximum fishing effort, we can calculate the maximum harvest by

$$\mathrm{H_{max}} = B\left(1\text{-}e^{-q \cdot \mathrm{f_{max}}}\right)$$

From that harvest, some part will be for the cooperator and some other part (the bigger part) for the cheater. Harvested biomass will be proportional to each player fishing effort. Then

$$\mathrm{H_C} = \frac{\mathrm{f_A}}{\mathrm{f_{max}}}\mathrm{H_{max}}$$

$$\mathrm{H_N} = \frac{\mathrm{f_B}}{\mathrm{f_{max}}}\mathrm{H_{max}}$$

But $\mathrm{f_C} = \mathrm{f}^*$ and $\mathrm{f_C} + \mathrm{f_N} = \mathrm{f_{max}}$. So, $\mathrm{f_N} = \mathrm{f_{max}}\text{-}\mathrm{f}^*$. And then, for $\mathrm{H_C}$ we have:

$$\mathrm{H_C} = \frac{\mathrm{f}^*}{\mathrm{f_{max}}}\mathrm{H_{max}}$$

$$\mathrm{H_C} = \frac{\mathrm{f}^*}{\mathrm{f_{max}}}B\left(1\text{-}e^{-q \cdot \mathrm{f_{max}}}\right)$$

$$\mathrm{H_C} = \frac{\mathrm{f}^*}{-\frac{\ln\left(\frac{c}{B \cdot P \cdot q}\right)}{q}}B\left(1\text{-}e^{-q\cdot\left(-\frac{\ln\left(\frac{c}{B \cdot P \cdot q}\right)}{q}\right)}\right)$$

$$\mathrm{H_C} = -\frac{q \cdot \mathrm{f}^*}{\ln\left(\frac{c}{B \cdot P \cdot q}\right)} \cdot B\left(1\text{-}e^{\ln\left(\frac{c}{B \cdot P \cdot q}\right)}\right)$$

$$\mathrm{H_C} = -\frac{q \cdot \mathrm{f}^*}{\ln\left(\frac{c}{B \cdot P \cdot q}\right)} \cdot B\left(1\text{-}\frac{c}{B \cdot P \cdot q}\right)$$

$$\mathrm{H_C} = -\frac{q \cdot \mathrm{f}^*}{\ln\left(\frac{c}{B \cdot P \cdot q}\right)} \cdot B\left(\frac{B \cdot P \cdot q\text{-}c}{B \cdot P \cdot q}\right)$$

$$\mathrm{H_C} = -\frac{\mathrm{f}^*}{\ln\left(\frac{c}{B \cdot P \cdot q}\right)} \cdot \left(\frac{B \cdot P \cdot q\text{-}c}{P}\right)$$

$$H_C = -\frac{\left(B \cdot q - \frac{c}{P}\right) \cdot f^*}{\ln\left(\frac{c}{B \cdot P \cdot q}\right)}$$

Similarly, for H_N, we have:

$$H_N = \frac{f_N}{f_{max}} H_{max}$$

$$H_N = \frac{f_{max} - f^*}{f_{max}} B\left(1 - e^{-q \cdot f_{max}}\right)$$

$$H_N = \frac{-\frac{\ln\left(\frac{c}{B \cdot P \cdot q}\right)}{q} - f^*}{-\frac{\ln\left(\frac{c}{B \cdot P \cdot q}\right)}{q}} B\left(1 - e^{-q \cdot -\frac{\ln\left(\frac{c}{B \cdot P \cdot q}\right)}{q}}\right)$$

$$H_N = \frac{-\frac{\ln\left(\frac{c}{B \cdot P \cdot q}\right) - q \cdot f^*}{q}}{-\frac{\ln\left(\frac{c}{B \cdot P \cdot q}\right)}{q}} B\left(1 - e^{\ln\left(\frac{c}{B \cdot P \cdot q}\right)}\right)$$

$$H_N = \frac{\ln\left(\frac{c}{B \cdot P \cdot q}\right) - q \cdot f^*}{\ln\left(\frac{c}{B \cdot P \cdot q}\right)} B\left(1 - \frac{c}{B \cdot P \cdot q}\right)$$

Now we can calculate π_{CN} and π_{NC}. First π_{CN}:

$$\pi_{CN} = H_A \cdot P - c \cdot f_A$$

$$\pi_{CN} = -\frac{\left(B \cdot q - \frac{c}{P}\right) \cdot f^*}{\ln\left(\frac{c}{B \cdot P \cdot q}\right)} \cdot P - c \cdot f^*$$

$$\pi_{CN} = -\frac{(B \cdot P \cdot q - c) \cdot f^*}{\ln\left(\frac{c}{B \cdot P \cdot q}\right)} - c \cdot f^*$$

$$\pi_{CN} = \frac{(c - B \cdot P \cdot q) \cdot f^*}{\ln\left(\frac{c}{B \cdot P \cdot q}\right)} - c \cdot f^*$$

And, further, π_{NC}:

$$\pi_{NC} = H_B \cdot P\text{-}c \cdot f_B$$

$$\pi_{NC} = \frac{\ln\left(\frac{c}{B \cdot P \cdot q}\right)\text{-}q \cdot f^*}{\ln\left(\frac{c}{B \cdot P \cdot q}\right)} B\left(1\text{-}\frac{c}{B \cdot P \cdot q}\right) \cdot P\text{-}c \cdot (f_{max}\text{-}f^*)$$

$$\pi_{NC} = \frac{\ln\left(\frac{c}{B \cdot P \cdot q}\right)\text{-}q \cdot f^*}{\ln\left(\frac{c}{B \cdot P \cdot q}\right)} B\left(1\text{-}\frac{c}{B \cdot P \cdot q}\right) \cdot P\text{-}c \cdot \left(\text{-}\frac{\ln\left(\frac{c}{B \cdot P \cdot q}\right)}{q}\text{-}f^*\right)$$

Adding the tendency to cooperate δ we have:

$$\pi'_{CN} = \delta \cdot \left(\frac{(c\text{-}B \cdot P \cdot q) \cdot f^*}{\ln\left(\frac{c}{B \cdot P \cdot q}\right)}\text{-}c \cdot f^*\right)$$

and

$$\pi'_{NC} = (1\text{-}\delta) \cdot \left(\frac{\ln\left(\frac{c}{B \cdot P \cdot q}\right)\text{-}q \cdot f^*}{\ln\left(\frac{c}{B \cdot P \cdot q}\right)} B\left(1\text{-}\frac{c}{B \cdot P \cdot q}\right) \cdot P\text{-}c \cdot \left(\text{-}\frac{\ln\left(\frac{c}{B \cdot P \cdot q}\right)}{q}\text{-}f^*\right)\right)$$

Case 3 – Cheater meets cheater

In this case both players are cheating upon fishing regulation. We considered, as in [1], zero payoff for both cheaters in this case. When there isn't any regulation above harvest, fishermen act as in an open access fishery and fishes until revenue matches fishery costs. So:

$$\pi'_{A_{NN}} = (1\text{-}\delta) \cdot 0 = 0$$

2.8.2 Supplementary Material *S2* – Manipulating the model.

We manipulate the model in order to get some independency from stock size. To do so we divided all payoffs by constant K, the carrying capacity, introducing, then, two new parameters: $B' = \frac{B}{K}$ and $c' = \frac{c}{K}$.

$$\frac{\pi'_{CC}}{K} = \frac{\delta \cdot \left(B(1\text{-}e^{-18\cdot q}) \cdot P\text{-}c \cdot f^{*}\right)}{K}$$

$$\frac{\pi'_{CC}}{K} = \delta \cdot \left(\frac{B}{K}(1\text{-}e^{-18\cdot q}) \cdot P\text{-}\frac{c}{K} \cdot f^{*}\right)$$

$$\frac{\pi'_{CC}}{K} = \delta \cdot \left(B' \cdot (1\text{-}e^{-18\cdot q}) \cdot P\text{-}c' \cdot f^{*}\right)$$

Similarly, for payoffs in case 2 we have:

$$\frac{\pi'_{CN}}{K} = \frac{\delta \cdot \left(\frac{18 \cdot (c\text{-}B \cdot P \cdot q)}{\ln\left(\frac{c}{B \cdot P \cdot q}\right)}\text{-}c \cdot f^{*}\right)}{K}$$

$$\frac{\pi'_{CN}}{K} = \delta \cdot \left(\frac{f^{*} \cdot \frac{(c\text{-}B \cdot P \cdot q)}{K}}{\ln\left(\frac{c}{B \cdot P \cdot q}\right)}\text{-}\frac{c}{K} \cdot f^{*}\right)$$

$$\frac{\pi'_{CN}}{K} = \delta \cdot \left(\frac{\left(\frac{c}{K}\text{-}\frac{B}{K} \cdot P \cdot q\right) \cdot f^{*}}{\ln\left(\frac{c}{B \cdot \frac{K}{K} \cdot P \cdot q}\right)}\text{-}c' \cdot f^{*}\right)$$

$$\frac{\pi'_{CN}}{K} = \delta \cdot \left(\frac{\left(c'\text{-}B' \cdot P \cdot q\right) \cdot f^{*}}{\ln\left(\frac{c}{B' \cdot K \cdot P \cdot q}\right)}\text{-}c' \cdot f^{*}\right)$$

$$\frac{\pi'_{CN}}{K} = \delta \cdot \left(\frac{\left(c'\text{-}B' \cdot P \cdot q\right) \cdot f^*}{\ln\left(\frac{c'}{B' \cdot P \cdot q}\right)} \text{-}c' \cdot f^* \right)$$

For the cheater in the same case we have:

$$\frac{\pi'_{NC}}{K} = \frac{(1\text{-}\delta) \cdot \left(\frac{\ln\left(\frac{c}{B \cdot P \cdot q}\right)\text{-}q \cdot f^*}{\ln\left(\frac{c}{B \cdot P \cdot q}\right)} B\left(1\text{-}\frac{c}{B \cdot P \cdot q}\right) \cdot P\text{-}c \cdot \left(\text{-}\frac{\ln\left(\frac{c}{B \cdot P \cdot q}\right)}{q} \text{-}f^* \right)\right)}{K}$$

$$\frac{\pi'_{NC}}{K} = (1\text{-}\delta) \cdot \left(\frac{\ln\left(\frac{c}{B \cdot P \cdot q}\right)\text{-}q \cdot f^*}{\ln\left(\frac{c}{B \cdot P \cdot q}\right)} \cdot \frac{B}{K}\left(1\text{-}\frac{c}{B \cdot P \cdot q}\right) \cdot P\text{-}\frac{c}{K} \cdot \left(\text{-}\frac{\ln\left(\frac{c}{B \cdot P \cdot q}\right)}{q} \text{-}f^* \right)\right)$$

$$\frac{\pi'_{NC}}{K} = (1\text{-}\delta) \cdot \left(\frac{\ln\left(\frac{c}{B \cdot \frac{K}{K} \cdot P \cdot q}\right)\text{-}q \cdot f^*}{\ln\left(\frac{c}{B \cdot \frac{K}{K} \cdot P \cdot q}\right)} \cdot B' \cdot \left(1\text{-}\frac{c}{B \cdot \frac{K}{K} \cdot P \cdot q}\right) \cdot P\text{-}c' \cdot \left(\text{-}\frac{\ln\left(\frac{c}{B \cdot \frac{K}{K} \cdot P \cdot q}\right)}{q} \text{-}f^* \right)\right)$$

$$\frac{\pi'_{NC}}{K} = (1\text{-}\delta) \cdot \left(\frac{\ln\left(\frac{c'}{B' \cdot P \cdot q}\right)\text{-}q \cdot f^*}{\ln\left(\frac{c'}{B' \cdot P \cdot q}\right)} \cdot B' \cdot \left(1\text{-}\frac{c'}{B' \cdot P \cdot q}\right) \cdot P + c' \cdot \left(\frac{\ln\left(\frac{c'}{B' \cdot P \cdot q}\right)}{q} + f^* \right)\right)$$

For case 3, not so much work to do:

$$\frac{\pi'_{NN}}{K} = \frac{0}{K} = 0$$

Note that $B' = \frac{B}{K}$ measures the relative stock size. Then, even if we don't know the real stock size, we can work with overfishing, underfishing and other kinds of scenarios.

2.8.3 Supplementary Material S3 – Algorithms (software: R)

Algorithm

```
############################################################
##                                                        ##
##   Strategic game for restricted fishing effort small-scale fisheries     ##
##                                                        ##
##   Author: Eric Zettermann Dias de Azevedo              ##
##   Date of creation: 16/09/2019                         ##
##   Last update: 22/01/2020                              ##
##                                                        ##
############################################################

### DESCRIPTION#############################################
#                                                          #
# This algorithm models restricted fishing effort small-scale fisheries      #
# using game theory. Two fishers decide to cooperate or not to              #
# cooperate with the fishing effort restriction regulation. To cooperate    #
# is to follow the restriction and not to cooperate is to fish until       #
# maximize profit.                                         #
#                                                          #
# This simulations aims to evaluate cooperative behaviour in different   #
# scenarios of control perception and risk tolerance       #
#                                                          #
############################################################


ls() # List objects
rm(list=ls()) # Remove objects
if(!require(plot3D)){install.packages("plot3D");library(plot3D)}
if(!require(RColorBrewer)){install.packages("RColorBrewer");library(RColorBrewer)}

####################
#  Initial Set up  #
####################

risk <- 0.3 # risk coefficient
# Represents risk profile of the fisher.
# Values variate from 0 (high-risk toleration fisher) to 1 (low-risk toleration fisher)

alpha <- 1 # Control perception
# Represents how much the fisher feel that the fishery is being controled by autorithies
# Values variate from 0 (fisher did not feel any regulation enforciment) to 1 (fisher
# feel completely controled).
```

```
P <- 23 # Market price of the resourse (currency unit)

f <-18 # value of fishing units aloud by restriciotn of the fishing effort

q <- 0.023  # Catchability
# Prepresent how efficient is the fishing gear used to harvest.
# (biomass in kg per fishing unit per season)

cline <- 2*10^(-5) # cost divided per carrying capacity

# Variable Parameters #

r <- seq(0.01,2,0.01)  # growth rate.
Bline <- seq(0.01,1,0.01) # relative stock size
# represents how is the stock size relative to its carrying capacity.
# B'>> 1 means a stock in its maximum potencial
# B'>> 0 menas a stock too small compared to this potencial to be.

delta <- alpha/(1+risk/r) # tendency to cooperate
# represents how much the fisher is tending to cooperate
# accouting its control perception, risk tolerance and
# the stock growth rate

# Bulding outcomes #

Resultado <- matrix(nrow=100,ncol=200,data=rep(0,2000))
for (i in 1:200){
  for (j in 1:100) {

    Game<- matrix(
      nrow =2,
      ncol=2,
      data=c(delta[i]*(Bline[j]*(1-exp(-f*q))*P-f*cline), # cooperate and cooperate payoff
             (1-delta[i])*((log(cline/(Bline[j]*P*q))-f*q)/log(cline/(Bline[j]*P*q))*Bline[j]*(1-
cline/(Bline[j]*P*q))*P+cline*(log(cline/(Bline[j]*P*q))/q+f)), # non-cooparator's payoff when the other cooperates
             delta[i]*(f*(cline-Bline[j]*P*q)/(log(cline/(Bline[j]*P*q)))-f*cline), #cooparator's payoff when the other not
cooperates
             0)
    )

    # Checking for possibles outcomes - Strategies' dominance
    # Using Nowak (2006) criteria.
```

```
    output<- ifelse(Bline[j]*P*q<cline,0,                         # no fishing here. Costs are higher than revenue.
             ifelse(Game[1]>Game[2] & Game[3]>Game[4],1,            # domination of cooperation
                ifelse(Game[1]<Game[2] & Game[3]<Game[4],2,          # domination of non-cooperation
                   ifelse(Game[1]>Game[2] & Game[3]<Game[4],3,         # biestability
                      ifelse(Game[1]<Game[2] & Game[3]>Game[4],4,5))))) # Coexistence
    #For the coexistence outcome, we determinate cooperative strategy frequency in the equilibrium point (Nowak(2006)).

    output<- ifelse(output==4 & (Game[4]-Game[3])/(Game[1]-Game[3]-Game[2]+Game[4])<0.5,3.5,
             ifelse(output==4 & (Game[4]-Game[3])/(Game[1]-Game[3]-Game[2]+Game[4])>0.5,4,output))

    Resultado[j,i]<-output # creating output matrix.
  }
}

#   Ploting graph  #

Resultado[1]<-0 # just to set color scale
Resultado[2]<-4 # from 0 to 4
layout(matrix(c(1,1,2), 3, 1, byrow = TRUE))  # adjust plot window
image2D(t(Resultado), x = seq(0.01,2,0.01), y = seq(0.01,1,0.01),xlab="r",ylab="B'", lighting = F, main = "Game's outputs")
#ploting graph
mtext(paste("risco=",risk, " alpha1=",alpha," P=",P," q=",q ," c'=",cline, " f*=",f),side=3) # showing parameters
plot(0, 0, type = "n", bty = "n", xaxt = "n", yaxt = "n",xlab="",ylab="") # adjust for subtitles
legend("topleft", legend=c("no fishing", "domination of cooperation","cooperative coexistence"),fill=c("darkblue",
"#0071FF","darkred"),cex=1, bty="n") # subtitles
legend("top", legend=c("domination of non-cooperation", "biestability", "non-cooperative coexistence" ),
fill=c("palegreen","orange","red"),cex=1, bty="n") # subtitles

# Evolution of cooperative strategy frequency #

risk<-0.7
alpha<-1
layout(matrix(1, 1, 1, byrow = TRUE))
r <- seq(0.01,2,0.01)
Blinha<- seq(0.1,1,0.1)
freq <- c(rep(0,200))
plot(freq~r,type="l",lwd=3,col="white",ylim=c(0,1),ylab="Frequency of the cooperative strategy")
cores <- c(brewer.pal(n=9,name='PuRd'),"black") # set color scale

# ploting
for (j in 1:10 ){
```

```
            for (i in 1:200){
            delta <- alpha/(1+risk*r[i])  #tendency to cooperate
PM <-matrix(              # payoff's matrix
   nrow =2,
   ncol=2,
   data=c( delta*(Bline[j]*(1-exp(-f*q))*P-f*cline),
        (1-delta)*((log(cline/(Bline[j]*P*q))-f*q)/log(cline/(Bline[j]*P*q))*Bline[j]*(1-
cline/(Bline[j]*P*q))*P+cline*(log(cline/(Bline[j]*P*q))/q+f)),
        delta*(f*(cline-Bline[j]*P*q)/(log(cline/(Bline[j]*P*q)))-f*cline),
        0)
  )


 fC <- (PM[4]-PM[3])/(PM[1]-PM[3]-PM[2]+PM[4]) # frequency of cooperative strategy in equilibrium Nowak(2006)

  fC<-ifelse(fC>1|fC<0,1,fC) # for the case of a domination
  freq[i]<-fC

}
par(new=T)
plot(freq~r,type="l",lwd=3,ylim=c(0,1),col=cores[j],ylab="")
}

mtext(paste("risk=",risk, "control=",alpha," P=",P," q=",q ," c'=",cline, " f*=",f),side=3) # showing parameters
legend("topright",legend=c("B'=0.1","B'=0.2","B'=0.3","B'=0.4","B'=0.5","B'=0.6","B'=0.7","B'=0.8","B'=0.9","B'=1.0"),col
=cores,lwd=1) # subtitles for B' values.
```

Algorithm 2

```
##########################################################
##                                                      ##
##   Strategic game for restricted fishing effort small-scale fisheries     ##
##                                                      ##
##   Author: Eric Zettermann Dias de Azevedo            ##
##   Date of creation: 16/09/2019                       ##
##   Last update: 22/01/2020                            ##
##                                                      ##
##########################################################

######### DESCRIPTION ####################################
#                                                        #
# This algorithm builds payoff's matrix, generations matrix and a graph  #
```

```
# for frequency of the cooperative strategy in a evolutive game using     #
# Replicator's equation (Nowak, 2006)                                     #
# scenarios of control perception and risk tolerance                      #
#                                                                         #
###########################################################################


ls() # List objects
rm(list=ls()) # Remove objects
if(!require(plot3D)){install.packages("plot3D");library(plot3D)}

# Parameters #

risk <- 0.3
alpha <- 1
P <- 23
q <- 3*10^(-6)
cline <- 1.92*10^(-5)
Bline <- 0.3
r <- 1

fC <- 0.1 # initial population frequency
fN <- 0.9 #FC + FN = 1

#   Payoff's Matrix   #

delta <- alpha/(1+risk*r)  #tendency to cooperate

MP <-matrix(              #payoff's matrix
    nrow =2,
    ncol=2,
    data=c( delta*(Bline*(1-exp(-18*q))*P-18*cline),
          (1-delta)*((log(cline/(Bline*P*q))-18*q)/log(cline/(Bline*P*q))*Bline*(1-
cline/(Bline*P*q))*P+cline*(log(cline/(Bline*P*q))/q+18)),
          delta*(18*(cline-Bline*P*q)/(log(cline/(Bline*P*q)))-18*cline),
          0)
   )

colnames(MP)<-c("Cooperate","Not cooperate") #names for the columns
rownames(MP)<-c("Cooperate","Not Cooperate") #names for the rows
print("MATRIZ DE PAYOFFS (MP)") #print payoff's matrix
print(MP)                    #on screen
```

```
MP<-MP/max(MP) # adjust matrix values in relation to the bigger value.

# Generation's matrix (G) #

G <- matrix(nrow=101,ncol=2,data=rep(0,202))  # zero's matrix to start
G[1,] <- c(fC,fN) # first row is the initial condition of te frequencies
for (i in 1:100){      #loop for calculate each generation frequencies using replicator's equation (Nowak (2006))
  fit_C = G[i,1]*MP[1,1]+G[i,2]*MP[1,2] # cooperative fitness
  fit_N = G[i,1]*MP[2,1]+G[i,2]*MP[2,2] # non- cooperative fitness
  fit_M = G[i,1]*fit_C+G[i,2]*fit_N     # mean fitness

  var_C = G[i,1]*(fit_C - fit_M) #cooperative frequency variation for the next generation
  var_N = G[i,2]*(fit_N - fit_M) #non- cooperative frequency variation for the next generation

  G[i+1,1]<-G[i,1]+var_C # cooperative frequency for next generation
  G[i+1,2]<-G[i,2]+var_N # non-cooperative frequency for next generation

  k=i+1 #counter

 ifelse(G[i+1,1]>1 |G[i+1,1]<0 ,break,0)  # domination allert
  ifelse(G[i+1,2]>1| G[i+1,2]<0 , break,0) #

  }

G <- G[seq(1,k,1),]              # adjusting matrix
print("Generation Matrix (G)")   # printing
print(G)

#   Ploting graph  #

par(mfrow=c(1,1))    #ajust window
x <- seq(1,k,1)      # genarations vector
plot(G[,1]~x,type="l",ylim=c(0,1),col="blue",main="Dinamic of the
strategies",ylab="Frequency",xlab="generations",lwd=2) # frequency of coperative strategy for each genaration
lines(G[,2]~x,col="red",lwd=2) # frequency of non-coperative strategy for each genaration

legend("right", legend=c("coperative", "non-cooperative"), lty=c(1,1), col=c("blue","red"), lwd=2, bty="n") # subtitles

ifelse(k<100 & G[k,1]>G[k,2],mtext(paste("Cooperative strategy dominates in ",k," generations"),side=3),    # decide
between dominance and coexistence and show informations
      ifelse(k<100 & G[k,1]<G[k,2],mtext(paste("Non-cooperative strategy dominates in",k," generations"),side=3),
```

```
mtext(paste("Coexistence with: fC= ",round(G[100,1],digits=2)," e fN= ", round(G[100,2],digits=2)),side=3)))
mtext(paste("risk=",risk, " alpha=",alpha, " P=",P," q=",q," c'=",cline, " B'=",Bline," r=",r," fC=",fC ," fN=",fN),side=4)
#show parameters
```

