博士論文

Adaptive management in population ecology: Cases of COVID-19 and Japanese sardine (*Sardinops melanostictus*)

個体群生態学における順応的管理：COVID-19 とマイワシ（*Sardinops melanostictus*）を例として

横浜国立大学大学院
環境情報学府

渡邉聡
Akira Watanabe

2023 年 3 月

Contents

Abstract **1**

I　順応的管理の概要 **6**

II　フィードバック制御の有効性と **COVID-19** の感染死者数と対策費用のトレードオフ
Effectiveness of feedback control and the trade-off between death by COVID-19 and costs of countermeasures **13**

1　Introduction　15

2　Methods　17

2.1　Model 17

2.2　Feedback control of behavioral restrictions 21

2.3　Calculation of indicators 23

2.4　Management parameter 24

2.5　Simulation 25

3　Results　26

4　Discussion　28

Appendix A. Derivation of basic reproduction number $\Re_0$ 31

Appendix B. Algorithm for the feedback control 33

Supplementary materials 53

III 出口管理と漁獲圧制限の組み合わせによるマイワシ（***Sardinops melanostictus***）の漁獲管理の改善

Combining output control and fishing pressure limitations improves the management of the Japanese sardine *Sardinops melanostictus* **59**

1　Introduction　61

2　Methods　62

2.1　Prerequisite 62

2.2　Simulation 63

2.2.1　General approach 63

2.2.2　Population dynamics 63

2.2.3　Current HCR 64

2.2.4　New HCR 65

2.2.5 Stock assessment 66
2.3 Study design 67
2.3.1 Stock Recruitment Relationship scenarios 67
2.3.2 Design 68
2.3.3 Indicators 69
3 Results 69
4 Discussion 71
5 Conclusions 73
Appendix A 74
Appendix B 74
Appendix C 75
Supplementary materials 90
IV 新型コロナウイルス SARS-CoV-2 対策への総合的評価 98
1 Introduction 99
2 Review of countermeasures against SARS-CoV-2 99
2.1 Public health 99
2.2 Economics 101
3 Discussion 102
V 日本国の水産業及び水産資源管理の評価と展望 116
1 Introduction 117
2 Review of the Japanese fisheries policy 117
2.1 水産基本計画 117
2.2 水産関係予算 118
2.3 水産経済 119
2.3.1 生産性 119
2.3.2 輸出入 120
2.4 日本の主要魚種 121
3 Review of scientific literature 123
3.1 Maximum Sustainable Yield 123
3.2 Ecosystem Based Fishery Management 124

3.3 気候及び環境変動 125

4 Discussion 127

4.1 日本国の水産業と水産資源管理 127

4.2 展望 128

VI 新興感染症における意思決定のための戦略作成方法の提案 150

1 Introduction 150

2 MSE approach 151

2.1 Identify management objectives 152

2.2 Identify critical sources of uncertainty 152

2.3 Construct operating model(s) 152

2.4 Select operating model parameters 154

2.5 Identify management strategies to implement 155

2.6 Simulate application of management strategies 155

2.7 Summarize and interpret outcomes, refining process 155

3 Discussion 155

VII 総合的考察 166

Acknowledgements 170

Abstract

（日本語）

順応的管理はフィードバック制御と順応的学習で構成され、不確実性を持つ系を管理する際の一手段である。不確実性を持ち多くの人々に影響する社会課題に対し、順応的管理を用いて妥当な意思決定と戦略作りを目指すことを本論文の目的とする。とりわけ 2019 年末より感染が拡大した新型コロナウイルス SARS-CoV-2 への感染症制御と、資源量変動が大きくかつ重要な小型浮魚資源であるマイワシ太平洋系群（*Sardinops melanostictus*）の漁獲管理を順応的管理の適用例として取り上げた。感染症対策と水産資源管理に共通するのは、真の感染者又は資源量が正確に推定できず、管理行動が必ずしも狙い通りの効果を示さず、さらに個体群動態の機構が不明確で環境変動の影響を受ける場合もあることである。水産資源管理の分野では従来から順応的管理が適用されるが、人々の間の感染症の流行も同じような不確実性の要素を含んでおり、感染防止策として実行される医学的もしくは非医学的介入も順応的管理の実装と捉えることが可能である。第 1 章では順応的管理の概要を説明する。以後第 2 章と第 3 章で具体的な問題の提示及び新たな感染症制御則や漁獲管理規則の提案検討を行い、第 4 章と第 5 章で実際の結果から評価の枠組みや基準を考察する。第 6 章では個体群管理の視点から将来の新興感染症対策への戦略作りや意思決定に資する枠組みを提案する。第 7 章で順応的管理の総合的考察を述べて結びとする。