2.8.4 Supplementary Material S4 – The System.

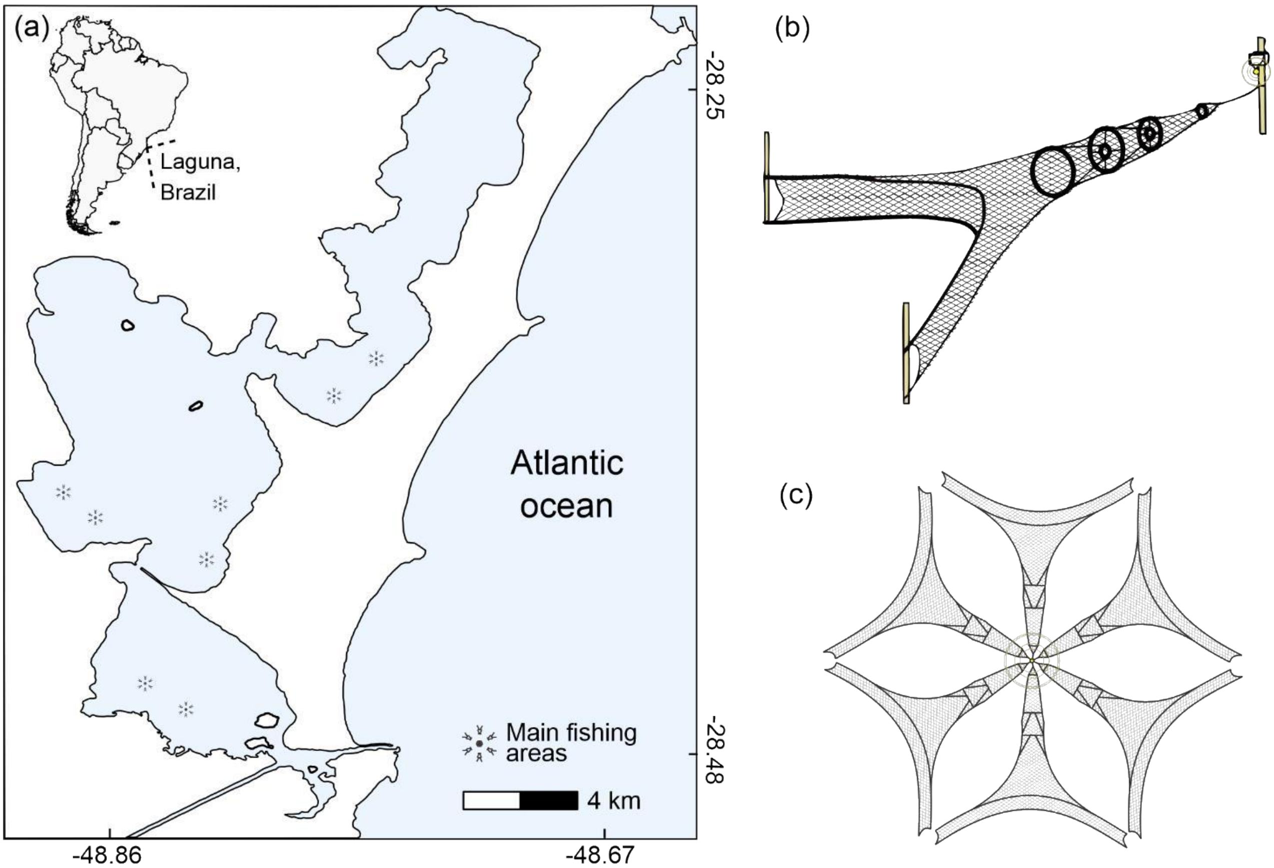

Figure S 2.1. Fishing system characterization. (a) locates the system in the globe showing the main fishing areas while (c) and (d) illustrates the unusual fishing gear used to capture shrimps.

Supplementary Material *S5* – Systems parameter's.

Table S 2.1. Bioeconomic parameters

Inputs	Description	Values	
B'	Relative stock size	$0 \leq B^{'} \leq 1$	[1]
r	Growth rate	$0 \leq r \leq 2$	[2]
q	Catchability	0.023	Empirical
P	Fish Market price	23.00	Market price
c'	Fishing unit cost/carrying capacity	2×10^{-5}	Empirical
α	Fisher's sense of control	$\alpha = 1$ (high fisher's perception of regulation) $\alpha = 0.8$ (low fisher's perception of regulation)	Empirical
b	Fisher's risk coefficient	$b = 0.3$ (high fisher's tolerance of risk) $b = 0.7$ (low fisher's tolerance of risk)	[1]

Empirical information and personal investigations, as well as data from technical reports from the case study were used to set the parameters for the model.

The value of B' had to be from zero to on, since it represents relative stock size (stock biomass divided by carrying capacity).

The value of r was taken from zero to two as a range the represents reasonable values for the species [2].

We set the catchability coefficient by $q = 0.023$. We empirically estimated CPUE using technical report data from one fishing season [3]. Then we extrapolated to estimate total stock size using the area of the gear and the area of the lagoons.

The shrimp market price was set in R$ 23,00. This value was researched on-line on May 05th of 2019. We made an arithmetic mean for all values founded.

The $c^{'} = \frac{c}{K}$ coefficient was set by $c^{'} = 2 \times 10^{-5}$. The fishing costs for one season, c was estimated using gas prices, vessels prices, gears prices and information of the logistics of the fishery (e.g. days of fishing and trips per day). We use the extrapolated value of the stock as carrying capacity value, K.

Fishermen’s high sense of control was set by $\alpha = 1$. The same parameter was set by $\alpha = 0.8$ for low control perception. Outcomes for the game when the value of this parameter was below 0.8 didn’t have any cooperation dominance or cooperative coexistence.

Fishermen’s risk tolerance was set by $b = 0.3$ and $b = 0.7$ for high and low tolerance, respectively. This values are the same used in Trisak’s model [1].

2.8.5 Supplementary material references

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2. Silva EF, Calazans N, Nolé L, Viana A, Soares R, Peixoto S, Frédou FL. 2015 Population dynamics of the pink shrimp farfantepenaeus subtilis (PÉREZ-FARFANTE ,1967) in northeastern Brazil. *J. Crustac. Biol.* **35**, 132–139. (doi:10.1163/1937240X-00002325)
3. Projeto de Monitoramento da Atividade Pesqueira no Estado de Santa Catarina - UNIVALI. 2018 Informativo estadual Nº 04 (Janeiro a Junho/2018). **02**.

3 CAPÍTULO 2: BIOECONOMIC BENEFITS OF MANAGING FISHING EFFORT IN A COEXISTING SMALL- AND LARGE-SCALE FISHERY GAME

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Manuscrito publicado na revista ***ICES journal of marine science*** *em 23 de Junho de 2021.*
https://doi.org/10.1093/icesjms/fsab121

Abstract

Fishing systems provide employment, income generation, poverty alleviation, and food security. The coexistence of small-scale fisheries (SSFs) and large-scale fisheries (LSFs) increases management complexity. Management actions have ecological and social implications that must be addressed carefully. We applied a bioeconomic game-theoretical model to the four-gear mullet fishery in southern Brazil — one industrial LSF (purse seine) and three artisanal SSFs (gillnet, beach seine and drift net). All fishing gears target adult individuals during mullet's reproductive migration. First, we explored whether the current fishing efforts of all fishing gears could persist over time. Second, we investigated their interactions through a non-cooperative game. Finally, we studied the response of these interactions when fishing effort was restricted. We found that when the current fishing effort was maintained, the stock reduced to 26.4% of its capacity in 25 years. In addition, under non-cooperation, the traditional beach seine fleet exited the fishery. Interestingly, the constrained scenario had a coexistence output with increasing values for the final stock size and the per capita labor income, suggesting that limiting fishing effort can maintain all fishing gears in the fishery with social and ecological benefits.

Keywords: bioeconomic models; game theory; natural resources management; non-cooperative game; small-scale fishery; socio-ecological system.

3.1 INTRODUCTION

Small-scale fisheries (SSFs) account for ca. 90% of the world's fishing vessels, and aid poverty alleviation, food security, employment, and cultural preservation (FAO, 2020). Large-scale fisheries (LSFs) are mainly focused on economic gains and are often highly subsidized by governments (Willis and Bailey, 2020). SSFs are diverse and dynamic varying in conditions (pre-harvest, harvest and pos-harvest), activities, technology and aquatic environment between different localities (Berkes et al., 2003; FAO, 2015; Jentoft et al., 2017). However, there are some common features. SSFs are often tied to their local communities and use, generally, a lower level of technology. The SSF communities usually have a high dependence on the fishing resources, and their harvest are frequently directed for subsistence or for the local supply (Chuenpagdee and Jentoft, 2019; Oyanedel et al., 2020). On the other hand, LSFs tend to use larger vessels with advanced technology, focusing on larger markets (e.g., national and international) and industry supplies (Carvalho et al., 2011). Thus, it typically generates a lower number of jobs per tonne of harvest than SSF (FAO, 2020). When SSF and LSF coexist in the system, complexity increases for management actions, leading to disproportional economic performance between fleets, differences in the ability to respond to new challenges such as climate change, and unequal representation in decision making (Schuhbauer and Sumaila, 2016).

A fishery system with SSF and LSF coexistence is, therefore, a challenge for any management decision. A typical fishery system combines the interaction between the natural system (the target species), the socioeconomic system (the fishing community) and the governing system (the regulation institutions), while management decisions are often considered accounting only the former and the latter (Chuenpagdee and Jentoft, 2009). However, to ensure sustainability in the broader sense in the fishery, it is necessary to find the balance between restrictive rules that might encourage illegal fishing or negatively impact the socioeconomic system, and less restrictive controls that could negatively impact the natural system. In cases where there are multiple fleets with different socioeconomic and technical characteristics, such as in the case of the SSF and LSF, finding this balance is even more important and more complex. Therefore, to empower and ensure efficient management decisions in this complex context, a bioeconomic understanding of both socioeconomic and natural systems is essential (Schuhbauer et al. 2017).

A bioeconomic model combines biological characteristics of the fish stock (e.g., growth rate and carrying capacity) with economic information about the fishery (e.g., revenue and costs) to describe the fishing system (Clark, 2007). Insightful behavior analysis for stakeholders can be conducted by combining bioeconomic models with game theory — a mathematical approach to study strategic interaction between agents (e.g., individuals, firms and countries) behaving in a competitive or cooperative context (Grønbæk et al., 2020). The existing literature on the application of game theory to fisheries includes different frameworks, such as coalition games (Lindroos et al., 2007; Pintassilgo, 2008), multispecies models (Kasperski, 2015; Salenius, 2018), ecosystem-based management (Cisneros-Montemayor et al., 2020; Miller et al., 2013), evolutionary games (Azevedo et al., 2020), and sequential games (Laukkanen, 2003; Punt, 2018), to cite a few. This literature is largely focused on international fisheries, in which several countries compete for one or more shared stocks. The application of game theory to national/regional systems is regarded as an underexplored field, a new frontier in fishery research (Grønbæk *et al.*, 2020).

In this study, we explore how SSF and LSF socioeconomic system interacts with possible management forces at a national/regional scale. In this strategic approach, different small- or large-scale fishing fleets/gears share the same fish stock but with possible asymmetries in costs, catchability, fish price, and fishing effort. Every single harvest would, therefore, diminish the available stock for the others, creating a negative externality effect (Grønbæk *et al.*, 2020). That is, the fishing activity of each fleet/fishing gear generates a cost for the others. Our model was implemented in the mullet (*Mugil liza,* Mugilidae) fishery in Southern Brazil, a traditional and economically important fishery that, together with 34.2% of the world's fisheries, is also overexploited (de Abreu-Mota et al., 2018; FAO, 2020; UNIVALI, 2020). We presented the first bioeconomic game-theoretic model for this fishery, building a game that considered 25 years of fishing for the following four different players (fleets/gears): industrial purse seine (IPS), artisanal gillnets (AG), artisanal beach seine (ABS) and artisanal drift nets (ADN) (Ministry of Agriculture Livestock and Supply, 2019). The former is an LSF that involves capturing, processing, and commercializing the mullet, thus generating income and food security for the system. The others are SSFs, which involves the fishers and their families for the whole pre-harvest, harvest, and post-harvest chain while promoting food security, income, maintenance and transmission of traditional ecological knowledge, collective action, and sense of place and attachment to the fishing livelihood (de Abreu-Mota *et al.*, 2018). They all target the same fish stock, when mature individuals migrate northwards to spawn (Lemos *et al.*, 2014; Machado *et al.*, 2021). Therefore, fishing effort choices from any of them will directly affect the fishing effort decisions of the others. As a socio-ecological system, this mullet fishery can collapse due to fish stock depletion (natural system collapse) or the non-profitability of some of its gears, leading to their extinction (socioeconomic system collapse).

To explore how these different SSF and LSF respond to management forces that constraint fishing effort, our model proposes a strategic non-cooperative approach, investigating the benefits for the system when restrictions are applied. The contribution of this work to the scientific literature is threefold. First, we present a bioeconomic model for the traditional mullet fishery in southern Brazil, which can be key for local management decisions. Second, by analyzing a regional fishery using a game-theoretic approach within a fine-country scale, we fill a gap in the literature on the application of game theory to fisheries management, which has mainly focused on large-scale international fisheries. Finally, and most importantly, through a non-cooperative game, we show how constraining effort could be an effective and fair solution for the whole system, the natural and the socioeconomic.

3.2 METHODS

3.2.1 Bioeconomic model

Let $P = \{1,2,\cdots,N\}$ be the set of players exploring the same fish resource during T periods of time. Each player is a fleet using a given fishing gear, with specific costs, catchability (q), fish price (p), and discount rate (δ). The different components of this model are detailed in the following subsections. Table 3.1 displays the variables, in upper-case letters, and parameters of the model.

Table 3.1. Glossary of parameters of the BGTM.

Parameter	Description	Parameter	Description
E	fishing effort (fishing day)	r	intrinsic rate
E_{2019}	fishing effort in 2019	X	biomass (tonnes)
H	harvest (tonnes)	X_0	initial stock size

q	catchability	X_{25}	stock size in year 25
c	cost of a unit of fishing effort (R$*)	NPV	net present value for all the periods
l	laborers' percentage	k	carrying capacity
o	other costs percentage	m	shaping parameter
di	directly involved laborers per fishing effort unit	B_{MSY}	biomass level in the maximum sustainable yield
TC	total cost	Π	profit (R$*)
δ	discount rate	TR	total revenue (R$*)
p	fish price (R$*/t)	T	number of periods
PV	present value of the profit	N	number of players

*The symbol R$ represent the actual currency in Brazil named Real (In 05/05/2021, 1 R$ = 0,19 USD).

3.2.1.1 Stock dynamics

We used the Pella-Tomlinson generalization of the Schaeffer model (Pella and Tomlinson, 1969) to assess the stock growth:

$$X_{t+1} = X_t + \frac{r}{m\text{-}1} \cdot X_t \cdot \left(1\text{-}\left(\frac{X_t}{k}\right)^{m\text{-}1}\right)\text{-}H_t \tag{1}$$

In equation (1), the biomass of the next period (X_{t+1}) was calculated as the actual biomass (X_t) plus the natural growth of the stock minus the amount harvested in that period (H_t). Natural growth depends on the intrinsic growth rate of the stock (r), the actual biomass (X_t), the carrying capacity of the ecosystem (k), and the shaping parameter (m). This last parameter is a measure of density dependence and introduces an asymmetry in the production curve (Chaloupka and Balazs, 2007).

3.2.1.2 Harvest function

The harvest function is a key element in a fisheries bioeconomic model, as it links the biological dimension (stock dynamics) to the economic dimension (revenues and costs). Several functional forms have been adopted in the literature. In our study, harvest (H) was considered proportional to catchability (q), fishing effort (E), and stock biomass (X):

$$H_{i,t} = q_i \cdot E_{i,t} \cdot X_t \tag{2}$$

Harvest varies from player to player (q and E are different for each player) and with time (X and E are different in each period of time, t). This functional form is widely used in the application of game-theory to fisheries (e.g. Grønbæk et al., 2020).

3.2.1.3 Revenue and costs

Total revenue (TR) is given by the product of the fish price (p) and harvest (H).

$$\mathrm{TR}_{i,t} = p_i \cdot H_{i,t} \tag{3}$$

Using equation (2) we can rewrite equation (3) to:

$$\mathrm{TR}_{i,t} = p_i \cdot q_i \cdot E_{i,t} \cdot X_t \tag{4}$$

Costs for each player could involve crew, fishing shack (building where fishers store their boats and equipment), fuel, fishing gear and vessel maintenance, license fees, and sustenance, depending on the fishing gear type. The cost of a fishing effort unit (c) combines the costs directly related to the fishing effort (e.g. fuel, fishing shack, and sustenance). From the difference between total revenue (TR) and total fishing effort costs, a percentage (o) is taken to cover other costs (e.g. emergencies and unexpected costs with the fishing gear or the vessel). Finally, the laborers' percentage (l) determines how much players will pay to the crew. The crew is paid only after deducting both fishing effort costs and other costs to revenue. Thus, the total cost (TC) of a player i in a given period t is given by:

$$\begin{aligned} \mathrm{TC}_{i,t} &= c_i \cdot E_{i,t} + o_i \cdot \left(\mathrm{TR}_{i,t} - c_i \cdot E_{i,t}\right) + l_i \cdot (1 - o_i) \cdot \left(\mathrm{TR}_{i,t} - c_i \cdot E_{i,t}\right) \\ &= \mathrm{TR}_{i,t} - (1 - o_i) \cdot (1 - l_i) \cdot \left(\mathrm{TR}_{i,t} - c_i \cdot E_{i,t}\right) \\ &= E_{i,t} \cdot [(p_i \cdot q_i \cdot X_t) - (1 - o_i) \cdot (1 - l_i) \cdot (p_i \cdot q_i \cdot X_t - c_i)] \end{aligned} \tag{5}$$

3.2.1.4 Profit and net present value (NPV)

Profit (Π) was calculated as the difference between total revenue (TR) and total cost (TC) for each player i in a given period t:

$$\Pi_{i,t} = TR_{i,t}\text{-}TC_{i,t} = (1\text{-}o_i) \cdot (1\text{-}l_i) \cdot \left(TR_{i,t}\text{-}c_i \cdot E_{i,t}\right)$$
$$= E_{i,t} \cdot (1\text{-}o_i) \cdot (1\text{-}l_i) \cdot (p_i \cdot q_i \cdot X_t\text{-}c_i) \quad (6)$$

The present value of the profit (PV) in each period was computed using the discount rate (δ):

$$PV_{i,t} = \frac{\Pi_{i,t}}{(1+\delta_i)^t} \quad (7)$$

Then, the net present value (NPV) of the player i was calculated by the sum of the present values of profits (PV) over all periods:

$$NPV_i = \sum_{t=1}^{T} PV_{i,t} \quad (8)$$

3.2.1.5 Labor impact

Labor impact was assessed through the labor effort (LE) in terms of the number of people directly involved, the total labor income (TLI) per year in million reais — the local currency; and the per capita labor income (PCLI) in reais per laborer per year. For each player, LE was calculated using fishing effort (E) for a specific player i in a specific year t, and the number of directly involved laborers per fishing effort unit (di) as:

$$LE_i = E_{i,t} \cdot di_i, \quad (9)$$

TLI corresponds to the amount of money that each player pays to its laborers in the year t:

$$TLI_{i,t} = l_i \cdot (1\text{-}o_i) \cdot \left(TR_{i,t}\text{-}c_i \cdot E_{i,t}\right) \quad (10)$$

PCLI was obtained dividing TLI by LE.

3.2.2 Case study

We built our model for the national mullet fishery in southern Brazil, an important economic and cultural fishery (Herbst and Hanazaki, 2014; de Abreu-Mota *et al.*, 2018). In this section, we: present the biological and ecological characteristics of the mullet; show the mullet fishery background; describe the elements and parameters of our model and present the different scenarios explored.

3.2.2.1 The mullet

The distribution of the mullet, *M. liza* is between Florida (USA) and Argentina (Mai *et al.*, 2014). During its life span, this pelagic species can be seen in estuaries, freshwater, or open sea (Garbin et al., 2014). At least two different stocks seem to occur in Brazil (Lemos et al., 2017). Considering the southern stock, growth and gonadal maturation take place between January and mid-April to May. From May to the end of June, a reproductive migration occurs (from the estuaries or coastal lagoons towards the sea) with peak-spawning in June in Santa Catarina's waters (Crosetti and Blaber, 2016). The reproductive phase ends by August–September. Then, the mullet stock moves southward to estuaries and coastal lagoons to feed and grow (Menezes *et al.*, 2003; Crosetti and Blaber, 2016). Temperature, salinity, sea currents, wind, and precipitation can affect mullet stock distribution and migratory behavior (Lemos et al., 2014). In addition, mullet has an important ecological value as a primary consumer, transferring energy between the bottom and top trophic levels (Crosetti and Blaber, 2016).

3.2.2.2 The mullet fishery

Mullets are harvested throughout the year in different ecosystems, at different phases of their life cycle, by various fleets and gears (de Abreu-Mota *et al.*, 2018). However, the mullet season is usually defined between May and July in southern Brazil, when dense schools of adult individuals are targeted during the reproductive migration (Herbst and Hanazaki, 2014). The states of Rio Grande do Sul and Santa Catarina together catch more than 75% of the combined catch of all other Brazilian states (Brasil, 2018a). In Santa Catarina, where most of the catches occur, the artisanal mullet fishery (an SSF) is recognized by law as an artistic, cultural, and historical heritage (Brasil, 2018a). Beach seines, gillnets, fish traps, and drift nets are the main artisanal fishing gear used by about 202 artisanal fishing communities to harvest mullets along the southern Brazilian coast (de Pina and Chaves, 2005; Steenbock, 2019). The industrial fleet (an LSF) mainly operates using purse seines, which also target the Brazilian sardine (*Sardinella brasiliensis*, Clupeidae) (Miranda et al., 2011). As the Brazilian sardine fishery declined in 2000, industrial mullet exploitation increased due to seasonal compensation, along with mullet roes valorization in the international market (Valentini and Pezzuto, 2006; de Abreu-Mota *et al.*, 2018).

The mullet production in Brazil shows rising (2000-2007), declining (2008-2015), and oscillating (2015-2019) periods over the last 20 years with a “super harvest” of almost 13 000 tonnes (t) in 2007 (de Abreu-Mota *et al.*, 2018; UNIVALI, 2020). This resource was considered overexploited in 2004 and a near-threatened species in 2018 (de Abreu-Mota *et al.*, 2018). The stock size in 2019 was estimated to be overexploited with the biomass at 30% of its carrying capacity (k) and 75% of its level at maximum sustainable yield (UNIVALI, 2020).

Since its beginning in 1969, legislation for the mullet fishery was built based on conflicting interests (Brasil, 2018a). In 1976 purse seines were obligated to maintain distance from rocky shores (800m) and from the coast (1800m) to protect beach seine community fisheries (Brasil, 1977). In 2008, after the 2007 “super harvest” event, only 60 purse seine vessels were permitted to fish in the mullet season, but this restriction was not implemented due to legal appeals (Brasil, 2008). In 2012 a committee was created to develop the first management plan for the mullet fishery and the restrictions on fishing effort raised. Based on the recommendations from the management plan disclosed in 2015, scientific studies started to assess the stock (Kinas and Sant’Ana, 2015; Sant’Ana *et al.*, 2017) to guide future management decisions. In 2018 and 2019, respectively, total and individual allowable catch quotas were created for both the purse seine and the drift nets fleets, based on the stock assessment (Brasil, 2018b, 2019, 2020). However, conflicting interests between stakeholders continue to pressure management restrictions, while government and fishing communities aim to consolidate the management policy for the fishery (Steenbock, 2019). A persistent conflict zone is the competition between the fishing sectors (industrial and artisanal). Besides competing to harvest the mullet during their migratory season — fishers call this the “mullet race”— the fishing sectors also battle inside management committees trying to achieve higher quotas and more vessel permissions for the industrial sector and mor visibility and decision power for the artisanal sector. Interestingly, each sector seems to have different motivations. While the season is an extremely profitable period for everyone involved in the industrial fisheries, this is a mean of livelihood and cultural maintenance for artisanal fishers.

3.2.2.3 The mullet fishery game

We constructed an asymmetric game with four players, in which each player is a fleet/ fishing gear — industrial purse seine (IPS), artisanal gillnets (AG), artisanal beach seine (ABS), and artisanal drift nets (ADN) — to describe the dynamics of mullet fisheries over 25 years. Both AG and ABS are traditional and not officially monitored fisheries and they represent the largest part of the labor employed in the mullet harvest (Steenbock, 2019). These fisheries are conducted by artisanal fishing communities along the southern Brazilian coast — from the states of São Paulo to Rio Grande do Sul (Brasil, 2018a). ADN is basically an adaptation of the AG technology to increase gear efficiency (Wahrlich, 2018) and occurs in that same range. This fleet has been officially monitored and only started to be regulated in 2015. IPS, which has also been officially monitored, has both the highest cost and catchability. For all these players, we assumed that catchability (q), fish price (p), costs (c, l and o), and discount rate (δ) were all constant during the 25-year period.

In our game, we assumed that each player would have to choose a constant fishing effort to operate during the next 25 years. As players share the same stock the fishing effort chosen by any player directly affects the stock available for the others and hence their fishing efforts and profits.

3.2.2.4 Scenarios

We had different rules for the players to fish for 25 years. Table 3.2 describes each working scenario. The base scenario (BS) presented the model's predictions considering the state of the fishery in 2019. In the strategic interaction approach, we used a non-cooperative game analysis. In the non-cooperative game scenario (NCG), all players aim to maximize their own profit considering the strategy of the other players. The same was done in a constrained non-cooperative game scenario (CNCG), but in this case, the fishing effort had a maximum boundary of 45% of the 2019 fishing effort. The constraint was applied only for the monitored players (Industrial purse seine, IPS and artisanal drift net, ADN), trying to mimic a possible management measure on the fishing effort. The maximum boundary for the fishing efforts was set empirically, based on the fishing efforts observed for these fleets over the last two decades. We also analyzed classic scenarios such as the sole owner, open access, and optimal management to improve our understanding of the system. Their results are available in the supplementary material (Table S 3.2 to S 3.8).

Table 3.2. Mullet game scenarios

Scenario		Description
Base scenario	BS	Fleets/fishing gears use the fishing effort from 2019, constantly, for 25 years.
Non-cooperative game	NCG	Fleets/ fishing gears choose their constant fishing effort aiming to maximize their individual net present value considering their opponents' strategies and their own (Nash Equilibrium) for the next 25 years. The net present value that players maximize, incorporates the year-by-year variation on the stock size in response to the chosen fishing effort.
Constrained non-cooperative game	CNCG	Fleets/fishing gears choose their constant fishing effort aiming to maximize their individual net present value considering their opponents' strategies and their own (Nash Equilibrium) for the next 25 years. The net present value that players maximize, incorporates the year-by-year variation on the stock size in response to the chosen fishing effort. Industrial purse seine (IPS) and Artisanal drift net (ADN) players have a maximum boundary of 45% of their fishing effort used in 2019.

3.2.3 Bioeconomic parameters

We parameterized our bioeconomic model for the mullet fishery using data from technical reports, scientific literature and personal communication with fishers (Table 3.3). While information about both monitored fleets (IPS and ADN) is available, information concerning non-monitored fisheries (AG and ABS) is very scarce. Therefore, we interviewed local fishers by phone, due to the COVID-19 pandemic restrictions. For both IPS and ADN fisheries, we obtained the fishing effort for 2019 (E_{2019}), in terms of fishing days, from the Ministry of Agriculture Livestock and Supply (2019) for IPS and ADN in terms of fishing days. The number of fishing communities for the ABS was assessed by Steenbock (2019), which we then converted to fishing days considering a 77-day effort (whole season duration; Brasil, 2020) for each fishing community. In the ABS, a large part of the fishing community participates in maintaining a continuous fishing effort while watching and waiting for the mullet during the whole season (Bannwart, 2013). We interviewed local fishers by phone to estimate the number of vessels for the AG player (707 vessels) and the profit margin of its revenue. We thus considered the profit for this player was 5% of its revenue. We estimated the AG's revenue using harvest information from 2019 (UNIVALI/EMCT/LEMA, 2020) and a fish price of 10 R$/kg. Equation

(6) was then solved for E. To obtain the fishing effort in terms of fishing days for the AG fleet, we also considered a 77-day effort for each vessel in this fleet. The players' catchability (q) was calculated as:

$$q = \frac{H}{E \cdot X} \tag{11}$$

We used data from 2019 to define harvest and the stock size (UNIVALI, 2020; UNIVALI/EMCT/LEMA, 2020). We used the information in Steenbock (2019) to estimate the cost of fishing effort (c), the laborers' percentage (l), the other costs percentage (o), and the number of laborers directly involved in the fishery (di) for IPS and ADN. We obtained the same information for AG and ABS from our informal interviews with local fishers. We assumed the same fish price (10 R$/kg) for all the players (Steenbock, 2019) and the same 5% discount rate for all players based on previous studies (Sumaila, 1997; Pintassilgo and Duarte, 2002). The biological characteristics of the stock (Pella-Tomlinson model's parameters) were determined using information of the 2020 stock assessment for the mullet stock in southern Brazil, which we used to set the initial stock size at 16594.4 t (30% of k) for all the scenarios (UNIVALI, 2020).

Table 3.3. Fishing, biologic, and game parameters for the mullet fishery

Parameter	Description	IPS	AG	ABS	ADN	Unit
fishing						
E_{2019}	2019 fishing effort	182	54 362	15 554	8778	days
q	catchability	3.6×10^{-4}	4.0×10^{-6}	3.9×10^{-6}	8.0×10^{-6}	-
c	cost per unit of fishing effort	30 769.00	300.00	300.00	351.95	R$
l	laborers' percentage	0.5	0.5	0.5	0.5	%
o	other costs percentage	0.1	0.1	0.1	0.1	%
di	laborers directly involved	2.7669	0.0900	0.1948	0.1039	person/day
p	fish price	10.00	10.00	10.00	10.00	R$/kg
δ	discount rate	0.05	0.05	0.05	0.05	0.05
biologic					game	
	$k = 55\ 314.5$	$r = 0.3945$	$X_0 = 0.3 \cdot k$	$m = 1.37$	$N = 4$	$T = 25$

The symbol R$ represent the actual currency in Brazil named Real (In 05/05/2021, 1 R$ = 0,19 USD). Players are: IPS, industrial purse seine; AG, artisanal gillnets; ABS, artisanal beach seine and ADN, artisanal drift nets. k, carrying capacity; r, growth rate; X_0, initial stock size; m, Pella-Tomlinson shaping parameter; N, number of players.

3.2.4 Analysis

We built our bioeconomic model of the mullet fishery under three different scenarios using MATLAB software (MATLAB 2020, version R2020a). We built a function called $\mathrm{mullet(E)}$, that receives the vector of the fishing efforts of the four players, $E = (E_{IPS}, E_{AG}, E_{ABS}, E_{ADN})$ and returned the outcomes of that choice, a constant fishing effort for 25 years in the mullet fishery, based on the bioeconomic model and the parameters described in sections 3.3.2.1 and 3.3.2.3, respectively. Outputs of mullet function were the stock size vector with 26 rows, one for each year (X_0 is the first row); the harvest matrix with five columns (one for each player's harvest and the last one for the total harvest) and 25 rows (one for each year); the NPV matrix with four columns (one for each player) and 1 row, showing, for each player, the sum of the profits obtained in each year of fishing, discounted to the base year, 2019.

In the base scenario (BS), the fishing effort vector is given, E_{2019}. Thus the outcomes were calculated directly by computing $\mathrm{mullet}(\mathrm{E}_{2019})$. Regarding the non-cooperative game (NCG) and the constrained non-cooperative game (CNCG), before calculating mullet function, we determined the Nash equilibrium. In a Nash equilibrium, each player is maximizing its benefit subject to other players doing the same. In a non-cooperative game, the Nash equilibrium is the most widely used solution concept, owing to both its intuitive inference and the fact that it is a natural outcome of dynamic adjustment in economic and social systems (Grønbæk *et al.*, 2020). Nash equilibrium analyses for the NCG and CNCG scenarios were made using a discrete set of strategies for each player, with 50 possible fishing effort choices uniformly distributed in ascending order between the minimum (zero) and maximum (twice the sole owner's optimal fishing effort for the respective player) value. In the CNCG scenario, the maximum fishing effort for the strategy set of the industrial purse seine (IPS) and for the artisanal drift net (ADN) was 45% of their fishing effort used in 2019 (see section 3.3.2.2.4). A total 4^{50} of fishing effort vectors were then generated. With the function $\mathrm{NE\_test}(\mathrm{E})$ we tested if each of these fishing effort vectors E were Nash equilibria or not. First, we calculated NPV values for the testing choice $\mathrm{E} = (\mathrm{E}_{\mathrm{i}})_{\mathrm{i=IPS,AG,ABS,ADN}}$. Second, we did the same for the choices $\mathrm{E}^{\mathrm{i+1}} = (\mathrm{E}_{\mathrm{IPS}}, \cdots, \mathrm{E}_{\mathrm{i}}^{+1}, \cdots, \mathrm{E}_{\mathrm{ADN}})_{\mathrm{i=IPS,AG,ABS,ADN}}$ and $\mathrm{E}^{\mathrm{i\text{-}1}} = \left(\mathrm{E}_{\mathrm{IPS}}, \cdots, \mathrm{E}_{\mathrm{i}}^{-1}, \cdots, \mathrm{E}_{\mathrm{ADN}}\right)_{\mathrm{i=IPS,AG,ABS,ADN}}$. The $\mathrm{E}_{\mathrm{i}}^{+1}$ represent the strategy after E_{i} in the strategy set of players i and $\mathrm{E}_{\mathrm{i}}^{-1}$ is the strategy before E_{i}. Finally, we compared the NPV values of those choices to determine if there was an incentive for any player to deviate from E, considering that other players would play according to E. If none of the players had an NPV incentive (i.e. higher values) to change their fishing effort choice, then we considered that vector choice, E, a Nash Equilibrium. Thus, each player's effort choice is a best response to the fishing effort of the others. Then the mullet function was calculated for each Nash equilibria determined.

Using the outputs of the mullet function, we computed the mean harvest ($\overline{\mathrm{H}}$) in tonnes per year for each player, the stock dynamics during the periods, the final stock size (X_{25}) as a percentage of the carrying capacity (k), and the net present value (NPV) in million reais for each player. Regarding labor impact, the following three indicators were calculated (see section 3.3.2.1.5) and compared: labor effort (LE) in number of laborers involved, total labor income (TLI) in million reais and per capita labor income (PCLI) in reais. We provide all the code and data to replicate our model and simulations in the open-access repository: https://bitbucket.org/ericzt/mullet_fishery_coding/downloads/.

3.2.5 Sensitivity analysis

Due to lack of systematic data collection for the non-monitored artisanal gillnet (AG) and artisanal beach seine (ABS) fleets, information on catches and fishing efforts may be less accurate for these gears. Hence, a sensitivity analysis to the catchability of these gears was performed, as this parameter is directly related both to catch and fishing effort data (see Equation (11)) For this purpose, we built models for all scenarios considering a $\pm 15\%$ deviation in both AG and ABS catchability.

We considered the same $\pm 15\%$ deviation for the fish price (p) and for the discount rate (δ) for the IPS fleet, assuming that the industrial fleet could have some differences at these parameters in comparison to artisanal players.

To account for stock uncertainty, we ran the model additionally considering values of carrying capacity (k) and intrinsic rate (r) at the maximum and at the minimum of the confidence interval presented in the mullet stock assessment (UNIVALI, 2020).

Our harvest function (equation (2) is a particular case of the Cobb-Douglas production function (CDPF) with increasing returns to scale. The CDPF for the mullet harvest would be:

$$H_{i,t} = q \cdot E^{\alpha} \cdot X^{\beta}$$

The coefficients α and β are harvest elasticity coefficients related to the fishing effort and to the stock size, respectively. In the original model, we used $\alpha = \beta = 1$. We also tested the model using a CDPF with constant returns to scale $\left(\alpha = \beta = \frac{1}{2}\right)$ and with diminishing returns to scale $\left(\alpha = \beta = \frac{1}{3}\right)$.

Considering all perturbations mentioned above, the model was executed 14 additional times, one time for each perturbation.

3.3 RESULTS

The base scenario (BS) was harmful for the stock size (Figure 3.1) ending in 26.4% of the carrying capacity in 25 years. In this scenario, artisanal gillnet (AG) had both the highest catch, with 3258 t per year (53% of total catch) and the highest net present value, with 110.6 million reais (Figure 3.2). However, its high fishing and labor efforts of 54362 fishing days and 4892 laborers, respectively, resulted in a low per capita labor income value (R$ 1497.40).

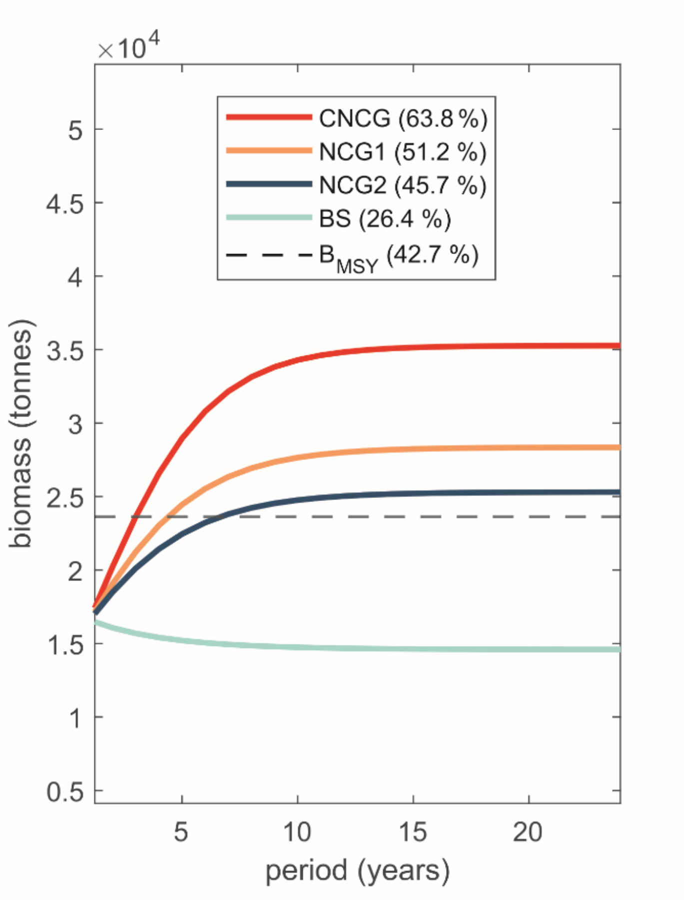

Figure 3.1. **Stock dynamics in tonnes for each scenario during 25 years of fishery**. Biomass axis varies from zero to carrying capacity (k). Stock size in the last period (X_{25}) is presented in the caption as a percentage of k. Scenarios: CNCG – Constrained non-cooperative game, NCG1 – Non cooperative game (solution 1), NCG2 – Non-cooperative game (solution 2), BS – Base scenario. B_{MSY} is the stock's biomass state where maximum sustainable yield (MSY) was achieved as a percentage of k.

For the unconstrained non-cooperative game (NCG), two different Nash equilibria (NCG1 and NCG2) were obtained. Artisanal drift net (ADN) had the highest values for all variables in both NCG1 and NCG2, except for the per capita labor income, which was higher for IPS (Figure 3.2). In the NCG1 and NCG2 solutions, the ADN raised its fishing effort to 148% and 198% of E_{2019}, respectively. The industrial purse seine (IPS) player also raised its fishing effort to 120% in NCG1 and 135% in NCG2 in comparison to E_{2019}. ABS and AG, the two traditional and non-monitored fisheries reduced their activity significantly. The ABS — the most traditional player with a high number of laborers involved — ended up exiting the fishery, whereas the latter decreased its fishing effort to only 23% and 19% of E_{2019} in NCG1 and NCG2, respectively. As a possible consequence of the reduced effort — or even the exit — of these more traditional players, the stock level in the final period (X_{25}) increased to 51.2% of k for the NCG1 scenario and 45.7% of k for the NCG2, when compared to the base scenario (Figure 3.1).

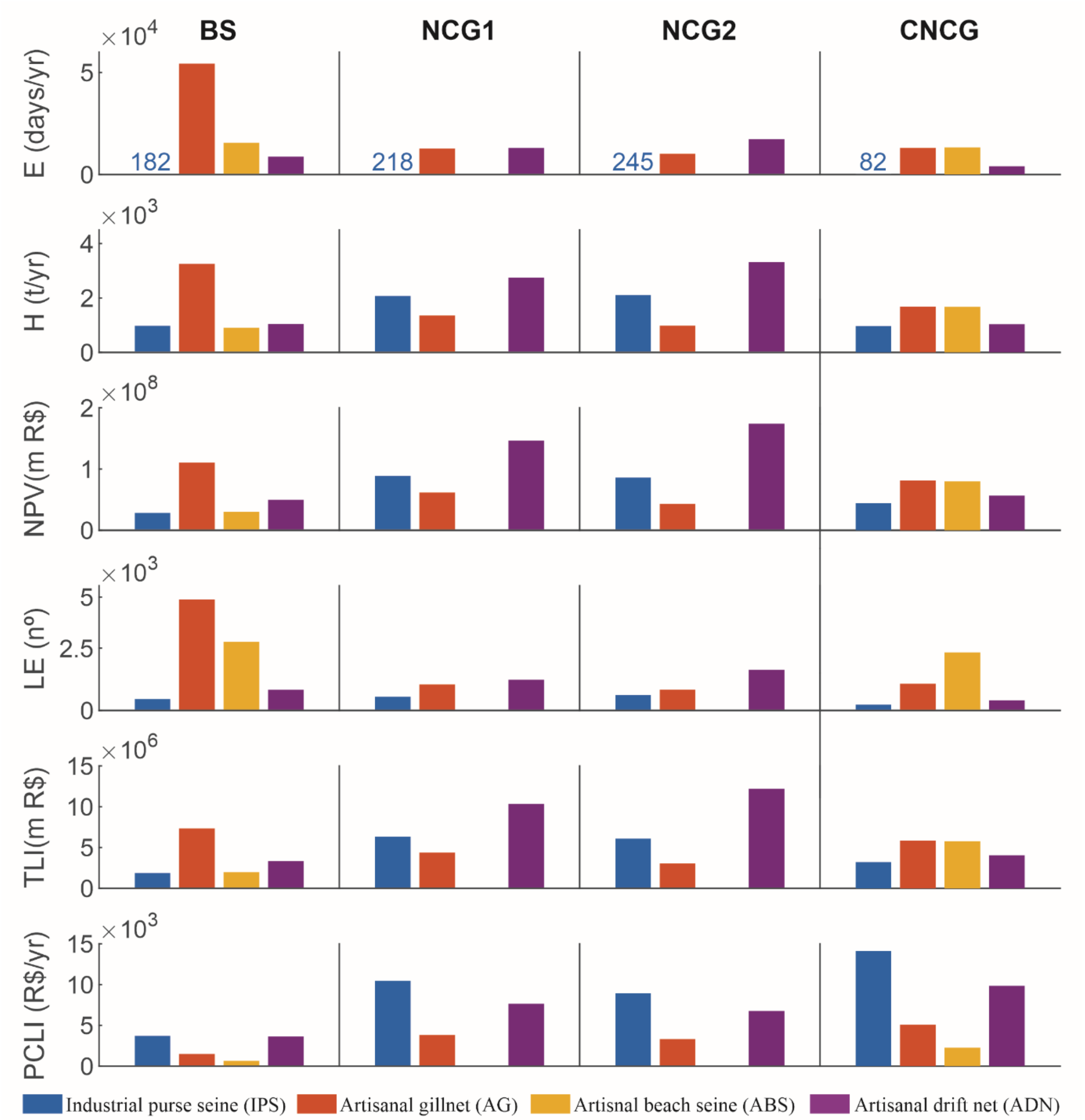

Figure 3.2. **Bioeconomic outputs for each scenario**. Fishing effort (E) in days, mean harvest ($\overline{\mathrm{H}}$) in tonnes per year, net present value (NPV) in million reais, labor effort (LE) in number of laborers involved, total labor income (TLI) in million reais and per capita labor income (PCLI) in reais per laborer per year are presented for the following scenarios: BS, base scenario; NCG1, non-cooperative game (solution 1); NCG2, non-cooperative game (solution 2) and CNCG, constrained non-cooperative game. The numbers in the graph were shown whenever the size of the bar was too small to be seen.

In the constrained non-cooperative game (CNCG), however, the final stock size was 63.8% of the carrying capacity, the highest X_{25} considering all scenarios (). In the CNCG solution, all players coexisted but reduced their fishing effort, compared to the base scenario (BS). IPS and ADN reduced their fishing effort to the value forced by the constraint (45% of E_{2019}) while

AG and ABS reduced their fishing effort to 23.5% and 83.9% of E_{2019}, respectively. Interestingly, the Nash equilibrium for the CNCG also had the highest per capita labor income value for each player, considering all presented scenarios (Table 3.2).

Our sensitivity analysis show that our results are consistent even when perturbating the catchability of AG and ABS, the fish price and the discount rate of IPS as well as the carrying capacity and intrinsic rate of the stock. We found no relevant changes to the main results.

We also tested the model considering production functions with constant returns to scale $\left(H_{i,t} = q_i \cdot E_i^{\frac{1}{2}} \cdot X_t^{\frac{1}{2}}\right)$ and with diminishing returns to scale $\left(H_{i,t} = q_i \cdot E_i^{\frac{1}{3}} \cdot X_t^{\frac{1}{3}}\right)$. As expected, these production functions affected the intensity of the results. However, the main relations in the original analysis were preserved. The readers can find more about our sensitivity analysis in supplementary material (Table S 3.9).