第 2 章では新型コロナウイルスによる新興感染症（COVID -19）への感染症制御案を提示する。COVID-19 の流行対策に対しては、ワクチンや治療薬のない状況での非医学的介入を検討した。戦略の評価指標には感染死者数だけでなく自宅等隔離者数、入院者数、検査数、社会経済的な費用を用意してトレードオフを考察した。多段階の行動抑制政策の長所と短所を探求し、ウイルスへの曝露者もしくは感染者の検出率、及び感染しても発症せずに回復する無症候性感染者の割合が不確実な場合でも提案した感染症制御案が有効であることを示した点が新規性として挙げられる。

第 3 章ではマイワシの太平洋系群を用いて漁獲管理規則の例を示す。マイワシ太平洋系群の漁獲管理においては、現在実施されている出口管理と入口管理を組み合わせた漁獲管理規則を新しく提案した。生物学的許容漁獲量の算定から実施までの二年間の時間遅れ、及び資源量指数の観測誤差や漁獲圧の実行誤差をシミュレーション上で再現し、提案した規則の有効性を示したことが特徴である。評価指標には、最近十年間の平均資源量と平均漁獲量、管理期間の平均年変動を使用した。

第 4 章では公開データを用いて 2021 年末までにおける COVID-19 対策を公衆衛生と社会経済の総合的な視点から検討する。2019 年末に感染事例が確認され、2020 年以降は世界中に感染

が拡大した新型コロナウイルスに対し、日本国は社会保障関係費とは別に 2020 年度と 2021 年度を合わせて約 100 兆円を対策のために計上した。しかし、新型コロナウイルスの対策が行われている期間にその他の疾病による死者の増減も報告されている。また、日本以外の G7 諸国やオーストラリアや韓国と比べた経済状況も考察に交えて、次の新興感染症発生時に必要な準備について言及した。

第 5 章では日本国における水産関係予算や水産基本計画の見直し、及び今後重要となる水産資源管理のテーマを 3 つ挙げて先行研究をまとめることから新たな提言をする。得られた結論としては、過去に発表した水産基本計画の評価検証を定期的に行うこと、TAC のような出口管理の適切な運用のために、予算から漁獲活動の監視費用の割り当てを増やし効果的な監視体制を整備すること、日本人の消費及び日本の貿易上重要と思われる魚種の資源管理を見直し、必要があれば改善すること、一人一日当たりの漁労利益のような経済指標も導入し、水産基本計画に数値目標として設定することを挙げた。

第 6 章では公衆衛生と水産資源管理分野における順応的管理と戦略設計についての提案を行う。公衆衛生には Evidence based public health という科学的根拠を重視する意思決定の枠組みがあり、水産資源管理には Management Strategy Evaluation (MSE) という不確実性の存在を前提にした戦略作りの枠組みがある。これらの枠組みの特徴を考慮し、計算機上のシミュレーションを行った。不確実性のある問題への戦略作りに用いられる MSE は感染症の流行にも適用可能であることを示す。

公衆衛生と水産資源管理は、政策決定や意思決定で異なる姿勢や方針があるものの、公共政策として共に重大な分野である。個体群の管理という大きな枠組みで見たとき、二つの分野で共通して重要なことは、不確実性の高い問題に対しても数理モデルはある程度有力であること、新しい知見を得たときに順応できる意思決定の仕組みがあること、そしてウイルスの感染者数や水産資源量の動向を監視する体制が存在することである。