3.4 DISCUSSION AND CONCLUSION

In this paper, we identified important characteristics of the following fisheries (players) in the mullet fishery: The industrial purse seine (IPS), the artisanal gillnet (AG), the artisanal beach seine (ABS) and the artisanal drift net (ADN). The results show that limiting the fishing effort could be a solution that benefits the mullet stock dynamics and supports the coexistence of all fishing gears with the highest per capita labor income. ADN was the most competitive fleet. Surprisingly, IPS was not a sufficiently competitive fleet, even with high catchability, due to its high costs. When players interacted strategically in the unconstrained non-cooperative game scenario (NCG), we found two different Nash equilibria. For a social-ecological system, multiple Nash equilibria could be seen as alternative stable states that depend on the system's characteristics and environmental perturbations (Levin *et al.*, 2013). AG and ABS players, the most traditional and non-monitored fleets, had 7930 laborers involved in 2019. Both AG and ABS had their fishing effort extremely reduced in the unconstrained non-cooperative game scenario — in particular, ABS exited the fishery.

Considering that the Nash equilibrium can be seen as a natural path for the fishery, with players guiding their choices only by their profit, we argue that this result is an important sign concerning the economic pressure on the traditional players AG and ABS. By analyzing the number of laborers involved and the per capita labor income for each player, we can see that IPS tend to concentrate income with a few laborers receiving a considerable per capita income. On the contrary, ABS and AG distribute income by many laborers who receive a small per capita income. This is in line with Schuhbauer and Sumaila (2016), who refer that profit-based management actions can intensify the economic pressure to reduce SSF and contribute to unbalance the social-ecological system of a given fishery. This could compromise the social benefits of SSFs, such as poverty alleviation, food security, and cultural preservation. In contrast, when the fishing effort was restricted (CNCG) — IPS and ADN players could not exceed 45% of the 2019 fishing effort — coexistence was obtained with the monitored fleets on their maximum threshold. Additionally, a positive effect in per capita labor income and a healthier condition for the stock was observed.

The success of the ADN, the most competitive fleet, seems to be critical to the discussion on how the different fleets/gears could coexist and maintain the fishery sustainable. ADN is a recent fleet adapted from the AG to increase catchability (Wahrlich, 2018). The adaptation added weights at the bottom of the net to form a seine when it is pulled. Therefore, ADN is a small seine that can be used for quick trips, and that has low costs compared to IPS. These characteristics explain the competitiveness of ADN. However, reducing the efforts of the most traditional players, such as AG and ABS, seem inevitable. For example, the base scenario suggested that the fishing effort of 2019 was unsustainable, with the mean annual catch for AG much higher than any other player. Therefore, this artisanal fleet can play a key role in the decline of stock size. Yet, even with a high catch, AG (or any other artisanal fleet) generates a small per capita income for their crew because of its high number of laborers that share the harvest benefits. Low economic performance and low remuneration of labor are actual issues for SSF that contribute to their marginalization as an important but not explicitly valorized fishing class (Schuhbauer *et al.*, 2017). Curiously, our results show that by limiting the fishing effort of ADN and IPS, then AG and ABS will be indirectly encouraged to reduce their fishing effort to maximize their incomes.

The current management measure to regulate the mullet fishery aims to enforce catch quotas for the IPS and ADN , the two monitored fleets. This measure started in 2018 and is still under assessment by the state committee (Steenbock, 2019). In our simulation, for instance, IPS and ADN fleets would operate with 45% of fishing effort used in 2019. That reduction causes respectively 276 and 502 fewer employees. However, net present value (NPV) increases by 15 and 5 million reais, respectively. On the other hand, a healthier stock and higher per capita labor income would emerge. Therefore, the trade-off of particular rent (profit), social rent (employment, food security and poverty alleviation) and environment (stock health) must be carefully accounted for in management decisions (Chuenpagdee and Jentoft, 2019; Willis and Bailey, 2020). The management of the mullet fishery could maintain all fleets and gears in the system with economic, ecological, and social benefits. Management measures that facilitate the persistence of the different stakeholders, from SSF to LSF, point towards the sustainability of the system. To achieve this, however, traditional fishers must be included in the decision-making process. It could start by assessing systematic information on artisanal catches, from multiple and alternative sources of data (Machado *et al.*, 2021).

This study has limitations, which open avenues for further research. First, we adopted constant effort strategies over time. Extending the analysis to variable fishing efforts is a natural extension of our analysis. Second, individualized and more refined constraints in the non-cooperative game could be explored. Third, as the mullet stock is uncertain, modeling the fishery scenarios in a stochastic setting could offer interesting insights, such as biological and economic risks. Finally, the mullet fishery has great influence by climatic factors (e.g. wind, temperature) (Lemos, 2015). A model that could incorporate the changes in environmental conditions with the fishery would be interesting and an important contribution to predictive analysis.

LSF and SSF coexistence management is a complex challenge worldwide (Schuhbauer *et al.*, 2017; Chuenpagdee and Jentoft, 2019). As this study points out, the coexistence of all fleets and fishing gears, managing both their fishing effort and individual gains, could benefit the fishery in its ecological, economic, social, and cultural dimensions. A “Laissez faire” policy is likely to lead to the fading of SSF, and with it, a unique heritage. As the mullet fishery game shows, facilitating the coexistence of different players by limiting fishing effort may contribute decisively to the health and sustainability of the socio-ecological system.

3.5 ACKNOWLEDGEMENTS

The authors would like to thank all contacted artisanal fishers for essential information provided. We also thank to Alexandre Marcel da Silva Machado for the insightful comments on the final version of the manuscript. Finally, we would like to thank to the three anonymous referees which help us to improve our study. This work was supported in part by the Coordenação Nacional de Aperfeiçoamento de Pessoal de Nível Superior (CAPES - 88887.468519/2019-00). F.G.D.J. thanks for a research grant received from the Conselho Nacional de Desenvolvimento Científico e Tecnológico (CNPq – 308867/2019-0). P.P. acknowledges supported by the FCT ─ Portuguese Foundation for Science and Technology under project UID/ECO/04007/2020.

3.6 AUTHORS CONTRIBUTIONS

F.G.D.J., E.Z.D.A, and P.P conceived the study; E.Z.D.A. and D.V.D organized data for the study. E.Z.D.A and P.P. explored and analyzed the data; E.Z.D.A, P.P. and F.G.D.J. interpreted the data; E.Z.D.A wrote the original draft of the manuscript. All authors discussed the data, reviewed the manuscript, and gave final approval for publication.

3.7 DATA AVAILABILITY STATEMENT

Input data and parameters used in the model are available in Table 3.3. We provide all the code and data to replicate our model and simulations in the open-access repository: https://bitbucket.org/ericzt/mullet_fishery_coding/downloads/.

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3.9 SUPPLEMENTARY MATERIAL

3.9.1 History of fishing mortality for the mullet stock in Southern Brazil

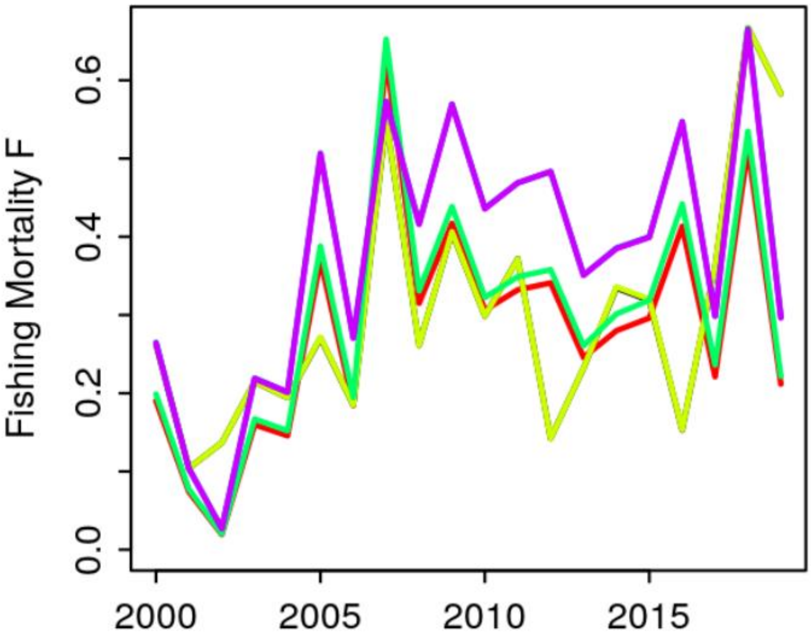


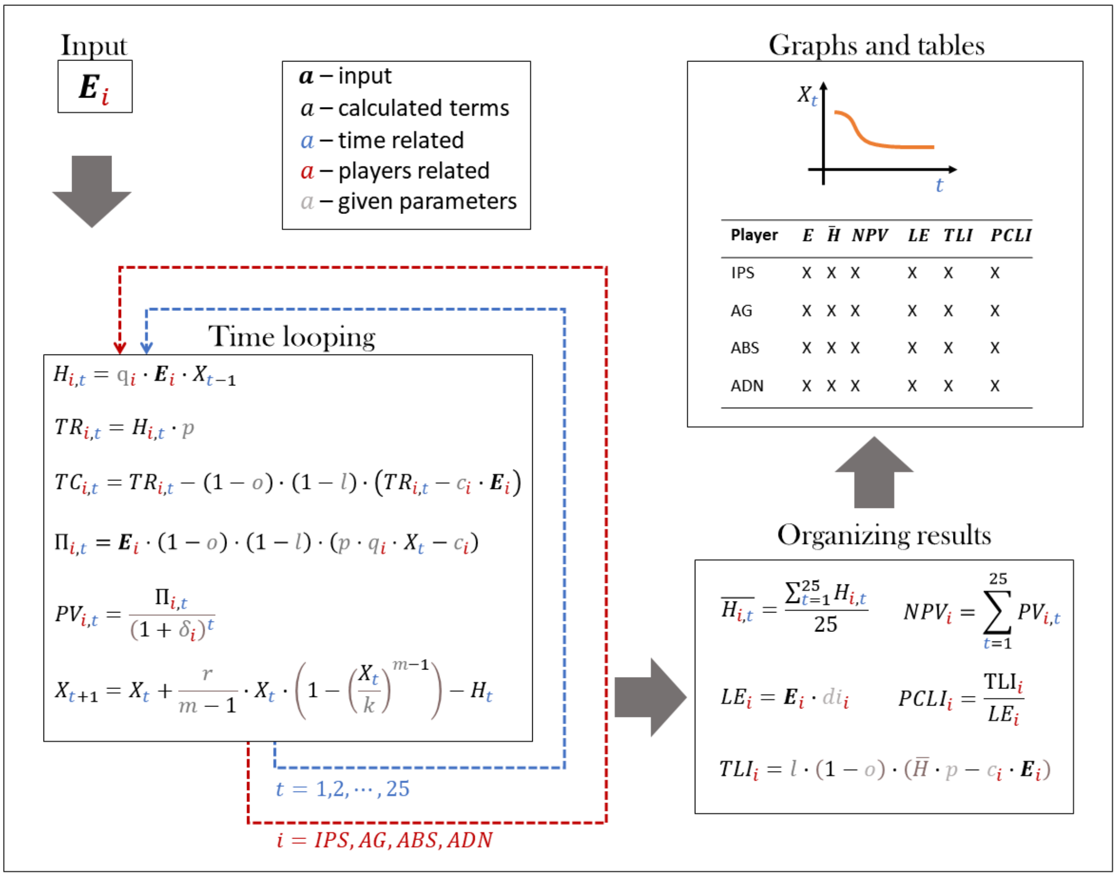
Figure S 3.1. Fishing mortality from 2000 to 2020 for the mullet fishery. Different colors represent different adjusted models. Source: UNIVALI, 2020 (stock assessment for the mullet)

3.9.2 Scenarios' description

Table S 3.1. Different scenarios for the mullet game and their respective description.

Scenario		Description
Base scenario	BS	Fleets/gears use the fishing effort from 2019, constantly, for 25 years.
IPS/AG/ABS/ADN Sole Owner	IPS SO/ AG SO/ ABS SO/ ADN SO	As a sole owner of the fishery, IPS/AG/ABS/ADN player finds a constant fishing effort that will maximize net present value for the next 25 years.
Optimal management	OM	Manager looks for optimal constant fishing effort that will maximize global net present value for the next 25 years.
Open access	OA	Fleets/gears start using E_{2019} and, for 25 years, they raise or decrease their effort by 10% for the next year if they have, respectively, positive, or negative profit.
Non-cooperative game	NCG	Fleets/gears choose their constant fishing effort aiming to maximize their individual net present value considering their opponents' strategies and their own (Nash Equilibrium) for the next 25 years. The net present value that players should maximize incorporates the year-by-year variation on the stock size in response to the chosen fishing effort.
Constrained non-cooperative game	CNCG	Fleets/gears choose their constant fishing effort aiming to maximize their individual net present value considering their opponents' strategies and their own (Nash Equilibrium) for the next 25 years. The net present value that players should maximize incorporates the year-by-year variation on the stock size in response to the chosen fishing effort. Industrial purse seine (IPS) and Artisanal drift net (ADN) players have a maximum boundary of 45% of their fishing effort used in 2019.

3.9.3 Function's flow



Player	E	$\bar{H}$	NPV	LE	TLI	$PCLI$
IPS	X	X	X	X	X	X
AG	X	X	X	X	X	X
ABS	X	X	X	X	X	X
ADN	X	X	X	X	X	X

$$H_{i,t} = q_i \cdot \boldsymbol{E}_i \cdot X_{t-1}$$

$$TR_{i,t} = H_{i,t} \cdot p$$

$$TC_{i,t} = TR_{i,t} - (1-o) \cdot (1-l) \cdot \left(TR_{i,t} - c_i \cdot \boldsymbol{E}_i\right)$$

$$\Pi_{i,t} = \boldsymbol{E}_i \cdot (1-o) \cdot (1-l) \cdot (p \cdot q_i \cdot X_t - c_i)$$

$$PV_{i,t} = \frac{\Pi_{i,t}}{(1+\delta_i)^t}$$

$$X_{t+1} = X_t + \frac{r}{m-1} \cdot X_t \cdot \left(1 - \left(\frac{X_t}{k}\right)^{m-1}\right) - H_t$$

$t = 1,2,\cdots,25$

$i = IPS, AG, ABS, ADN$

$$\overline{H_{i,t}} = \frac{\sum_{t=1}^{25} H_{i,t}}{25} \qquad NPV_i = \sum_{t=1}^{25} PV_{i,t}$$

$$LE_i = \boldsymbol{E}_i \cdot di_i \qquad PCLI_i = \frac{\mathrm{TLI}_i}{LE_i}$$

$$TLI_i = l \cdot (1-o) \cdot (\bar{H} \cdot p - c_i \cdot \boldsymbol{E}_i)$$

Figure S 3.2. Mullet function flow. E- fishing effort, H-harvest, q-catchability, X-stock size, TR- total revenue, p-fish price, TC- total cost, o- other cost percentages, l- laborers percentage, c- cost of a unit of the fishing effort, Π- profit, PV- present value, r- intrinsic rate, k- carrying capacity, m- shaping parameter, IPS- industrial purse seine, AG- artisanal gillnet, ABS- artisanal beach seine, ADN- artisanal drift net, H̅- mean harvest, NPV- net present value, LE- labor effort, PCLI- per capita labor income, TLI- total labor income, t- period.

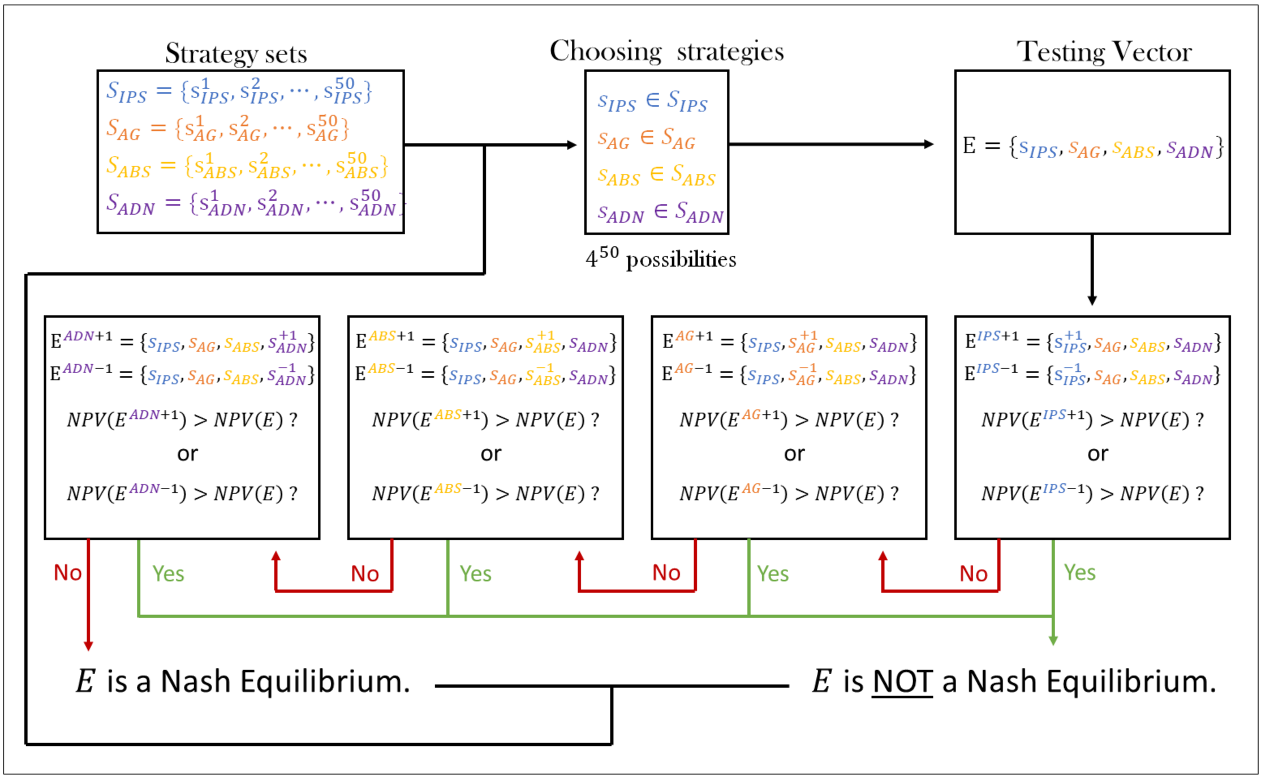


Figure S 3.3. Nash Equilibrium test function flow. S- strategy set, s- strategy, E- fishing effort vector, IPS- industrial purse seine, AG- artisanal gillnet, ABS- artisanal beach seine, ADN- artisanal drift net, NPV- net present value, s_i^{+1}- strategy consecutively after s_i in S_i, s_i^{-1}- strategy consecutively before s_i in S_i.

3.9.4 Complementary results

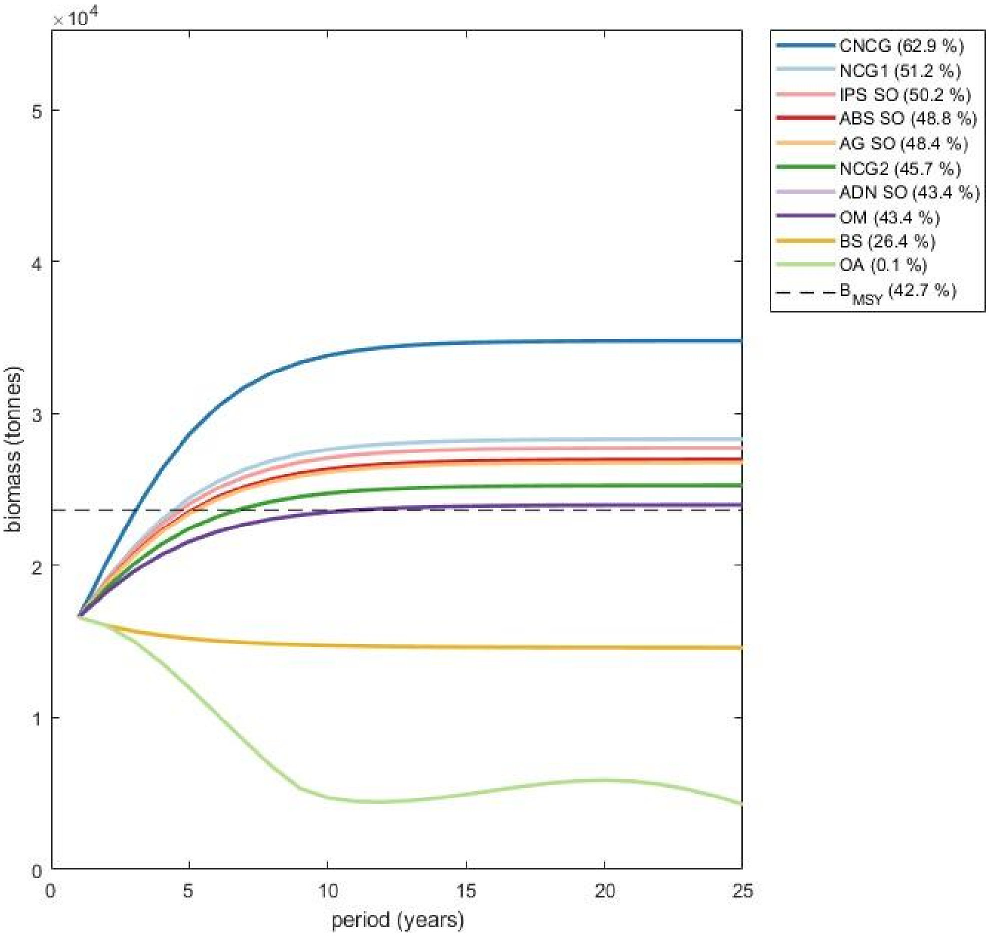


Figure S 3.4. Stock dynamics for all scenarios

Table S 3.2. Comparative analysis of all different scenarios (see Table 3.1) for the mullet fishery in southern Brazil. Fishing effort (E), mean harvest ($\overline{H}$), net present values (NPV), labor effort (LE), total labor income (TLI) and per capita labor income (PCLI) for each scenario. Scenarios: BS – Base scenario, IPS SO – Industrial purse seine sole owner game, AG SO – artisanal gillnet sole owner game, ABS SO – Artisanal beach seine sole owner game, ADN SO – Artisanal drift net sole owner game, OM – Optimal management, OA – open access, NCG1 – Non-cooperative game (solution 1), NCG2 – Non-cooperative game (solution 2) and CNCG – Constrained non-cooperative game.

	$\overline{H}$ (t/yr)	X_{25} (% of K)	NPV (m R$)	LE (ind)	TLI (m R$)	PCLI (R$/yr)
Status quo scenario						
BS	6 186.8	26.4	218.6	9 338	14.5	1 551.80
Limit scenarios						
IPS SO	6 236.2	50.2	264.3	1 849	18.8	10 177.00
AG SO	6 312.3	48.4	282.3	5 622	20.0	3 561.40
ABS SO	6 298.2	48.8	278.7	12 393	19.8	1 593.90
ADN SO	6 466.7	43.4	336.7	3 680	23.5	6 383.40
OA	4 430.0	0.1	37.9	318 210	112.1	352.30
OM	6 466.7	43.4	336.7	3 680	23.5	6 383.40
Strategic coexistence scenarios						
NCG1	6 185.0	51.2	296.7	3 101	21.0	6 783.40
NCG2	6 407.1	45.7	303.2	3 398	21.3	6 272.40
CNCG	5 279.4	63.8	257.5	4 330	18.5	4 274.10

3.9.5 Base Scenario (BS)

Table S 3.3. Fishing effort (E), mean harvest ($\overline{H}$), net present values (NPV), labor effort (LE), total labor income (TLI) and per capita labor income (PCLI) for each player in the base scenario. IPS = Industrial Purse Seine, AG = Artisanal Gillnet, ABS = Artisanal Beach Seine, ADN = Artisanal Drift Net.

Gear	E (days)	$\overline{H}$ (t/yr)	NPV (m R$)	LE (ind.)	TLI (m R$)	PCLI (R$/yr)
IPS	182	975.1	28.3	504	1.9	3 706.50
AG	54 362	3 258.9	110.6	4900	7.3	1 495.14
ABS	15 554	906.1	29.9	3030	2.0	652.69
ADN	8 778	1 046.7	49.8	912	3.3	3 640.25

	6 186.8	218.6	9346	14.5	1 551.47

3.9.6 Open access (OA)

Table S 3.4. Mean harvest ($\overline{H}$), net present values (NPV), labor effort (LE), total labor income (TLI) and per capita labor income (PCLI) for each player in open access. IPS = Industrial Purse Seine, AG = Artisanal Gillnet, ABS = Artisanal Beach Seine, ADN = Artisanal Drift Net.

Gear	$\overline{H}$ (t/yr)	NPV (m R$)	LE (ind)	TLI (m R$)	PCLI (R$/yr)
IPS	497.5	-6.0	11 731	10.3	877.38
AG	1 800.1	0.4	129 880	44.6	345.86
ABS	500.5	-1.7	79 814	11.8	148.07
ADN	1 631.9	45.1	97 781	45.4	464.66
	4 430.0	37.8	319 206	112.1	351.18

3.9.7 Optimal management (OM)

Table S 3.5. Fishing effort (E) with its respective variation from base fishing effort (E_{2019}), mean harvest ($\overline{H}$), net present values (NPV), labor effort (LE), total labor income (TLI) and per capita labor income (PCLI) for each player in the optimal management scenario. IPS = Industrial Purse Seine, AG = Artisanal Gillnet, ABS = Artisanal Beach Seine, ADN = Artisanal Drift Net.

Gear	E % of E_{2019} (days)	$\overline{H}$ (t/yr)	NPV (m R$)	LE (ind)	TLI (m R$)	PCLI (R$/yr)
IPS	0.0	0.0	0.0	0	0.0	0.00
AG	0.0	0.0	0.0	0	0.0	0.00
ABS	0.0	0.0	0.0	0	0.0	0.00
ADN	35 418 403%	6 466.7	336.7	3 680	23.5	6 383.40
		6 466.7	336.7	3 680	23.5	6 383.40

3.9.8 Non-cooperative game (NCG)

Table S 3.6. Fishing effort (E) with its respective variation from base fishing effort (E_{2019}), mean harvest ($\overline{H}$), net present values (NPV), labor effort (LE), total labor income (TLI) and per capita labor income (PCLI) for the first solution in the non-cooperative game. IPS = Industrial Purse Seine, AG = Artisanal Gillnet, ABS = Artisanal Beach Seine, ADN = Artisanal Drift Net.

Gear	E % of E_{2019} (days)	$\overline{H}$ (t/yr)	NPV (m R$)	LE (ind)	TLI (m R$)	PCLI (R$/yr)
IPS	218 120%	2 074.7	88.6	604	6.3	10 463.00
AG	12 726 23%	1 354.9	61.6	1 145	4.4	3 823.30
ABS	0 0%	0.0	0.0	0	0.0	0.00
ADN	13 011 148%	2 755.4	146.5	1 352	10.3	7 647.90
		6 185.0	296.7	3 101	21.0	6 772.01

Table S 3.7. Fishing effort (E) with its respective variation from base fishing effort (E_{2019}), mean harvest ($\overline{H}$), net present values (NPV), labor effort (LE), total labor income (TLI) and per capita labor income (PCLI) for the second solution in the non-cooperative game. IPS = Industrial Purse Seine, AG = Artisanal Gillnet, ABS = Artisanal Beach Seine, ADN = Artisanal Drift Net.

Gear	E % of E_{2019} (days)	$\overline{H}$ (t/yr)	NPV (m R$)	LE (ind)	TLI (m R$)	PCLI (R$/yr)
IPS	245 135%	2 108.7	86.1	679	6.1	8 969.90
AG	10 181 19%	979.3	43.0	916	3.0	3 309.30
ABS	0 0%	0.0	0.0	0	0.0	0.00
ADN	17 348 198%	3 319.1	174.0	1 802	12.2	6 762.30
		5 607.6	273.1	3 397	21.3	6 270.24

3.9.9 Constrained non-cooperative game (CNCG)

Table S 3.8. Fishing effort (E) with its respective variation from base fishing effort (E_{2019}), mean harvest ($\overline{H}$), net present values (NPV), labor effort (LE), total labor income (TLI) and per capita labor income (PCLI) in constrained non-cooperative game. IPS = Industrial Purse Seine, AG = Artisanal Gillnet, ABS = Artisanal Beach Seine, ADN = Artisanal Drift Net.

Gear	E % of E_{2019} (days)	$\overline{H}$ (t/yr)	NPV (m R$)	LE (ind)	TLI (m R$)	PCLI (R$/yr)
IPS	82 45.0%	950.6	43.6	227	3.1	13 863.00
AG	12 791 23.5%	1 661.3	79.9	1 151	5.7	4 993.80
ABS	13 050 83.9%	1 647.0	78.5	2 542	5.6	2 222.40
ADN	3 950 45%	1 020.5	55.5	410	4.0	9 664.60
		5 279.4	257.5	4 330	18.4	4 249.42

Sensitivity analysis

Table S 3.9. Sensitivity analysis of the bioeconomic model for the mullet fishery. Scenarios: BS, base scenario; NCG, non-cooperative-game; CNCG, constrained non-cooperative game. Players: IPS, industrial purse seine; AG, artisanal gillnet; ABS, artisanal beach seine; ADN, artisanal drift net. x is the stock size in the last period of the simulation (25 years). E represents the fishing effort in fishing days.

Perturbations	x_{BS} (% of k)	Exclusion of ABS in NCG? (nº solutions with exclusion/ nº total solutions)	x_{NCG} (% of k)	x_{CNCG} (% of k)	CNCG solution [E_{IPS} E_{AG} E_{ABS} E_{ADN}]
Original model	26.4	Yes (2/2)	51.2 and 45.7	63.8	[82 12791 13050 3950]
AG catchability (-15%)	30.1	Yes (1/2)	54.3 and 40.7	65.3	[82 12791 13050 3950]
AG catchability (+15%)	23	Yes (1/1)	48.6	60.4	[82 12791 13050 3950]
ABS catchability (-15%)	27.4	Yes (1/1)	48.9	63.5	[82 12791 13050 3950]
ABS catchability (+15%)	25.4	Yes (1/1)	48.9	62.1	[82 12791 13050 3950]
IPS fish price (-15%)	26.4	Yes (2/2)	50.2 and 41.9	63.8	[82 12791 13050 3950]
IPS fish price (+15%)	42.7	Yes (2/3)	49.7, 42.9 and 41.9	63.8	[82 12791 13050 3950]
IPS discount rate (-15%)	42.7	Yes (2/3)	50, 45.7 and 43.3	63.8	[82 12791 13050 3950]
IPS discount rate (+15%)	42.7	Yes (1/2)	49.9 and 43.4	63.8	[82 12791 13050 3950]
Carrying capacity, k (-)	42.7	Yes (1/2)	51.5 and 51.2	64.7	[82 9163 11558 3950]
Carrying capacity, k (+)	42.7	Yes (1/1)	42.2	58.2	[82 13247 20294 3950]
Intrinsic rate, r (-)	42.7	Yes (1/2)	49.7 and 43.2	63.0	[82 12160 12404 3950]
Intrinsic rate, r (+)	42.7	Yes (1/2)	50.2 and 43.7	62.1	[82 13424 17122 3950]
Cobb-Douglas $\alpha = \frac{1}{2}, \beta = \frac{1}{2}$	13.5	No (0/2)	50 and 51.9	57.2	[82 25201 5008 3950]

Cobb-Douglas $\alpha = \frac{1}{3}, \beta = \frac{1}{3}$	0.0*	No (0/1)	64.3	65.9	[82 8237 3975 3405]

*The stock collapse in the 19th year.

4 CAPÍTULO 3: BIOECONOMIC MODELLING OF A MULTISPECIES SMALL-SCALE FISHERY SYSTEM

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*Manuscript in preparation for submission to **Ecological Economics** journal*

Abstract

A fishery includes an ecologic, a socioeconomic, and a governing embedded system. Fisheries management requires addressing all these systems simultaneously and is hence a challenging undertaking. In this setting, fisheries bioeconomic models have become important tools. A bioeconomic model describes the fishing system gathering information from both the biologic and the socioeconomic system. Combined with game theory— a mathematical theory born in economics to understand agents behaviors in decisions making situations—a variety of scenarios can be explored to understand how relation between ecologic, economic, and social dimensions could support fishery management decision making. This is especially relevant in small-scale fisheries, which are often complex, overlooked and poorly understood. Here we built and present a multispecies and multigear bioeconomic model using the case of Laguna, in Southern Brazil—home to a diversity of small-scale fisheries that urge for integrative management measures—to investigate how our model behaves empirically. The model accounts for biologic and technologic interactions between species and fishing gears, including the Lahille's bottlenose dolphin, the lebranch mullet, the pink shrimp species, and casting nets, gillnets, shrimp fyke nets. We implemented it with specific assumptions, in three 25-year different scenarios—base (BS), open access (OA) and optimal management (OM) scenario. In BS we analyzed fishing gears dynamics starting with 2019 fishing effort levels. In OA, fishing efforts raise or decrease every year based in positive or negative profit values, respectively. Finally, in OM we play a social planner game starting with fishing effort that maximizes combined net present value (NPV). Our results showed an important tradeoff between labor effort, species conservation and NPV. In OM, the gillnets left the system, the casting nets raised fishing effort until maximum boundary and the shrimp fyke net fishing effort was similar of the one in BS. Consequently, fishing effort decrease 23% of BS's levels. However, *per capita* incomes and stocks conservation reached the best outcome between the scenarios increasing respectively, in average, 31.3% and 59.6%, considering BS levels. We argue that our game-theoretic bioeconomic model for multispecies small-scale fisheries can generate meaningful scenarios and shed light in important management issues, inspiring sustainable decision making for the system.

Key words: bioeconomic models; game theory; natural resources management; multispecies; small-scale fishery; socio-ecological system. *Tursiops truncatus gephyreus*. *Mugil liza*. *Farfantepenaeus paulensis*. *Farfantepenaeus brasiliensis.*

4.1 INTRODUCTION

A fishery system includes natural, socioeconomic, and a governing subsystem. Only two out of these three axes—the resource (natural subsystem) and the regulative measures (governing subsystem)—are commonly considered in management decisions (Chuenpagdee and Jentoft, 2009). However, people involved in the pre-harvest, harvest, and post-harvest chain—composing the socioeconomic system—interact directly with management actions and resource dynamics and hence should be considered in any management effort (Berkes *et al.*, 2001). Single species-based management actions in a multispecies fishery system could be successful (Hilborn *et al.*, 2020). However, that management strategy are usually limited by ignoring ecological relationships among species, and its social and economic effects, tending to lead to overfishing outcomes (Hoff *et al.*, 2010). Accounting for intra and interspecies interactions information such as competition and predation is crucial when modeling species population dynamics and, consequently, assessing fishery sustainability (Capitani *et al.*, 2021). On the other side, technological and economic interactions between fishing gears, such as bycatch and concurrence, could also intervene in the system balance by affecting, respectively, the health of a fishery stock or the fishers' foraging decisions (Kasperski, 2015).

Fisheries science constantly values and advocates, when possible, the use of ecosystem-based management as the most efficient strategy to achieve integrated sustainability (May *et al.*, 1979; de Abreu-Mota *et al.*, 2018; Cisneros-Montemayor *et al.*, 2020). However, the complexity of fisheries systems challenges the built and use of ecosystem-based models to define biological reference points and clear guidelines for regulating a fishery (Ulrich *et al.*, 2002; Berkes, 2012). In this context, bioeconomic models built in a multispecies context and with a game theory framework can be a game-changer for a better understanding of such complex systems with all their elements, helping management decisions objectively (Gurney *et al.*, 2016; Grønbæk *et al.*, 2018). A fishery bioeconomic model describes the fishing system gathering information from the natural system (e.g. growth rate and carrying capacity of the species) and the socioeconomic system (e.g. fishing effort, revenue and costs of the fishing gears). When a bioeconomic model is combined with game theory—a mathematical approach to study strategic interaction between agents (e.g. individuals, firms, and countries) in a competitive or cooperative context—a variety of behavioral scenarios can be explored (Clark, 2007). A lot could be done applying game-theory to fisheries management (Laukkanen, 2003; Lindroos *et al.*, 2007; Pintassilgo, 2008;

Azevedo *et al.*, 2020), particularly considering multispecies systems and ecosystem-based management (Miller *et al.*, 2013; Kasperski, 2015; Salenius, 2018; Cisneros-Montemayor *et al.*, 2020; Lai *et al.*, 2021).

Artisanal systems, however, are complex, overlooked and then poorly understood (Berkes *et al.*, 2001; Jentoft and Chuenpagdee, 2015; Schuhbauer and Sumaila, 2016). In this challenging context, building bioeconomic models drawn for specific systems can shed light in key drivers in fishery's dynamics. Laguna, in southern Brazil, is home of a diversity of small-scale fisheries with conflicts and issues that urge for integrative management measures (Dantas, 2018). This fishery system provide a good opportunity to develop such multispecies bioeconomic models: (a) there are long term monitoring efforts on some fishing activities in the area that provide initial data to define empirical model inputs (Bezamat *et al.*, 2020); (b) the main fishing activities are spatially restricted, in ecological, economic and social terms, facilitating the mapping of interactions in these three axes; (c) there are signs of overfishing or predatory and unsustainable fishing that encourage the simulation of management scenarios (Sunye *et al.*, 2014; Dantas, 2018; UNIVALI, 2020); (d) the area is inhabited by a resident population of Lahille's bottlenose dolphins (*Tursiops truncatus gephyreus*), an apex predator that plays a key ecological role in the fishery dynamics; (e) and last, but not least, these wild dolphins assist traditional casting net fisheries by herding fishing schools (mainly mullets) toward the shore, where fishers stand in line waiting for dolphins behavioral cues that indicates the ideal time and place to cast their nets (Simões-lopes *et al.*, 1998). All these pieces favor building a model that simplifies and depicts this system, allows to simulate management scenarios, and explore their bioeconomic outcomes.

In this paper, we built a bioeconomic game-theoretic model to describe a multispecies and multi-gear fishery system, using the Laguna fishery system to investigate how our model behaves empirically. Biologic interactions such as predation and competition were added to the model, that also accounts for bycatch interactions between different gears. Our outputs are biologic (e.g. stock dynamics, harvest) and socioeconomic (e.g. net present value, labor effort, per capita labor income). We simulated the fishery system using a 25-year horizon, three different gears and three different target species, assuming both technological and ecological interactions between them. The gears were casting net, gillnet, and shrimp fyke net. The species were lebranch mullet (*Mugil liza*), pink shrimp (*Farfantepenaeus paulensis* and *Farfantepenaeus brasiliensis*) and the bottlenose dolphins (*Tursiops truncatus* *gephyreus*). Bottlenose dolphins are not a target species for any of these fishing gears, however, it is a central piece in our model since they (a) prey on mullet; (b) their survivor is threatened by the gillnet fleet accidental bycatch and as aforementioned, (c) they interact with artisanal casting net fishers in an apparent cooperative context to catch mullets (see additional details below) and (d) they cause behavioural effects in fishery dynamics. By applying our model for an empirical case, we contributed to (a) illustrate how a bioeconomic model can contribute to account for the economic and ecological elements of a fishery system, (b) and how such a model can guide ecosystem-based management plans. We conclude by discussing the strengths and weaknesses of our approach and point the way forward for further research.

4.2 METHODS

4.2.1 Bioeconomic model

Let $G = \{g_1, g_2, \cdots, g_M\}$ be the set of M different fishing gears exploiting N different species in $S = \{s_1, s_2, \cdots, s_N\}$, during T periods of time. Each fishing gear, with specific costs (TC, c, l, o), catchability (q), fish price (p), and discount rate (δ). The different components of this model are detailed in the following subsections. Table 4.1 displays the variables, in upper-case letters, and parameters of the model.

4.2.1.1 Stock dynamics

Each different species s, has its specific growth function $F(X^s)$ according to its biologic characteristics. The consequences of a possible biologic interaction between different species—as predation or competition—would be incorporated in the product $X_t \cdot I$. Here, X_t is a row vector with N columns. The s-th column of X_t computes the stock size of species s in the time t. I is a $N \times N$ matrix with interaction coefficients (i_{ab}) that indicates how much one unit (biomass or individual) of species a impact (positively or negatively) in species b population. Besides the growth function, stock dynamics for each species will also depend on the harvest (H). So, for each species $s \in S$ we can determine the stock for the next period using the following expression:

$$\mathrm{X}_{t+1} = \mathrm{X_t} + \mathrm{F}(X_t) - H_t + X_t \cdot I \tag{12}$$

In equation (12), X_{t+1} is the stock size row vector in the next period determined by $\mathrm{X_t}$, the current stock size row vector, the growth function row vector $\mathrm{F}(X_t)$, the harvest vector

H_t, and the biologic interactions term $X_t \cdot I$. The latter could be positive or negative, depending on the interaction. Note that H_t vector computes harvest of each species (columns) by all fishing gears in period t.

4.2.1.2 Harvest function

The harvest function is a key element in a fisheries bioeconomic model, as it links the biological dimension (stock dynamics) to the economic dimension (revenues and costs). Several functional forms have been adopted in the literature. In our study, we consider a Cobb-Douglas function, in which harvest (H) depends on catchability (q), fishing effort (E), and stock biomass (X):

$$H^{s}{}_{g,t} = q_g^s \cdot (E_{g,t})^{\alpha_g^s} \cdot (X_t^s)^{\beta_g^s} \tag{13}$$

Here, $H_{g,t}^s$ is the harvest of species s by fishing gear g in period t. Harvest varies with time, gear, and species. Parameter q_g^s represent the catchability of the fishing gear g related to species s. The term X_t^s is the species s stock size in period t. Coefficients α_g^s and β_g^s are the elasticities of the harvest of species s to the fishing effort of fishing gear g and to stock size, respectively. In economics, elasticity is the responsiveness of one variable (e.g., harvest) with the change of another variable (e.g., fishing effort or stock size). This functional form is widely used in the application of game-theory to fisheries (e.g., Grønbæk et al., 2020).

4.2.1.3 Revenue and costs

Total revenue ($TR_{g,t}$) can be calculated for any gear g in any period t. $TR_{g,t}$ is given by the product of the fish price (p_g^s) and harvest (H_g^s) for each species.

$$TR_{g,t} = \sum_{s \in S} p_g^s \cdot H_{g,t}^s \tag{14}$$

Using equation (2) we can rewrite equation (3) to:

$$TR_{g,t} = \sum_{s \in S} p_g^s \cdot q_g^s \cdot (E_{g,t})^{\alpha_g^s} \cdot (X_t^s)^{\beta_g^s} \tag{15}$$

It is assumed that costs for each gear involve crew, fishing shack (the building where fishers store their boats and equipment), fuel, fishing gear and vessel maintenance, license fees, and food, depending on the fishing gear type. The cost of a fishing effort unit (c) combines the costs directly related to the fishing effort (e.g. fuel, fishing shack, and sustenance). From the difference between total revenue (TR) and total fishing effort costs, a percentage (o) is taken to cover other costs (e.g. emergencies and unexpected costs with the fishing gear or the vessel). Finally, the laborers' percentage (l) determines how much will be paid to the crew (Azevedo *et al.*, 2021). The crew is paid only after deducting both fishing effort costs and other costs to revenue—if the crew is not paid, as in a one person fishing gear, $l = 0$. Thus, the total cost ($TC_{g,t}$) of a fishing gear g in period t is:

$$TC_{g,t} = c_g \cdot E_{g,t} + o_g \cdot \left(TR_{g,t} - c_g \cdot E_{g,t}\right) + l_g \cdot \left(1 - o_g\right) \cdot \left(TR_{g,t} - c_g \cdot E_{g,t}\right)$$

$$= TR_{g,t} - \left(1 - o_g\right) \cdot \left(1 - l_g\right) \cdot \left(TR_{g,t} - c_g \cdot E_{g,t}\right) \tag{16}$$

4.2.1.4 Profit and net present value (NPV)

Profit (Π) was calculated as the difference between total revenue (TR) and total cost (TC) for each player i in period t:

$$\Pi_{g,t} = TR_{g,t} - TC_{g,t} = \left(1 - o_g\right) \cdot \left(1 - l_g\right) \cdot \left(TR_{g,t} - c_g \cdot E_{g,t}\right) \tag{17}$$

The present value of the profit (PV) in each period t for each fishing gear g was computed using the discount rate (δ_g) for each fishing gear:

$$PV_{g,t} = \frac{\Pi_{g,t}}{\left(1 + \delta_g\right)^t} \tag{18}$$

Then, the net present value (NPV) of the fishing gear g was calculated by the sum of the present values of profits (PV) over all periods:

$$NPV_g = \sum_{t=1}^{T} PV_{g,t} \tag{19}$$

4.2.1.5 Labor impact

Labor impact for each fishing gear was assessed through the labor effort (LE) in terms of the number of people directly involved, the total labor income (TLI) per year in million reais — the local currency; and the per capita labor income (PCLI) in reais per laborer per year. For each fishing gear, LE was calculated using fishing effort (E) for a specific gear g in a specific period t, and the fishers per fishing days ratio (fd) as:

$$LE_{g,t} = E_{g,t} \cdot \mathrm{fd_g} \tag{20}$$

TLI corresponds to the amount of money that each fishing gear pays to its laborers in the period t:

$$TLI_{g,t} = l_g \cdot (1 - o_g) \cdot (TR_{g,t} - c_g \cdot E_{g,t}) \tag{21}$$

PCLI for each gear, was obtained dividing total TLI by total LE:

$$PCLI_g = \frac{\sum_{t=1}^{T} TLI_{g,t}}{\sum_{t=1}^{T} LE_{g,t}}$$

Table 4.1. Glossary of parameters of the BGTM.

Parameter	Description
G	gears set
g	fishing gear in the set M
M	number of fishing gears in the model
N	number of species in the model
S	species set
s	species in the set S
T	number of periods considered as time horizon
TC	total cost
c	cost of a unit of fishing effort (R$)
l	laborers' percentage
o	other costs percentage
q	catchability
p	fish price (R$/t)
δ	discount rate
X	stock size (biomass, individuals, …)
$F(X)$	growth function
I	species interaction matrix
i	interaction coefficient
H	harvest (tonnes)
E	fishing effort (fishing day)
TR	total revenue (R$)
Π	profit (R$)

PV	present value of the profit
NPV	net present value for all the periods
LE	labor effort (number of people directly involved)
TLI	total labor income
$PCLI$	*per capita* labor income
fd	Fishers per fishing days ratio ($n^\circ fishers/E$)

The symbol R$ represent the actual currency in Brazil named Real (In 05/05/2021, 1 R$ = 0,19 USD).