(English)

Adaptive management consists of feedback control and adaptive learning, and is a means of managing systems with uncertainty. The purpose of this paper is to use adaptive management to make valid decisions and strategies for social issues that have uncertainty and affect many people. In particular, the control of infectious disease caused by the novel coronavirus SARS-CoV-2, which has spread since the end of 2019, and the fishery management of the Pacific stock of Japanese sardine (*Sardinops melanostictus*), an important small pelagic fish stock with large fluctuations in abundance, are taken up as examples of the application of adaptive management. Common to both infectious disease control and fisheries resource management is that the true number of infectious cases or stock abundance cannot be accurately estimated, management actions do not always have the desired effect, and the mechanism of population dynamics may be unclear and affected by environmental changes. While adaptive management has traditionally been applied in the field of the fishery management, the prevalence of infectious diseases among people involves a similar element of uncertainty, and medical or non-pharmaceutical interventions implemented as infection control measures can also be viewed as an implementation of adaptive management. Chapter 1 provides an overview of adaptive management. Subsequently, Chapters 2 and 3 present specific issues and discuss proposals for infectious disease control and harvest control rules, and Chapters 4 and 5 present the actual results of the evaluation. Chapters 4 and 5 discuss the evaluation framework and criteria based on actual results and historical data. Chapter 6 proposes a framework for developing strategies and decision making against emerging infectious diseases in the future from a population management perspective. Chapter 7 concludes this study with a synthesis of adaptive management.

In Chapter 2, an infection control rule against COVID -19, an emerging infectious disease caused by the novel coronavirus, is proposed. Non-pharmaceutical interventions in the absence of a vaccine or specific medicine were considered for the control of the COVID-19. Trade-offs were considered by providing not only the number of infected deaths but also the number of home and other isolation cases, the number of hospitalizations, the number of tests, and socio-economic costs as indicators for evaluating the control rule. The advantages and disadvantages of a multilevel behavioral control policy were explored. The novelty is that this research showed that the proposed infection control rule is effective even when the detection rate of those exposed or infected with the virus and the proportion of asymptomatically infected persons who are infected but recover without developing the disease are uncertain.

Chapter 3 presents a harvest control rule using the Pacific stock of Japanese sardine. For the Pacific stock of Japanese sardine, a new harvest control rule that combines current output and input controls is proposed. The effectiveness of the proposed rule was demonstrated by simulating the two-year time delay between the calculation of the allowable biological catch and its implementation, as well as by reproducing errors in the observation of abundance indices and the implementation of fishing pressure. Average stock abundance and average catch over the most recent decade and average annual variavility over the management period were used as evaluation indices.

Chapter 4 examines the COVID-19 measures to date using publicly available data from a comprehensive public health and socio-economic perspective. In response to the novel coronavirus, for which cases of infection were confirmed at the end of 2019 and which spread worldwide from 2020 onward, the Japanese government allocated approximately 100 trillion yen to the countermeasures in 2020 and 2021 (fiscal year), apart from social welfare expenditures. However, during the period when measures against the novel coronavirus are being taken, an increase or decrease in deaths due to other diseases has also been reported. The necessary preparations for the next outbreak of emerging infectious diseases are proposed, including consideration of the economic situation compared to G7 countries other than Japan, as well as Australia and South Korea.

In Chapter 5, new recommendations are made based on a review of the fisheries-related budget and the basic plan for fisheries in Japan, as well as a summary of previous studies on three themes of fisheries resource management that have been important. The conclusions obtained include: (1) the evaluation and verification of the fisheries basic plan announced in the past should be conducted on a regular basis; (2) an effective monitoring system should be established by increasing the allocation of monitoring costs for fishing activities from the budget for the appropriate operation of exit management such as TAC; (3) resource management of fish species considered important for Japanese consumption and trade in Japan should be reviewed and improved if necessary; (4) the management of fish species considered important for consumption by Japanese people and for Japan's trade should be The management of fish stocks considered important for Japanese consumption and Japanese trade should be reviewed and improved if necessary; and (5) economic indicators such as fishing profit per person per day should be introduced and set as key performance indicators in the basic plan for fisheries if necessary.