4.2.2 Case study

To illustrate the outputs and the performance of the model, we use the Southern Lagoon Complex of Santa Catarina (LCSC), Southern Brazil. The LCSC, composed of two connected sectors with three lagoons each (Barletta *et al.*, 2017), is an important social and ecological system. Despite anthropic pressure harming ecosystemic services, families living at the coast use the complex to earn income through small-scale fisheries, targeting a diversity of species with several fishing gears (Dantas, 2018). For this study case we analyzed the harvesting of the mullet and the pink shrimp with the presence of the bottlenose dolphin as a mullet predator.

4.2.2.1 Natural system

The lebranch mullet occurs between Florida (USA) and Argentina (Mai *et al.*, 2014). During its life cycle, the mullet uses estuaries, freshwater, or open sea (Garbin et al., 2014). In southern Brazil, reproductive migration for this species occurs—from the estuaries or coastal lagoons towards the open sea, and then northwards—between April and June, with a peak-spawning in June (Crosetti and Blaber, 2016). With the end of reproductive phase, the mullet stock moves southward to estuaries and coastal lagoons to feed and grow (Menezes *et al.*, 2003; Crosetti and Blaber, 2016). This pelagic species has an important ecological value as a primary consumer, transferring energy between the bottom and top trophic levels (Crosetti and Blaber, 2016). In the LCSC, the mullet is targeted by different fishing gears, such as casting nets and gillnets (Dantas, 2018).

Farfantepenaeus brasiliensis has a wide distribution—ranging from North Carolina, US to Rio Grande do Sul, Southern Brazil—with a high abundance in Rio de Janeiro and São Paulo, two states in Southeastern Brazil, while *Farfantepenaeus paulensis* is distributed from Bahia (Northern Brazil) to northeastern Argentina with high abundance in Santa Catarina and

São Paulo, southern and southeastern Brazil, respectively (D'Incao *et al.*, 2002; Leite and Petrere, 2006). Both species are known as the pink-shrimp and its life cycle has an oceanic phase — for reproduction and larval development—and an estuarine phase—for juvenile growth, development and migration (D'Incao, 1991). As a valuable fishery resource, these species are exploited both in the ocean and inside estuaries, in their adult and pre-adult stages, respectively (Salvati *et al.*, 2021). Inside LCSC, the pink shrimp is mostly harvested by artisanal fishers using the shrimp fyke net, a passive fishing gear with a luminous bait (Dantas, 2018; Farias *et al.*, 2019).

The bottlenose dolphin is a worldwide distributed small cetacean species that occurs from coastal to pelagic waters in a diversity of habitats such as estuaries, bays and lagoons, in some cases maintaining definable, long-term, multi-generational home ranges and then residency patterns (Wells and Scott, 1999). In the Southwestern Atlantic Ocean, morphological and genetic distinctions between coastal and offshore bottlenose dolphins suggests adaptation to different habitats (Costa *et al.*, 2016; Wickert *et al.*, 2016; Fruet *et al.*, 2017; Simões-Lopes *et al.*, 2019). Consequently, the Society for Marine Mammalogy has recognized the coastal bottlenose dolphins as the subspecies *Tursiops truncatus gephyreus* (Lahille's bottlenose dolphin), consisting of small discrete populations with high site fidelity to estuaries (Fruet *et al.*, 2014). This dolphin species has complex cognitive abilities with marked behavioral flexibility (Marino, 2004), engaging in a diversity of foraging tactics likely socially learned (Sargeant and Mann, 2009), and consuming mostly fish and squid but occasionally shrimp and other crustaceans (Teixeira *et al.*, 2021). The species plasticity is also well illustrated by how some populations adapted their feeding behavior to interact with human activities whether competing, consuming discard or even cooperating with them (Simões-lopes *et al.*, 1998; Wells and Scott, 1999; Read *et al.*, 2003). In LCSC, for instance, some individuals of the small resident population that inhabits the area (with 55 individuals approximately) specialized in interacting with mullet casting net artisanal fishers in a apparently cooperative foraging to catch fish, predominantly mullet (Simões-Lopes, 1991; Daura-Jorge *et al.*, 2012).

4.2.2.2 Socioeconomic system

The mullet fishery assisted by bottlenose dolphin has cultural, ecologic, and socioeconomic importance for the LCSC fishery system. In brief, dolphins drive schools of fish toward a line of fishers standing in shallow waters or in small boats and indicate with stereotyped behavioral cues—such as head slaps, back presentation, partial emersion or tail slaps—when and where the fishers should cast their nets (Simões-lopes *et al.*, 1998; Simões-Lopes *et al.*, 2016). This interaction seems to have benefits for both sides. Fishers clearly benefit by catching more and larger fish and, apparently, dolphins accrue similar benefits (Simões-lopes *et al.*, 1998). In addition, dolphins in this cooperative tactic use smaller home ranges (Cantor *et al.*, 2018)—likely because they concentrate their foraging activities around the few sites of interaction—and has survival benefits (Bezamat *et al.*, 2019), suggesting that foraging with fishers generates long-term gains for the dolphins. The cultural values of such unique human-dolphin cooperation are well-illustrated by recent domestic legislations that recognized this interaction as an Intangible Cultural Heritage (municipal law 17.084/2017, 2017). Non-material benefits related to this interaction are also perceived by local fishers, including sense of place, leisure and recreation (Machado *et al.*, 2019).

The mullet season is usually defined between late April and July in southern Brazil, when dense schools of adult individuals are targeted during the reproductive migration (Herbst and Hanazaki, 2014). In Santa Catarina, where most of the catches occur, the beach seine artisanal mullet fishery is recognized by law as an artistic, cultural, and historical heritage (Brasil, 2018). Beach seines, gillnets, fish traps, and drift nets are the main artisanal fishing gears used by about 202 artisanal fishing communities to harvest mullets along the southern Brazilian coast. In LCSC, mostly casting nets and gillnets are used to harvest mullets. The artisanal gillnet is a traditional and not officially monitored fishery conducted by artisanal fishing communities. As a passive fishing gear, gillnets are one of the main causes of cetacean bycatches (Read, 2008) and occasionally catch dolphins accidentally in LCSC, contributing to increase non-natural mortalities and threating long-term population viability (Bezamat *et al.*, 2021). However, the gillnets used to catch mullets—a small surface seine net—are not the major cause of dolphins' bycatch. Must bycatch is due to gillnets and trammel nets used in catfish harvesting, which are left at the bottom of the lagoon or across canals (Bezamat *et al.*, 2021). In case of a decline in the dolphin population, the fisher's engagement in the human-dolphin cooperation may also decline and alternative fishing techniques such as seine gillnets used in mullet fisheries or even trammel and gillnets used to catch other species, can be favored to satisfy the local demand for fish (Santos-Silva, 2021).

Both casting nets and gillnets could catch the pink shrimp. However, the massive biomass extraction for this species is from the shrimp fyke net fishery (UNIVALI/EMCT/LEMA, 2020). The casting net used to catch the shrimp is different from the one used to catch mullet in association with dolphins and has almost no contribution to shrimp biomass extraction. The shrimp fyke net is a passive fishing apparatus with two sleeves, a conic tunnel, and a bagger, and attracts preys using a lighted sign. Using a unique LED lamp, six fyke nets can be combined in a circular layout, trapping shrimp—and an expressive amount of other species individuals—from all directions (Farias *et al.*, 2019). The number of shrimp fyke nets spots found is more than the number of licensed fishers, indicating illegal harvesting in this economic important fishery (Sunye *et al.*, 2014).

4.2.2.3 The LCSC game

In our game, we gather the players by fishing gears to interact for 25 years. We assume that casting net gear catches both mullet and shrimp[1]. The gillnet gear catches mullets, shrimps, and dolphins[2] (as an accidental bycatch). The shrimp fyke net gear catches shrimps but also mullets in a non-marketable age as bycatch. In addition, the bottlenose dolphins and the mullet stock are, respectively, predators and preys, intervening directly in the stock dynamics of the system. The same occurs between the bottlenose dolphins and the shrimp (Figure 4.1). To better adapt the model for this case study the following additional assumptions were made:

(A1) **Natural growth of all species is stochastic.** Biologic growth parameters such as intrinsic rate (r) and carrying capacity (k) could be uncertain. In addition, seasonal unpredictable events could also perturb natural growth data.

(A2) The casting net fishing effort depends on the bottlenose dolphin population. When dolphins' population decreases (increases), casting net fishing effort decreases (increases) 5% for each dolphin. Moreover, 40% of casting net fishing effort loss is transferred to the gillnet. As the mullet casting net basically depends on the human-dolphin interaction to exist, a decrease in dolphins' population will jeopardize this

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[1] The shrimp casting net and the mullet casting net are different fishing gears used by different communities. We gathered them in the model for convenience. The catchability was adjusted to adequately represent fishing effort upon each species.

[2] The gillnet that bycatches the dolphin is not the same that the one that catches mullet and shrimp. The first is left in the bottom of the lagoon and the second is used to make a seine. We gathered them in the model for convenience. The catchability and percentages of variations was adjusted to adequately represent fishing effort upon each species.

fishing gear forcing fishers to leave the activity. As an alternative mullet fishery, the use of gillnet is expected to increase to satisfy local demands (Santos-Silva, 2021).

(A3) **The frequency of bottlenose dolphin accidental bycatch by gillnet increases with the decrease of the mullet stock.** With less mullet, the bottlenose dolphins will increase its home range to forage. Thus, the probability of accidental bycatch would also increase (Agrelo *et al.*, 2019).

In this game, players' strategy relies on the fishing effort choice. Payoffs are measured by the net present value of these choices. The choice of one player affects directly on the other players because they all harvest in the same natural system and, for some players, the targeting species are the same. Each choice of fishing effort by the players will affect the stock dynamics, as well as the socioeconomic outcomes of the system. To better explore the characteristics of the system, we considered three different situations.

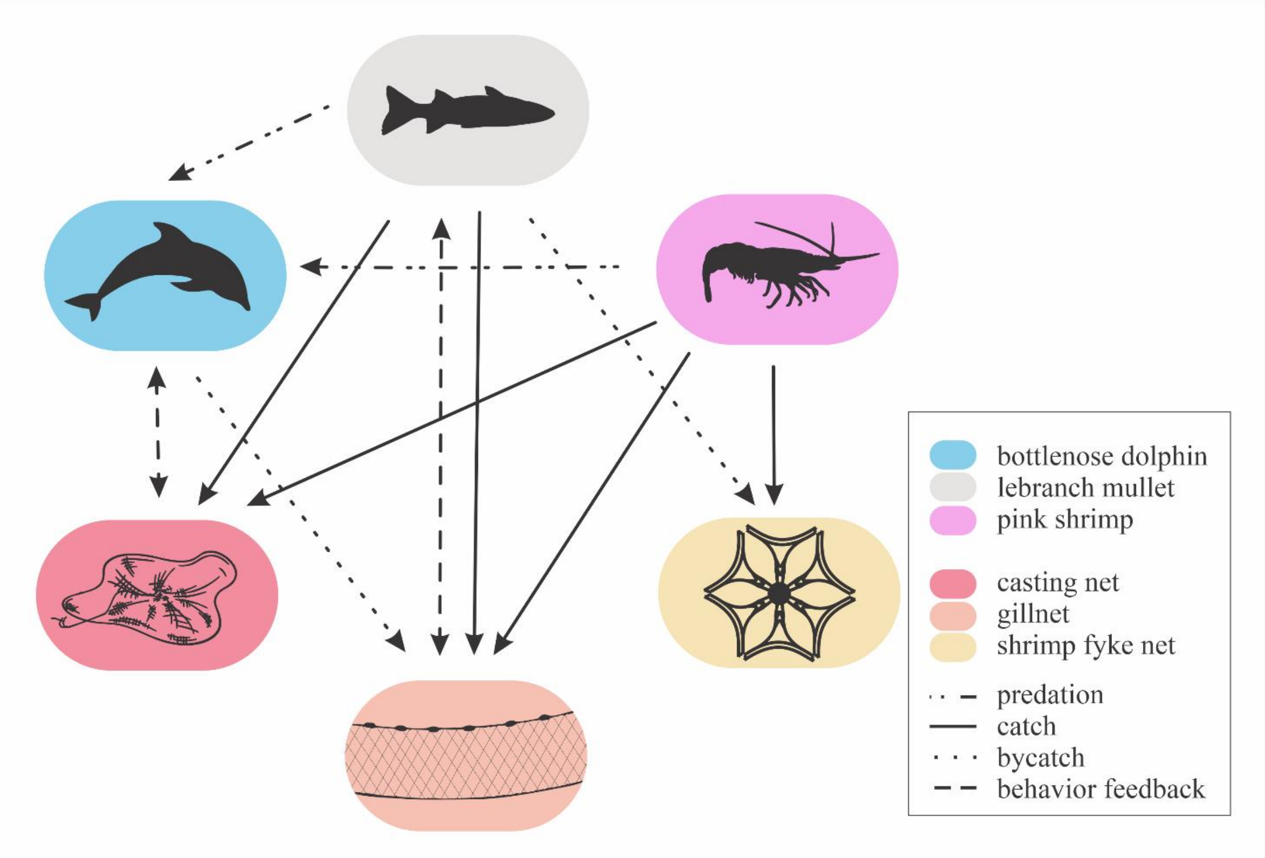

Figure 4.1. LCSC fishery system with all ecological, technological and behavioral interactions.

4.2.2.4 Scenarios

The scenarios considered in this paper were the base scenario (BS), the open access scenario (OA) and the optimal management scenario (OM). In the BS, we used the 2019 fishing effort levels and analyzed the system dynamics for 25 years. In the OA, the fishery starts with the 2019 fishing effort levels. Then, for each year along 25 years, players raise fishing effort in the presence of positive profit (gains), maintain it when profits are nil and reduce fishing effort in the presence of losses (negative profits). In the OM we made a social planner game, trying to find what are the fishing effort for each fishing gear that will maximize global net present value—the sum of the net present value of each player— in a 25-year horizon. In this scenario we optimize fishing efforts as if all fishing gear together were the same player (the social planner) with only one profit. Each fishing gear had an upper bound for the fishing effort of twice the 2019 fishing effort. In the social planner game, we might think of a hypothetical all-mighty decision maker who could set and enforce the fishing effort of all the fishing gears. In this game, all costs and revenues of the different fishing gears affect the same decision maker. Thus, the optimal solution will maximize the NPV considering the profits of all fishing gears.

4.2.2.5 Bioeconomic parameters

To illustrate the use of our bioeconomic model in the LCSC system, we used the bioeconomic parameters described in Table 4.2 and Table 4.3. Biologic information for the dolphins was taken from Bezamat *et al.* (2021) and Teixeira *et al.* (2020); for the mullet from UNIVALI (2020) and Azevedo *et al.* (2021); and for the pink shrimp from Azevedo *et al.* (2020). The mullet information on stock size was available only for the whole southern-southeastern stock. To estimate the mullet stock size within the LCSC we compared the mullet gillnet catch in all the range of the stock with the catch by the same gear inside LCSC. Then, we appied that same proportion to the entire mullet stock size. We estimated catchability (q) using $q = \frac{H}{E \cdot X}$ with catch information in UNIVALI/EMCT/LEMA (2020) and fishing effort information in Dantas (2018), Azevedo *et al.* (2021) and Azevedo *et al.* (2020). In our study each fishing gear is considered as one player, so the fishing effort of one fishing gear represent the sum of the fishing days of each fisher that harvest with that gear. Complementary, the fishers per fishing days ratio (fd) represent the average of fisher per day of fishing considering the whole period. As one fisher fishes more than one day at the period, the fd ratio a less than 1 value. To better understand fishing effort values in Table 4.2, and visualize how many fishers, in average, are fishing per day for each gear, we could compute $\frac{E0}{fd \cdot E0}$. Considering values in Table 4.2, 50 fishers are throwing nets, 50 fishers are setting gillnets and 14 fishers are using the shrimp fyke nets, in average per day of fishing in LCSC. For the other fishing gear parameters we used information in Dantas (2018) and additional field observations. Due to the lack of precise and specific information, some of the parameters were estimated indirectly.

Table 4.2. Bioeconomic parameter of the three fishing gears in the socioeconomic system: casting net, gillnet, and shrimp fyke net.

gear	casting net	gillnet	shrimp fyke net
initial fishing effort (E_0)	20841 days	60368 days	35000 days
catchability for the bottlenose dolphin (q_{bd})	0	6.02E-03	0
catchability for the lebranch mullet (q_{lm})	2,00E-02	3.00E-02	3,06E-05
catchability for the pink shrimp (q_{ps})	1,00E-05	1.00E-06	1,20E-01
cost per unit of fishing effort (c)	R$ 10.00	R$ 195.00	RS 20.00
labor cost (l)	0 %	50 %	0 %
other costs (o)	0 %	10 %	0 %
fishers per fishing days ratio (fd)	0.02 ind/day	0.02 ind/day	0.07 ind/day
market price for the lebranch mullet (p_{lm})	13000 R$/t	7000 R$/t	-
market price for the pink shrimp (p_{ps})	23000 R$/t	18000 R$/t	23000 R$/t
opportunity rate (δ)	5 %	5 %	5 %

Table 4.3. Bioeconomic parameters of the three different species in the natural system: bottlenose dolphin, lebranch mullet and pink shrimp.

species	bottlenose dolphin	lebranch mullet	pink shrimp
growth parameters	$r^{bd} = 0.0139$ $SD_{r^{bd}} = 0.0561$ $k^{bd} = 90$ $SD_{k^{bd}} = 9$	$r^{lm} = 0.3945$ $SD_{r^{lm}} = 0.00537$ $k^{lm} = 24117$ $SD_{k^{lm}} = 1849.63$ $m^{lm} = 1.37$ $SD_{m^{lm}} = 0.1663$	$r^{ps} = 0.7$ $SD_{r^{ps}} = 0.07$ $k^{ps} = 15000$ $SD_{k^{ps}} = 400$
initial stock size (X_0)	55 individuals	7235.1 t	9000 t

growth model	logistic (Bezamat *et al.*, 2020)	Pella-Tomlinson (Azevedo *et al.*, 2021)	logistic (Azevedo *et al.*, 2020)
interaction with bottlenose dolphin	0	-2	-1
interaction with lebranch mullet	0.001	0	0
interaction with pink shrimp	0.001	0	0

The growth function used for each species was:

bottlenose dolphin

$$F^{bd}\left(X_t^{bd}\right) = X_t^{bd} \cdot \left(r^{bd} + SD_{r^{bd}} \cdot \mu_{r^{bd},t}\right) \cdot \left(1 - \frac{X_t^{bd}}{k^{bd} + SD_{k^{bd}} \cdot \mu_{k^{bd},t}}\right)$$

lebranch mullet

$$F^{lm}\left(X_t^{lm}\right) = \frac{X_t^{lm}}{m^{lm} + SD_{m^{lm}} \cdot \mu_{m^{lm},t}} \cdot \left(r^{lm} + SD_{r^{lm}} \cdot \mu_{r^{lm},t}\right) \cdot \left(1 - \left(\frac{X_t^{lm}}{k^{lm} + SD_{k^{lm}} \cdot \mu_{k^{lm},t}}\right)^{m^{lm} + SD_{m^{lm}} \cdot \mu_{m^{lm},t} - 1}\right)$$

pink shrimp

$$F^{ps}\left(X_t^{ps}\right) = X_t^{ps} \cdot \left(r^{ps} + SD_{r^{ps}} \cdot \mu_{r^{ps},t}\right) \cdot \left(1 - \frac{X_t^{ps}}{k^{ps} + SD_{k^{ps}} \cdot \mu_{k^{ps},t}}\right)$$

In these expressions bd, lm and ps are abbreviations for the bottlenose dolphins, lebranche mullet and pink shrimp, respectively. F^s represents the growth function of species s, X_t^s represent the stock size of species s in time t, r^s is the growth rate of species s, k^s is the carrying capacity of species s, SD_{Y^s} is the standard deviation of variable Y of the species s, m^{lm} is the shaping parameter of the Pella-Tomlinson model and $\mu_{Y,t}$ represents a random variable from a standard normal distribution for the variable Y in period t.

4.2.3 Analysis

We built our bioeconomic model of the LCSC system under three different scenarios using MATLAB software (MATLAB 2021, version R2021a). In each scenario we used the fishing effort of the players as the starting point. With fishing effort information, we computed harvest (H), total revenue (TR), total cost (TC), labor effort (LE), total labor income (TLI), per capita labor income ($PCLI$) and profit present value (PV) for the first year.

Using this information together with the growth functions, we calculated the stock size for the next year of each species. Finally, we applied assumptions A2 and A3 of section 4.2.2.3 to vary fishing effort and/or catchability for the next year if the conditions were satisfied. This same procedure was applied for 25 years. In both, base (BS) and open access (OA) scenario, we used the 2019 fishing effort levels as the input. In the OA, we additionally increased (or decreased) the fishing effort of a player when its profit was positive (or negative). In the optimal management scenario (OM), to compute the optimal fishing effort vector, we use the MATLAB function *fmincon*.

When using stochastic growth for all the species, we run a thousand iterations of the procedure previously described for each scenario. In OM scenario we founded a thousand optimal solutions—one for each iteration—and computed the bioeconomic consequences for each solution. In this scenario, each optimal solution was used as an initial fishing effort level. In the result plots, dark-colored lines represent mean values of all iterations while correspondent light-colored lines represent data from all iterations. Bar plots were built using mean values. We provide all the code and data to replicate our model and simulations in the open-access repository: https://github.com/ericztt/LCSC_model.

4.3 RESULTS

Our multispecies and multi-gear bioeconomic model was applied to the Southern Lagoon Complex of Santa Catarina (LCSC) considering the casting net, the gillnets, and the shrimp fyke nets as fishing gears and the bottlenose dolphin, the lebranch mullet and the pink shrimp species. In the base scenario (BS), fishing gears adopted the 2019 fishing effort levels over the 25-year time horizon. In this scenario, stock size for the dolphins, the mullets and the shrimp ended in 25.7 %, 52.8 % and 38.2 % of their own carrying capacity. Dolphins' stock showed a steady decreasing trend over the 25-year. Both mullet and shrimp stock size stabilized at the end. However, the evolution of the stock is markedly different, with the mullet stock exhibiting an increasing trend and the shrimp stock a decreasing trend. (Figure 4.2, top). The mullet stock size grew despite the pressure of all three gears. On the other hand, bottlenose dolphin and pink shrimp natural growth were not enough to overcome the pressure from the accidental bycatch and the shrimp fishing, respectively. The fishing effort of the casting net decreased 27.5% in 25 years, which indicates a potential abandonment from the casting net in response to dolphins' loss (assumption A2). In contrast, the gillnet fishing effort increased 4%. The shrimp fyke net fishing effort — the biggest shrimp catcher fishing gear — stay the same, as expected (Figure 4.2, middle). With that fishing effort dynamics, the system lost 65 fishers, from 4074 to 4009, totalizing 1.6% of loss (Figure 4.5, left). The annual per capita labor income (PCLI) for the casting net, the gillnet and the shrimp fyke net stabilized respectively at R$ 16,040.00, R$ 5,571.00 and R$ 22,857.00. The first two—focused on the mullet stock—presented an increasing trend for the PCLI in the 25 years. The shrimp fyke PCLI, in contrast, had a decreasing trend (Figure 4.2, bottom).

In the open access scenario (OA), fishing gears started with the fishing effort of 2019 and fished for 25 years, increasing, or decreasing their fishing effort in 10% in every year that they had profit or loss, respectively. In this scenario, as expected, stock size for all species finished in a low level with 3.2 % of carrying capacity for the bottlenose dolphin, 11.2 % for the mullets and 0 % for the shrimps. Only the mullets had a period of stock increase, up to year (Figure 4.3, top). Fishing efforts increased 99.6 %, 257.5 % and 238.6 % of the initial fishing effort for the casting net, the gillnet and the shrimp fyke net, respectively (Figure 4.3, middle). The fishing effort dynamics led to an increase in the number of fishers from 4074 to 12809 fishers over the 25-year period, a variation of 214 % considering the whole fishing system (Figure 4.5, middle). The per capita labor income (PCLI) for the casting net, the gillnet and the shrimp fyke net at the end of 25 years was respectively R$ 3,481.70, R$ 1,008.50 and R$ 0.00. All gears presented a decreasing trend in this socioeconomic indicator (Figure 4.3, bottom).

In the optimal management scenario (OM), fishing gears started with optimal fishing effort—in this social planner game, optimal fishing effort is the one that maximize the sum of the net present value of all fishing gears—and fished for 25 years. In all the iterations, the optimal solution for the initial fishing effort for the casting net had reached the upper bound (see section 4.2.2.4) with 200 % of the 2019 fishing effort level. The optimal solution excluded the gillnets system in every simulation. For the shrimp fyke net, the optimal solution slighted variated in all iterations, maintaining an average of 91.7 % of 2019 fishing effort level. In this scenario, stock size for the dolphins, the mullets and the shrimp ended in 68.2 %, 77.2 % and 43.5 % of their carrying capacity, the best scenario considering the health of the natural system. Dolphins' stock size increased throughout the 25-year period. Both mullet and shrimp stock size stabilized at the end. The first with an increasing pattern and the last with a decreasing trend (Figure 4.4, top). The fishing effort of the casting net increased 6.9 % in 25 years in response to dolphins’ population growth (assumption A2). The gillnet and the shrimp fyke net fishing effort stay constant, as expected (Figure 4.4, middle). With this fishing effort dynamics, the system gained 60 fishers, from 3080 to 3140, totalizing a 1.9 % variation (Figure 5, right). The initial labor effort of the whole system in OM less than in BS by 994 fishers, a variation of 32.2 %. The per capita labor income (PCLI) for the casting net, the gillnet, and the shrimp fyke net at the end of 25 years was R$ 23,708.00, R$ 0.00 and R$ 25,505.00. The first with an increasing and the last with a decreasing trend of the PCLI (Figure 4.4, bottom).

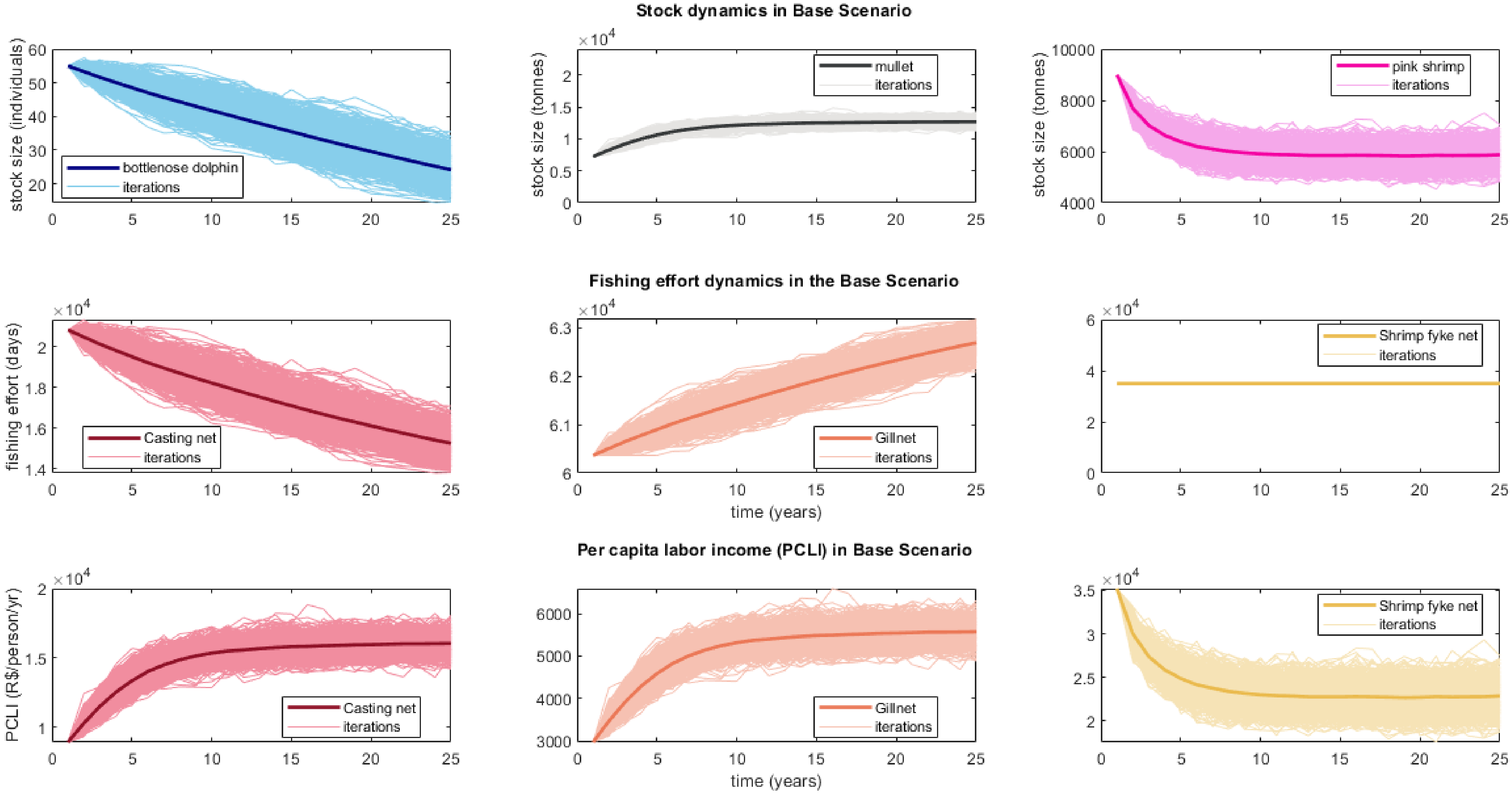

Figure 4.2. Stock, fishing effort and per capita labor income dynamics for the base scenario (BS). Dark colored lines represent mean values of 1000 iterations, light correspondent lines contain iteration data.

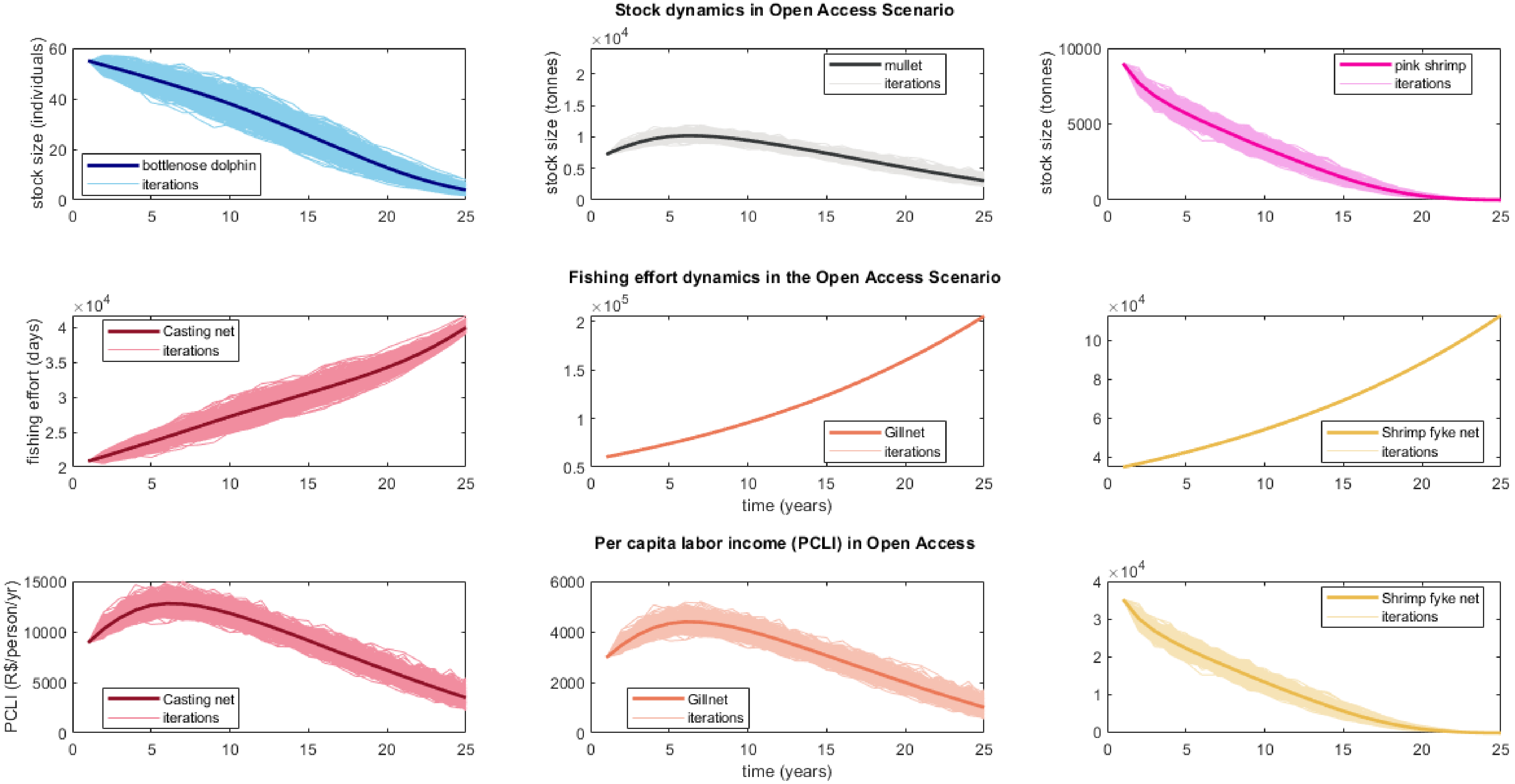

Figure 4.3. Stock, fishing effort and per capita labor income dynamics for the open access scenario (OA). Dark colored lines represent mean values of 1000 iterations, light correspondent lines contain data from all iterations. Scale vary frame to frame.

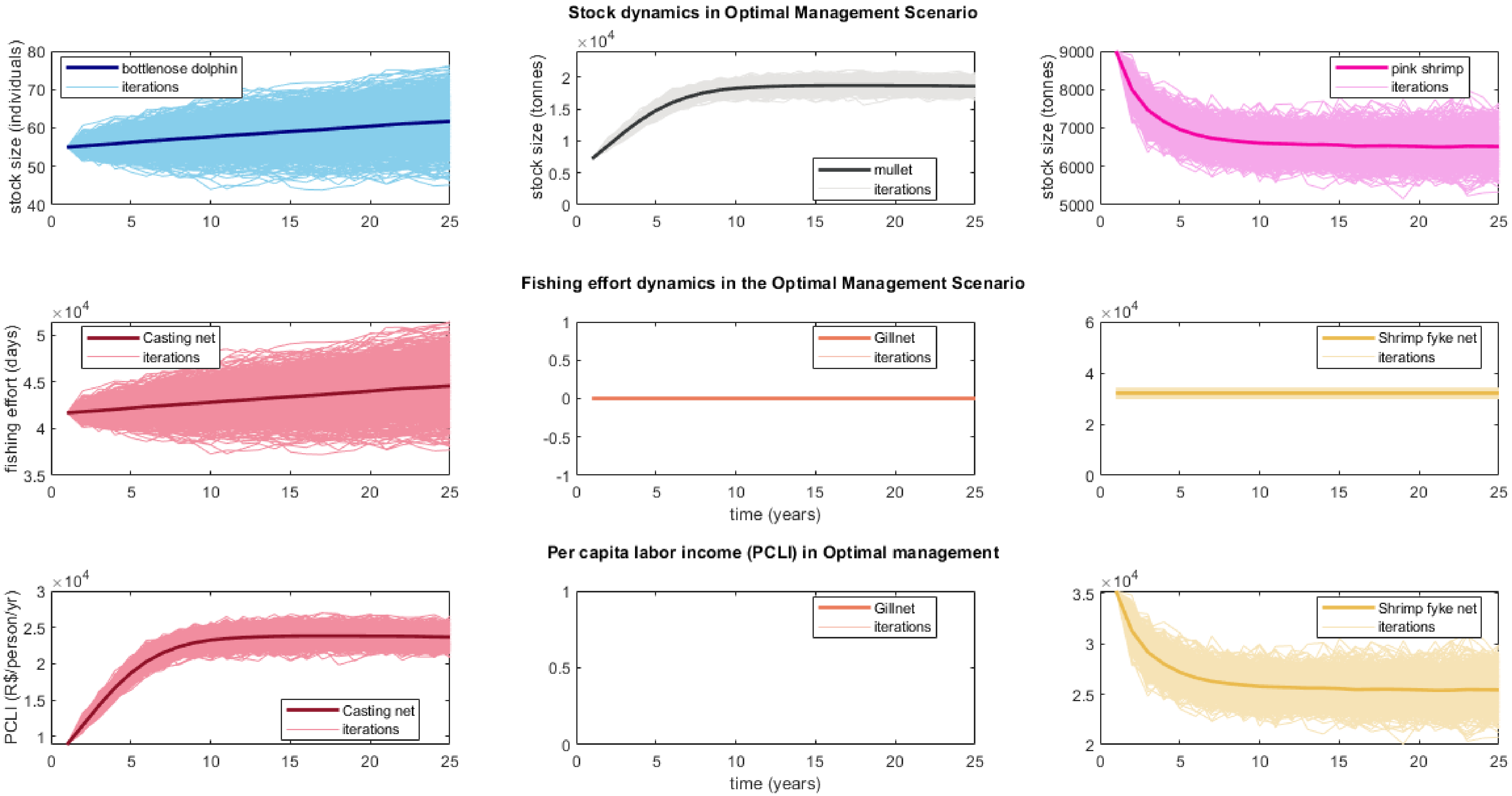

Figure 4.4. Stock, fishing effort and per capita labor income dynamics for the optimal management scenario (OM). Dark colored lines represent mean values of 1000 iterations, light correspondent lines contain data from all iterations. Scale vary frame to frame.

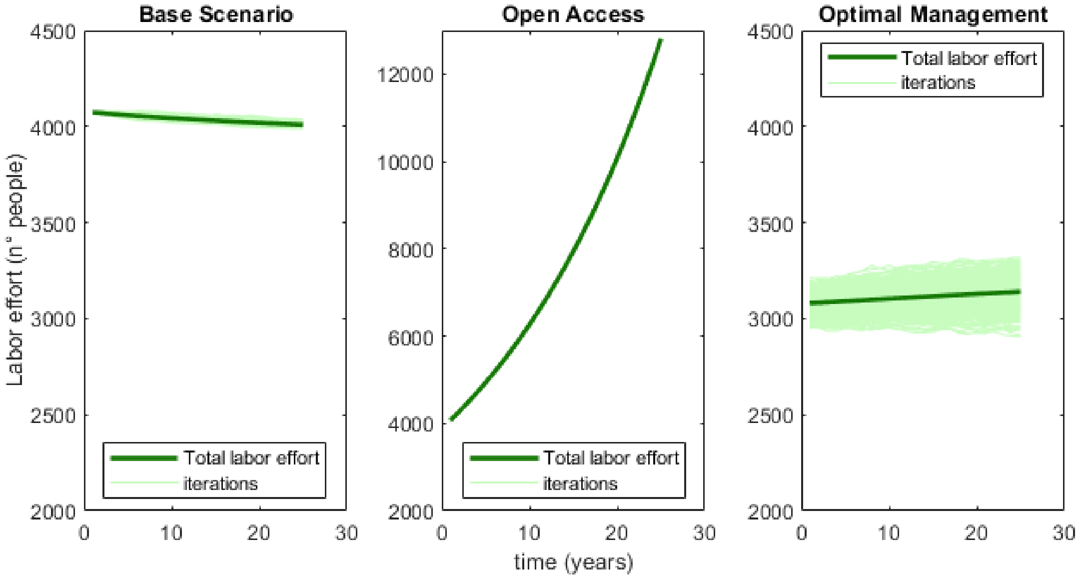

Figure 4.5. Total labor effort (LE) in each scenario.

The shrimp fyke net had the highest net present value (NPV), labor effort (LE), total labor income (TLI) and per capita labor income (PCLI) in all scenarios (Figure 4.6). The gillnet caught more mullet than the other gears in both base and open access scenarios. The gillnet fishing gear did not participate in the optimal management scenario. Except for absence of the gillnets on the OM, the hierarchic relation between gears' variables was maintained in all scenarios. Shrimp harvest by the casting net and the gillnet was not high enough to appear in the graph. The same occurred with the mullet bycatch from the shrimp fyke net. Casting net had its highest labor effort in the optimal management scenario, when the dolphins were not threatened by the gillnet bycatch, excluded from this scenario. Optimal management scenario—the best scenario considering the natural system conservation—had the high per capita labor income value (PCLI) for both the casting net and the shrimp fyke net gears but was null for the gillnet. Considering the three gears in each scenario, the average of PCLI for the whole system was R$ 10,925.90 in the base scenario, R$ 4,583.64 in the open access scenario and R$ 14,306.17 in the optimal management scenario. The total labor income (TLI) generated by all gears was 1,146.6 in the base scenario, 938.5 in the open access scenario and 1,158.8 million reais in the optimal management scenario. Numerical tables for each gear in each scenario Tables S1, S2 and S3 are in the supplementary electronic material.

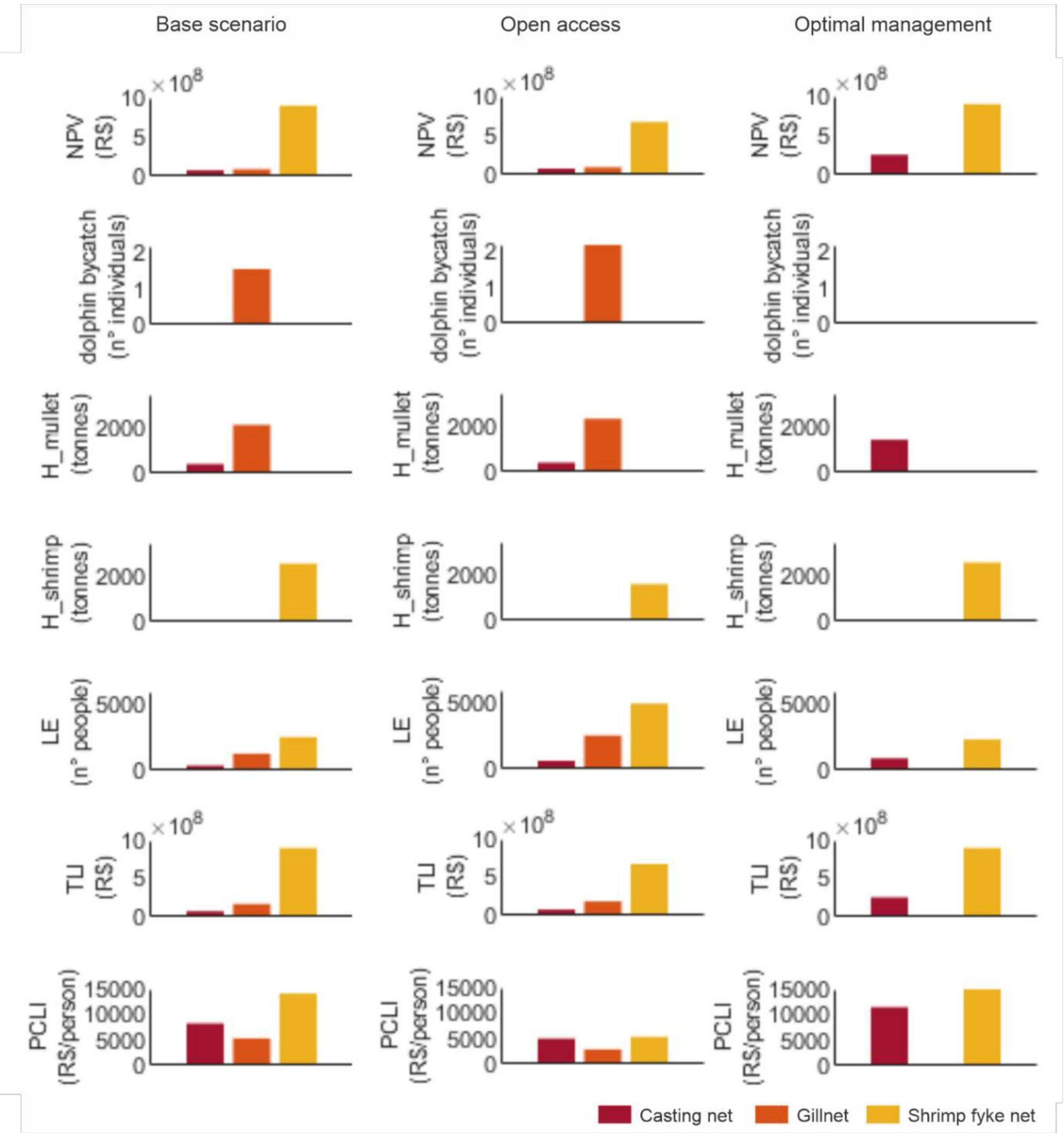

Figure 4.6. Mean values outputs for all scenarios. NPV – net present value in reais (R$), H – harvest in tonnes, LE – labor effort in number of people, TLI – total labor income in reais (R$), PCLI – per capita labor income in reais per person per year (R$/person).

4.4 DISCUSSION AND CONCLUSION

In this study we presented a multispecies and multigear bioeconomic model for a small-scale fishery system. We illustrate the model using a case study fishery with three fishing gears and a three species natural system in the Southern Lagoon Complex of Santa Catarina (LCSC), Southern Brazil. All fishing gears—casting net, gillnet, and shrimp fyke net—are small-scale fisheries conducted by fishing communities near by LCSC (see section 4.2.2.2). The species considered—bottlenose dolphin, lebranch mullet and the pink shrimp—interact with one another and some of them intervene directly in the fishing effort of the gears (see section 4.2.2.1). The general model—described in section 4.2.1—was adapted to include specific ecological behaviors of the system (see section 4.2.2.3).