In Chapter 6, we propose adaptive management and strategy design in the areas of public health and fisheries resource management. In public health, there is evidence based public health, a decision-making framework that emphasizes scientific evidence, and in fisheries resource management, Management Strategy Evaluation (MSE), a strategy-making framework that assumes the existence of uncertainty. Considering the characteristics of these frameworks, we conducted a computer simulation. We show that MSE, which is used for strategy making for uncertain problems, can be applied to infectious disease epidemics.

Public health and fisheries resource management are both critical areas of public policy, although they have different stances and policies in policy making and decision making. When viewed within the larger framework of population management, what is important in common between the two fields is that mathematical models are somewhat powerful in dealing with highly uncertain issues, that there are decision-making mechanisms that can adapt to new knowledge as it becomes available, and that there is a system for monitoring trends in the number of people infected with the virus and in the amount of fish stocks.

Chapter I

順応的管理の概要

個体群生態学の公共政策への応用例の一つとして、個体群の管理がある。個体群の管理には本質的に不確実性が伴うことが言及されており [2, 4, 8, 12, 13]、具体的には少なくとも四種類の不確実性、つまり環境変動、不十分な観測可能性、不十分な制御可能性、構造もしくは過程の不確実性がある [4, 12]。本論文では公衆衛生における感染症対策と水産資源管理について Table 1 のような共通点と相違点を見出し、それぞれを個体群の管理として捉えた。これらの課題に共通するのは、個体群動態が環境変動のような外部からの影響のみで駆動するのではなく、人間の制御や管理行動も完全とは言えないまでも影響力を持つことである。

順応的管理 (Adaptive management) はフィードバック制御と順応的学習で構成され、不確実性を持つ系を管理する際の一手段である [7, 9]。その利点は、不確実性を無視したり、管理行動を排除するために使用したりするのではなく、不確実な未来に対処するための回復力と柔軟性を育み、避けられない変化や想定されていなかった出来事を認識する管理手段を開発することができる点である。順応的管理の手順は先行研究によって細かい差異はあるが、本質は、問題の定義、目的の特定、管理計画の作成、管理計画の実装、影響の監視、結果の評価、調整及び改善の過程を反復することにある [2, 5, 13]。順応的管理は、それによって問題への学習を深め、変化や不確実性に適応する実践的な手法である。Scenario planning のような不確実性を持つ系を管理する別の手段も存在するが、部分的な制御可能性を持つ不確実性のある個体群の中では順応的管理がより有効な手段となる [1, 10]。

本論文では、順応的管理の視点から新型コロナウイルス SARS-CoV-2 における COVID-19 の感染対策とマイワシ (*Sardinops melanostictus*) を例とした水産資源管理の問題に取り組む。論文の構成を Figure 1 に示す。順応的管理の手順に基づき、「目的の特定」を行うと、前者については、2019 年 12 月から感染拡大が始まった新型コロナウイルスに対し、感染死者数の抑制、医療資源の確保、経済活動の維持が目的である。また、後者については、小型浮魚類の代表種であるマイワシの太平洋系群を取り上げ、一定水準以上の資源維持、中長期的な漁獲量最大化、漁獲量変動の最小化を目的としてより良い水産資源管理を検討する。

第 2 章と第 3 章は順応的管理における「管理計画の作成」と「管理計画の実装」に相当する。第 2 章は Watanabe and Matsuda [14] を再掲し、目的達成のための感染症制御則を提案し検証を行った。ワクチンや治療薬のような医学的な介入がなく、行動抑制や検出率が不確実な RT-PCR 検査のような介入で感染死者数拡大抑止と社会経済的費用の削減を目指した。第 3 章ではマイワシの太平洋系群を用いて漁獲管理規則の例を示す。生物学的許容漁獲量の算定から実行までの時間遅れ、資源量指数の観測誤差、管理行動の実行誤差をシミュレーション上で再現し、提案した規則の有効性を示したことが特徴である。評価指標には、最近十年間の平均資源量と平均漁獲