The base scenario is an extrapolation of the actual reality. In this scenario our model captures behaviors and interactions—positive or negative—of the system that are important to consider in a management context. In our case study illustration, accidental bycatch of the bottlenose dolphins is leading this iconic species to extinction—in corroboration with Bezamat et al. (2021). With the decreasing of dolphins' population, casting net fishery loses fishing effort and trigger an increase of the gillnets fishing effort. The increasing on the gillnets impacts directly in the conservation of the natural system, because gillnets damage biodiversity — with dolphins' bycatch and higher catches of mullet — more than the casting net fishery (Silvano et al., 2017; Bezamat et al., 2021). Moreover, in the base scenario the shrimp population is severely harvested, due to the fishing effort and catchability of the fyke shrimp net gear. The optimal fishing effort for this gear was 91.88 % of 2019's fishing effort indicating that this gear will raise its NPV if operate with less fishing effort. However, in both cases those fishing efforts were not sufficient to provide healthy levels for the shrimp stock.

In the open access scenario, players adopt a "myopic behavior" and adjust their fishing effort every year only based on the profits of the previous year. In this classical setting, fishing efforts adjust until the resource rent is fully dissipated (Pintassilgo and Duarte, 2002; Diekert, 2012). Considering the mullet fishery, the gillnets will exit the fishery (in 45 years, out of our 25-year time horizon) and casting net will stay as the more economic efficient fishing gear—low cost and high catchability.

The increasing behavior of the fishing effort of the three fishing gears in open access scenario throughout the 25 years indicates that they all had profits overtime—even with low levels of the fishing stock at the final years. This occurs because all the gears presented low costs. In the open access scenario, players will not stop to raise their fishing effort unless they have economic losses. Thus, a rent dissipation in the future is a certainty for this game, by definition (Grønbæk et al., 2020).

The optimal fishing effort shows how the fishing effort from the players can be combined to produce the maximum NPV, considering all fishing gears together. If a social planner in our case study, with all three gears available would have to choose how much each fishing gear should fish to generate the highest NPV value to the system, the gillnet would stop fishing. The casting net, on the other hand, would raise its fishing effort until reaching its upper bound. As the shrimp catches of casting net and gillnet are insignificant, shrimp fyke net acts as a sole owner in this game, and its optimal effort is 91.7 % of 2019's fishing effort.

Our model shows the socioecological implications of this scenario. The optimal fishing effort reduced the initial total labor effort of the system by 23.3 % in comparison to 2019's initial total labor effort. This reduction is due to the reallocation of the fishery effort and to the exit of the gillnet, which can be related to the challenges that traditional fisheries have to carry on cultural assets from one generation to another due to economic issues (Armitage and Marschke, 2013; Schuhbauer et al., 2017; Chuenpagdee and Jentoft, 2019). On the other hand, the natural system and per capita labor income had their best outcome in this scenario. The tradeoff between social rent and health of the natural system is an important management issue and has to be properly and carefully accounted considering each system's peculiarities (Chuenpagdee and Jentoft, 2019; Willis and Bailey, 2020).

Our model showed that to achieve the optimal management scenario the system had to reduce around a quarter of total fishing effort. On the other hand, in comparison with the base scenario, the income generated for the labor effort is higher—total labor income (TLI) 14.7 million reais higher in optimal management. That is, reducing effort people will have a higher quality of life—with a higher per capita income. However, reducing effort can lead some people to leave the system. According to Jentoft and Eide (2011), a part of the solution on the poverty alleviation problem in small-scale fisheries is outside the fishing system. When social policy creates alternative livelihoods possibilities, for instance, those fishers unhappy with the activity, clamming that to fish is the only way to generate income, will naturally leave the fishery (Jentoft and Eide, 2011).

Shrimp fyke net is the player with highest NPV, total labor income, and per capita labor income in all three scenarios. As the casting net and gillnet fishing gears compete with one another for the mullet stock with insignificant shrimp harvests, shrimp fyke net has basically no competition in harvesting the shrimp. The pink shrimp is a high value fish resource and one of the main target species in shrimp fisheries at south and southern Brazil (Salvati et al., 2021). In LCSC, the shrimp fishery—attracting both professional fishers and occasional fishers looking for an alternative income—has issues in regulate the access to this fishery, lacks monitoring and consequently science-based management actions (Dantas, 2018).

Nieminen et al. (2012) compared status quo with optimal management scenario for the Baltic cod (*Gadus morhua callarias*), Baltic herring (*Clupea harengus membras*), and sprat (*Sprattus sprattus*) fishery in the Baltic Sea. Their bioeconomic model accounted for predator and prey interaction but it considered only one player, the social planner. As we did in our model, their optimal management scenario maximized the total NPV from harvesting all the species. Their results showed that the optimal scenario reduce pressure upon the fish stocks and increase global net present value (Nieminen et al., 2012). However, tradeoff between these benefits and social consequences was not addressed by the authors. In our work, as the economic and biologic benefits raised in optimal management scenario, fishing effort decreased and, consequently, labor effort decreased, implying a loss in the fisher's access to the system.

Other studies also analyzed multispecies fishery systems. Kasperski (2015, 2016) modeled a three-species fishery in the Bering Sea including the walleye pollock (*Gadus chalcogrammus*), the Pacific cod (*Gadus macrocephalus*), and Arrowtooth flounder (*Atheresthes stomias*) and their ecological interaction. The author used a two stage optimization to address the system. In the first stage vessels optimize how much fishing effort they will use for each fishing gear, in the second stage the social planner—aware of the first stage choice—determine the annual quota for each species by maximizing global net present value. Lai et al. (2021) studied the effect of a food web between herring (*Clupea harengus*), salmon (*Salmo salar*) and grey seals (*Halichoerus grypus*) on the salmon and herring fisheries in the Northern Baltic Sea. The results of those studies showed significant differences on the outcomes when including ecological interactions in the model, suggesting that multispecies management must account those interactions. In our work, results did not respond strongly to the ecological interaction between the bottlenose dolphin, the mullets, and the shrimps (predation). However, it responded to fishers' behavior upon stock dynamics (see assumptions A2 and A3 in section 4.2.2.3 and Figures 4.2-4.4). On the other hand, ecologic interaction dominates fishing gears interaction in the cooperative scenario of Salenius (2018) who modeled a three-species and three-countries fishery in the Northeast Atlantic pelagic complex.

While previous studies focused on large-scale fisheries, Ulrich et al. (2002) implemented a multigear and multispecies bioeconomic analyses for the English Channel artisanal fisheries. Their study, differently from ours, did not accounted for biologic interactions between the species, but focused on the fishing gears competition. However, similarly to our work, their model was considered by the authors as an important tool to compare different management scenario, with a weak predictive power considering the future of the fishery system (Ulrich et al., 2002).

This study has limitations. The LCSC system has more species and fishing gears that the ones considered in this study (Dantas, 2018). This paper considered only a small part of that system, leaving for future work an ampliation on the gears—such as the crab traps and the bottom longlines—and species—such as the whitemouth croaker, the catfish, the blue crab and the tilapia. Additionally, ungroup bottom gillnets from surface gillnets and shrimp casting nets from mullets casting nets can improve clarity and consistence of the results. The 25-year time horizon in open access scenario was not sufficiently long to understand the trends dynamics. In a longer horizon, shrimp fyke net would oscillate together with the shrimp stock size in a harvest/recovery dynamic. Abiotic characteristics of the system are clearly important on the systems dynamics. A broader model considering environment variables that directly affect species distribution such as salinity and temperature would be an interestingly future challenge.

Ecosystem-management for a small-scale system is challenging, especially when socioeconomic and catch information about the fishery is not available. As this study points out, a multispecies and multigear bioeconomic model sheds light in insightful mechanisms of a fishing system that should be considered in management discussions. In LCSC—our case study—the influence of multispecies and multigear interactions upon the tradeoff of social, biologic, and economic interests should be better investigated. However, monitoring actions should be conducted in the first place. With more data, better and more robust results could be generated, more species and gears could be included in analysis and consequently better subsidies to management decisions will be brought to discussion.

4.5 ACKNOWLEDGEMENTS

The authors would like to thank all contacted artisanal fishers for essential information provided. We also thank to Alexandre Marcel da Silva Machado, Pedro Volkmer de Castilho and Bruna de Jesus for small contributions of big importance. FGDJ thanks for a research grant received from the Conselho Nacional de Desenvolvimento Científico e Tecnológico (CNPq–308867/2019–0). PP acknowledges supported by the FCT Portuguese Foundation for Science and Technology under project UID/ECO/04007/2020.

4.6 AUTHORS CONTRIBUTIONS

F.G.D.J., E.Z.D.A, and P.P conceived the study; E.Z.D.A. and D.V.D organized data for the study. E.Z.D.A and F.G.D.J explored and analyzed the data; E.Z.D.A, P.P. and F.G.D.J. interpreted the data; E.Z.D.A wrote the original draft of the manuscript. All authors discussed the data, reviewed the manuscript, and gave final approval for publication.

4.7 DATA AVAILABILITY STATEMENT

Input data and parameters used in the model are available in the manuscript. We provide all the code and data to replicate our model and simulations in the open-access repository: https://github.com/ericztt/LCSC_model.

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4.9 ELECTRONIC SUPPLEMENTARY MATERIAL

Bioeconomic implications of a game-theoretic model in a multispecies small-scale fishery system

Eric Zettermann Dias De Azevedo, David Valença Dantas, Pedro Pintassilgo, Fábio Gonçalves Daura-Jorge.

4.9.1 Base Scenario outputs

Table S 4.1. Numerical results for the base scenario. Except for NPV and TLI which are accumulated through the 25-years period, all the values are means per year. Bottom row computes for each column sum, except for PCLI column which was calculated by dividing the TLI total by the product of the LE total by 25.

Gear	Fishing effort (days)	Bottlenose dolphin catch (individuals)	Mullet catch (tonnes)	Shrimp catch (tonnes)	NPV (mR$)	LE (people)	TLI (mR$)	PCLI (R$)
Casting net	18,310	0	410.4	0.1	75.6	366	75.6	8,253.10
Gillnet	64,176	1.6	2,168.6	0.04	88.9	1,283	170.2	5,304.90
Fyke net	36,400	0	1.2	2,597.0	900.6	2,548	900.6	14,138.00
	18,886	1.6	2,580.2	2,597.1	1,065.1	4,197	1,146.4	10,925.90

4.9.2 Open Access Scenario outputs

Table S 4.2. Numerical results for the open access scenario. Except for NPV and TLI which are accumulated through the 25-years period, all the values are means per year. Bottom row computes for each column sum, except for PCLI column which was calculated by dividing the TLI total by the product of the LE total by 25.

Gear	Fishing effort (days)	Bottlenose dolphin catch (individuals)	Mullet catch (tonnes)	Shrimp catch (tonnes)	NPV (mR$)	LE (people)	TLI (mR$)	PCLI (R$)
Casting net	31,165	0	414.9	0.07	78.1	623	78.1	5,015.30
Gillnet	127,930	2.3	2,376.3	0.02	94.5	2,558	186.0	2,908.20
Fyke net	71,559	0	1.4	1,620.4	674.4	5,009	674.4	5,385.50
	230,654	2.3	2,792,6	1,620.5	847.0	8,190	938.5	4,583.64

4.9.3 Optimal Management Scenario outputs

Table S4.3. Numerical results for the optimal management scenario. Except for NPV and TLI which are accumulated through the 25-years period, all the values are means per year. Bottom row computes for each column's sum, except for PCLI column which was calculated by dividing the TLI total by the product of the LE total by 25.

Gear	**Fishing effort (days)**	**Bottlenose dolphin catch (individuals)**	**Mullet catch (tonnes)**	**Shrimp catch (tonnes)**	**NPV (mR$)**	**LE (people)**	**TLI (mR$)**	**PCLI (R$)**
Casting net	44,999	0	1,465.7	0.3	258.6	900	258.6	11,496.00
Gillnet	0	0	0	0	0	0	0	0
Fyke net	33,338	0	1.7	2,621.8	902.5	2,337	902.5	15,450.00
	78,379	0	1,465.7	2,621.9	1,161.1	3,237	1,161.1	14,347.85

5 CONCLUSÃO

Esse trabalho aplica uma perspectiva da teoria dos jogos à gestão de sistemas socioecológicos associados às pescarias. Exploramos a relação entre fatores ecológicos, sociais e econômicos em diferentes cenários, e a repercussão dessas relações para o sistema pesqueiro correspondente. As ferramentas utilizadas nesse trabalho—os modelos bioeconômicos integrados à teoria dos jogos—se mostraram efetivos ao descrever os sistemas pesqueiros explorados por essa tese, em especial ao modelar e analisar diferentes cenários de manejo e deus respectivos desdobramentos.

No primeiro capítulo utilizei, em parceria com os coautores, um jogo evolutivo para explorar o comportamento de agentes pesqueiros em um sistema de pesca local diante de uma decisão de seguir ou não seguir uma recomendação de restrição de esforço de pesca. Na pesca do camarão com o aviãozinho, em Laguna/SC, a restrição foi imposta em relação ao número de redes que poderiam ser usadas—baseada nas discussões de gestão à época. Simulei alguns cenários variando a percepção em relação a fiscalização da pesca e a tolerância ao risco desses agentes. Em cada cenário, acompanhei a evolução do comportamento cooperativo—definido como seguir a restrição de esforço de pesca. O objetivo desse capítulo foi entender como a percepção da fiscalização e a tolerância ao risco das pessoas que pescam poderiam influenciar no comportamento cooperativo. Os resultados mostraram que, sem qualquer manipulação a estratégia cooperativa não teria incentivo de permanecer na população. Por outro lado, ao aumentar a percepção de fiscalização e a tolerância ao risco, a estratégia cooperativa pôde sobreviver e ainda dominar o sistema. Ou seja, para motivar um comportamento pró restrição de esforço de pesca, se faz necessário aumentar a presença fiscalizatória (percepção de fiscalização), mas também a informação do real estado do estoque, para que as decisões baseadas na tolerância ao risco não sejam influenciadas por observações empíricas de variações pontuais do estoque. A fim de dar subsídios para esses resultados mostrei alguns exemplos de como a percepção da fiscalização e a tolerância ao riscos daqueles que pescam foi aumentada: a gestão participativa do Pirarucu na Amazônia (Hrbek et al., 2007), os times de pesca em Yucatán, Mexico (Salas et al., 2019), as cotas transferíveis em pescarias Holandesas (Ginkel, 2005) e as reformas na regulamentação das pequenas ilhas do Pacífico (Aqorau, 2000).

No segundo capítulo utilizei, juntamente com os coautores, um jogo não-cooperativo para simular cenários de manejo e analisar as respectivas consequências para o sistema socioecológico associado. Nesse capítulo, as partes que jogaram entre si não eram indivíduos como no capítulo inicial, mas petrechos ou frotas inteiras. O sistema explorado foi a pesca da tainha no Sul-Sudeste do Brasil. Cada um dos quatro petrechos—o cerco industrial, o emalhe de superfície artesanal, o cerco de praia artesanal e o emalhe anilhado artesanal—foram considerados como jogadores que, em cada cenário, buscariam tomar as melhores decisões. Os cenários explorados foram: (1) o cenário base—jogadores usaram o esforço de pesca de 2019, de forma constante, durante 25 anos; (2) o cenário não-cooperativo—jogadores escolheram um esforço de pesca para usar durante 25 anos, buscando maximizar seu lucro individual e considerando as escolhas dos demais jogadores e (3) o cenário não-cooperativo limitado—jogadores escolheram um esforço de pesca para usar durante 25 anos, buscando maximizar seu lucro individual e considerando as escolhas dos demais jogadores com um limite superior de 45% do esforço de pesca usado em 2019 para o cerco industrial e para o emalhe anilhado artesanal—as frotas oficialmente monitoradas. O objetivo desse capítulo foi analisar as implicações sociais e biológicas dos diferentes cenários bioeconômicos considerando a coexistência da pesca de pequena escala—emalhe de superfície artesanal, cerco de praia artesanal e emalhe anilhado artesanal—com a de grande escala—cerco industrial. Os resultados mostraram que limitar o esforço de pesca pôde trazer melhores benefícios para o sistema como um todo—para o estoque, para a renda *per capita* das pessoas que trabalham e para a preservação da continuidade de todos os petrechos. Por outro lado, em um contexto não-cooperativo voltado para a maximização do lucro individual, os resultados mostraram forte pressão para que os petrechos mais tradicionais—o emalhe de superfície e o cerco de praia—diminuíssem o esforço ou deixassem a pesca, gerando perdas para o sistema como um todo tanto em termos de saúde do estoque como em rendimentos *per capita*. Os resultados mostrados nesse capítulo evidenciaram a importância de se ler o sistema socioecológico como um todo para se pensar medidas que e minimizam perdas sociais, ambientais e econômicas.

No último capítulo explorei, com a colaboração dos coautores, um sistema multiespecífico com petrechos distintos, prestando atenção nas interações entre as espécies, entre os petrechos e entre petrechos e espécies. Ampliei novamente o modelo incluindo a complexidade das múltiplas espécies, juntamente com as interações entre elas. Em ambos os capítulos anteriores o recurso explorado consistia em apenas uma única espécie. No complexo lagunar sul de Santa Catarina explorei um recorte da pesca artesanal local: as tainhas e os camarões sendo explorados pelas tarrafas, redes de emalhes e aviãozinho. Também acrescentei o boto-da-tainha, tanto por ser predador de topo como por ser alvo de capturas acidentais por redes de emalhe. O objetivo desse capítulo foi investigar a aplicabilidade do modelo bioeconômico aliado à teoria dos jogos para analisar mecanismos sociais e ecológicos em um sistema pesqueiro multiespecífico. Os resultados mostraram que, em cada cenário estudado, a abordagem proposta—envolvendo os modelos bioeconômicos com a teoria dos jogos—levantou consequências socioeconômicas e ecológicas relevantes para a gestão da pescaria. No cenário base a captura acidental dos botos pelas redes de emalhe se mostrou diretamente relacionada ao declínio dessa espécie nesse cenário. No cenário de acesso livre, o modelo mostrou que as pescas da tainha e do camarão não tem relação direta e que em se tratando da tainha, as tarrafas são economicamente mais eficientes—baixo custo e maior capturabilidade. No cenário de manejo ótimo, o modelo mostrou que mesmo com uma redução do esforço, além de se manter os estoques mais saudáveis—em comparação aos outros cenários—, é possível gerar uma maior renda *per capita*.

5.1 ANÁLISE COMPARATIVA

Observando a tese como um todo (ver tabela 5.1), podemos identificar diferentes estratégias de manejo que podem contribuir para a sustentabilidade de um sistema pesqueiro. A restrição do esforço de pesca de maneira inteligente, considerando a dinâmica do sistema, pode trazer (a) benefícios ecológicos, melhorando o estado do estoque e consequentemente a disponibilidade de recurso; (b) benefícios sociais, aliviando a pressão econômica sobre os petrechos tradicionais que possuem grande valor cultural e baixo impacto ambiental; e (c) benefícios econômicos, melhorando a renda *per capita* para as pessoas do sistema (conclusão dos capítulos 2 e 3).

Após estabelecida a restrição de esforço de pesca, algumas medidas podem ajudar na hora de garantir a cooperação das pessoas envolvidas. O aumento da percepção de fiscalização, seja através da presença efetiva da fiscalização ou através de medidas alternativas como o envolvimento das comunidades na fiscalização ou como a transparência na discussão e na implementação das restrições, pode aumentar a colaboração das pessoas em seguir uma restrição de manejo (conclusão do capítulo 1).

O mesmo para o aumento da tolerância ao risco, que através de monitoramentos (participativos ou não) com transparência ou através do incentivo à colaboração entre as pessoas da pesca (cooperativas, revezamentos, times de pesca), pode diminuir a tentação das delas de trapacear em uma restrição de esforço buscando segurança contra a sensação de incerteza do estoque (conclusão do capítulo 1).

Os modelos bioeconômicos aliados à teoria dos jogos aplicados nos capítulos dessa tese levantaram importantes questões em relação ao comportamento dos agentes nos cenários de conflito em cada pescaria e as consequências bioeconômicas desses comportamentos para o sistema (ver conclusões na tabela 5.1). Destaca-se, portanto, as contribuições dessa metodologia para a gestão pesqueira gerando diferentes cenários e analisando as consequências ecológicas, sociais e econômicas de cada um deles.

Como hipótese geral essa tese buscou testar se os modelos bioeconômicos aliados à teoria dos jogos—considerando as interações entre os fatores ecológicos, sociais e econômicos inseridos no sistema socioecológico de uma pescaria—poderiam orientar soluções sustentáveis de manejo para o sistema. Tendo em vista que em cada capítulo os modelos apresentados produziram cenários de manejo com benefícios bioeconômicos—a partir da discussão de fatores ecológicos, sociais e econômicos—, consideramos que a hipótese foi corroborada.

De modo geral concluímos que independente da complexidade do sistema pesqueiro—seja uma pesca isolada de um único recurso, uma pescaria de uma única espécie-alvo com vários petrechos ou um conjunto de petrechos distintos explorando espécies variadas—a relação entre as pessoas e os recursos envolve dimensões ecológicas, sociais e econômicas diretamente ligadas entre si e que interferem diretamente no comportamento dessas pessoas dentro do sistema. Uma proposta de gestão deve, na medida do possível e do praticável, entender a pescaria em toda a sua dimensão socioecológica para que melhor se adeque a real necessidade daquele sistema. Para tal, as pessoas envolvidas no sistema, as diferentes realidades percebidas por diversas áreas de conhecimento e o apoio das entidades governamentais devem ser levados em consideração. Definir uma proposta de manejo não é uma tarefa fácil e talvez a alternativa perfeita—que beneficie todos sem prejuízos para ninguém—não esteja disponível. Por outro lado, os sistemas pesqueiros precisam de atenção das pessoas que gerem e das que participam dele para mitigar seus problemas, por mais diversos, complexos e dinâmicos que sejam. Para tanto, ter uma proposta que consiga minimamente considerar a pescaria como um sistema sociológico interagindo com um sistema que governa, pode ser uma opção razoável.

Tabela 5.1 Análise comparativa dos capítulos da tese.

	Sistema pesqueiro	Jogadores	Espécies	Principal questão	Conclusões
Cap. 1	pesca do camarão com o aviãozinho em Laguna/SC	1. pessoas que pescam com o aviãozinho	camarão *farfantepenaeus paulensis* *farfantepenaeus brasiliensis*	influência da percepção da fiscalização e da tolerância ao risco no comportamento cooperativo em relação a uma restrição de esforço de pesca.	o cenário com alta percepção de fiscalização e alta tolerância ao risco facilitou a invasão e a dominação do comportamento cooperativo.
Cap. 2	pesca da tainha no Sudeste/Sul do Brasil	1. cerco industrial 2. emalhe de superfície artesanal 3. cerco de praia artesanal 4. emalhe anilhado artesanal	tainha *mugil liza*	benefícios bioeconômicos de um jogo não-cooperativo com e sem restrição de esforço de pesca.	o cenário não-cooperativo sem restrições excluiu o petrecho mais tradicional (cerco de praia artesanal) do sistema. o cenário não cooperativo com restrição obteve o melhor estado do estoque, todas as artes no sistema e maior renda *per capita*.
Cap. 3	Pesca artesanal no complexo estuarino de Laguna/SC	1. tarrafas de mão 2. redes de emalhe 3. aviãozinho	boto-da-tainha *Tursiops truncatus gephyreus* camarão *farfantepenaeus paulensis* *farfantepenaeus brasiliensis* tainha *mugil liza*	análise bioeconômica em um sistema de pesca multipetrecho e multiespecífico com interações ecológicas, tecnológicas e comportamentais.	o cenário de manejo ótimo apresenta redução no esforço sistema, melhora na condição dos estoques e aumento da renda *per capita*.

5.2 REFERÊNCIAS

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