量、管理期間の平均年変動を使用した。

第 4 章と第 5 章は順応的管理における「影響の監視」、「結果の評価」、「調整と改善」に相当する。第 4 章では公開データを用いて 2021 年末までにおける COVID-19 対策を公衆衛生と社会経済の総合的な視点から検討する。2019 年末に感染事例が確認され、2020 年以降は世界中に感染が拡大した新型コロナウイルスに対し、日本国は社会保障関係費とは別に 2020 年度と 2021 年度を合わせて約 100 兆円を対策のために計上した。しかし、新型コロナウイルスの対策が行われている期間にその他の疾病による死者の増減も報告されている。また、日本以外の G7 諸国やオーストラリアや韓国と比べた経済状況も考察に交えて、次の新興感染症発生時に必要な準備について言及した。第 5 章では日本国における水産関係予算や水産基本計画の見直しを行い、それに加えて今後重要となる水産資源管理のテーマを 3 つ挙げて先行研究をまとめることから新たな提言をする。得られた結論としては、過去に発表した水産基本計画の評価検証を定期的に行うこと、TAC のような出口管理の適切な運用のために、予算から漁獲活動の監視費用の割り当てを増やし効果的な監視体制を整備すること、日本人の消費及び日本の貿易上重要と思われる魚種の資源管理を見直し、必要があれば改善すること、一人一日当たりの漁労利益のような経済指標も導入し、水産基本計画に数値目標として設定することを挙げた。

第 6 章では公衆衛生と水産資源管理分野における順応的管理と戦略設計についての提案を行う。公衆衛生には Evidence based public health という科学的根拠を重視する意思決定の枠組み [3] があり、水産資源管理には Management Strategy Evaluation (MSE) という不確実性の存在を前提にした戦略作りの枠組み [6, 11] がある。これらの枠組みの特徴を考慮し、計算機上のシミュレーションを行った。不確実性のある問題への戦略作りに用いられる MSE は、流行する感染症対策にも有効であるかを検討した。

第 7 章で順応的管理の総合的考察を述べて結びとする。

References

[1] Allen, C.R., Gunderson, L.H., 2011. Pathology and failure in the design and implementation of adaptive management. Journal of Environmental Management 92, 1379-1384.

.

[2] Allen, C.R., Fontaine, J.J., Pope, K.L., Garmestani, A.S., 2011. Adaptive management for a turbulent future. Journal of Environmental Management 92, 1339-1345.

.

[3] Brownson, R.C., Fielding, J.E., Maylahn, C.M., 2009. Evidence-Based Public Health: A Fundamental Concept for Public Health Practice. Annual Review of Public Health, 175-201.

.

[4] Conroy, M.J., Runge, M.C., Nichols, J.D., Stodola, K.W., Cooper, R.J., 2011. Conservation in the face of climate change: The roles of alternative models, monitoring, and adaptation in confronting and reducing uncertainty. Biological Conservation 144, 1204-1213.

.

[5] Gillson, L., Biggs, H., Smit, I.P., Virah-Sawmy, M., Rogers, K., 2019. Finding common ground between adaptive management and evidence-based approaches to biodiversity conservation. Trends in Ecology & Evolution 34, 31-44. .

[6] Goethel, D.R., Lucey, S.M., Berger, A.M., Gaichas, S.K., Karp, M.A., Lynch, P.D., Walter, J.F., Deroba, J.J., Miller, S., Wilberg, M.J., 2019. Closing the feedback loop: on stakeholder participation in management strategy evaluation. Canadian Journal of Fisheries and Aquatic Sciences , 1895-1913. .

[7] Katsukawa, T., 2007. Studies on the adaptive management of fisheries resources. Nippon Suisan Gakkaishi 73(4), 656-659. .

[8] Loehle, C., 2006. Control theory and the management of ecosystems. Journal of Applied Ecology 43, 957-966. .

[9] Matsuda, H., Abrams, P.A., 2004. Effects of predator-prey interactions and adaptive change on sustainable yield. Canadian Journal of Fisheries and Aquatic Sciences 61, 175-184.

.

[10] Peterson, G.D., Cumming, G.S., Carpenter, S.R., 2003. Scenario Planning: a Tool for Conservation in an Uncertain World. Conservation Biology 17, 358-366.

.

[11] Punt, A.E., Butterworth, D.S., de Moor, C.L., De Oliveira, J.A.A., Haddon, M., 2016. Management strategy evaluation: best practices. Fish and Fisheries 17, 303-334.

.

[12] Williams, B.K., Eaton, M.J., Breininger, D.R., 2011. Adaptive resource management and the value of information. Ecological Modelling 222, 3429-3436.

.

[13] Williams, B.K., Brown, E.D., 2016. Technical challenges in the application of adaptive management. Biological Conservation 195, 255-263.

.

[14] Watanabe, A. Matsuda, H., 2022. Effectiveness of feedback control and the trade-off between death by COVID-19 and costs of countermeasures. Health Care Management Science

.

Table 1: 個体群の管理としてみた感染症制御と水産資源管理

	感染症	水産資源管理
観測されるデータ	新規感染者数 検査陽性率 重症患者数 感染死亡者数	漁獲量 単位努力量あたりの漁獲量（CPUE） 資源量指数
データ収集、政策決定から実施までの期間	数週間	2 年
望ましくない状況	感染死者数の増大 医療資源の逼迫 経済活動の鈍化	資源の枯渇 食料生産力の低下 経済活動の縮小
管理目的	感染死者数の抑制 医療資源の確保 経済活動の維持	一定水準以上の資源維持 中長期的な漁獲量最大化 漁獲量変動の最小化
意思決定の根拠	観測データ 感染者数予測 予算 経済状況	観測データ 資源量予測 予算 経済状況
不確実性	真の感染者数 個体群動態の機構 各パラメータ（潜伏期間、致命割合、再生産数） 管理行動の効果	真の個体数（資源量） 個体群動態の機構 各パラメータ（自然死亡率、年齢別重量、再生産関係） 管理行動の効果

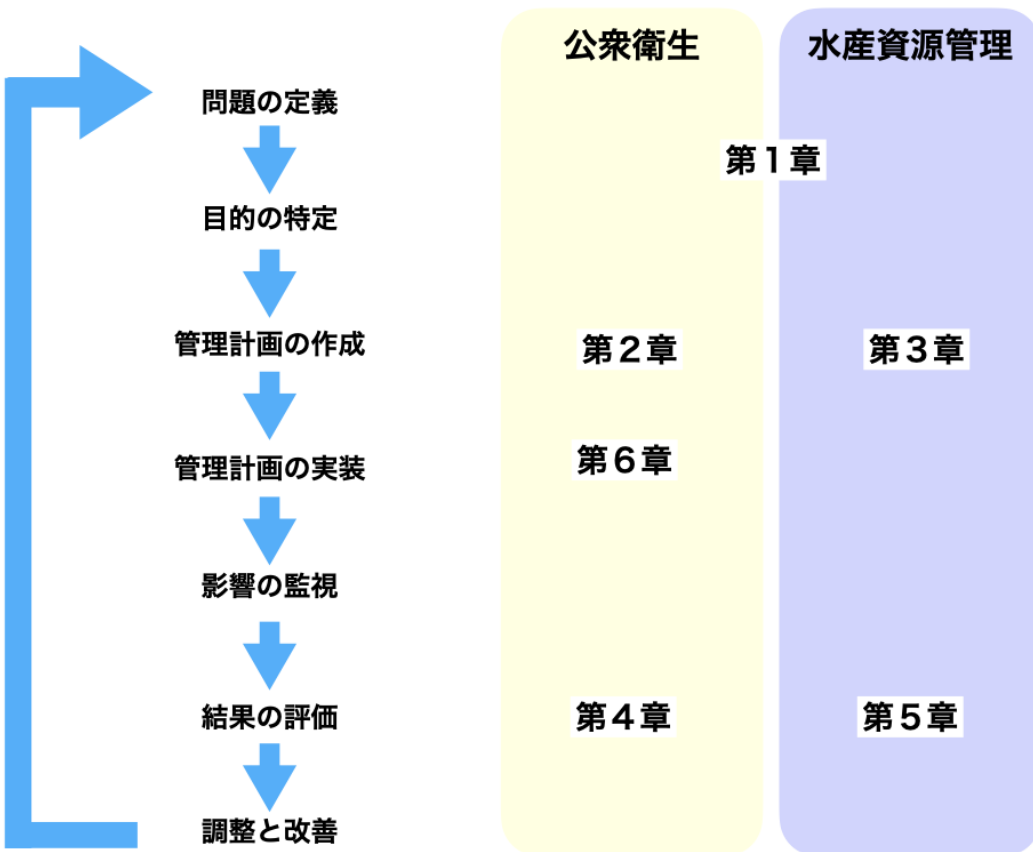


Figure 1: 順応的管理の手順と本論文の構成

Chapter II

フィードバック制御の有効性とCOVID-19の感染死者数と対策費用のトレードオフ

Effectiveness of feedback control and the trade-off between death by COVID-19 and costs of countermeasures

Abstract

We provided a framework of a mathematical epidemic modeling and a countermeasure against the novel coronavirus disease (COVID-19) under no vaccines and speci c medicines. The fact that even asymptomatic cases are infectious plays an important role for disease transmission and control. Some patients recover without developing the disease; therefore, the actual number of infected persons is expected to be greater than the number of con rmed cases of infection. Our study distinguished between cases of con rmed infection and infected persons in public places to investigate the effect of isolation. An epidemic model was established by utilizing a modi ed extended Susceptible-Exposed-Infectious-Recovered model incorporating three types of infectious and isolated compartments, abbreviated as SEIIIHHHR. Assuming that the intensity of behavioral restrictions can be controlled and be divided into multiple levels, we proposed the feedback controller approach to implement behavioral restrictions based on the active number of hospitalized persons. Numerical simulations were conducted using different detection rates and symptomatic ratios of infected persons. We investigated the appropriate timing for changing the degree of behavioral restrictions and con rmed that early initiating behavioral restrictions is a reasonable measure to reduce the burden on the health care system. We also examined the trade-off between reducing the cumulative number of deaths by the COVID-19 and saving the cost to prevent the spread of the virus. We concluded that a bang-bang control of the behavioral restriction can reduce the socio-economic cost, while a control of the restrictions with multiple levels can reduce the cumulative number of deaths by infection.

Keywords: non-pharmaceutical intervention; feedback control; epidemic model; isolation of asymptomatically infected persons; optimal control

1 Introduction

The number of novel coronavirus (COVID-19) cases, caused by severe acute respiratory syndrome coronavirus 2 (SARS-CoV-2), has been increasing worldwide since late 2019. The actual numbers of infected persons, isolated persons, and infection-related deaths depend on the effective reproduction number, which is de ned as the average number of people infected by an infectious person by the time of his or her recovery. Reducing the reproduction number is necessary to suppress this epidemic. Previous studies have shown that this can be achieved by reducing three factors, namely: the susceptibility of uninfected persons, contact rates in the population, or the infectiousness of infected persons [15].

Regarding measures against infectious diseases undertaken by policymakers, two fundamental strategies exist: suppression and mitigation [17]. The suppression strategy involves reducing the number of cases to a low level and is used in diseases with high mortality rates and low infection rates. In contrast, mitigation strategies involve slowing and reducing the peak of infections and are used in diseases with low mortality rates and high infection rates. The vaccine against the COVID-19 has been developed and released by some medicine companies since the outbreak. However, in the present study, we focus on the period without the aid of vaccines or speci c medicines and reducing contact rates in the population by conducting non-pharmaceutical interventions. Anti-contagion policies and measures have been discussed in some countries, and their effects, estimated, (e.g., [11, 15, 16, 24]). The Japanese government undertook several countermeasures, such as declaring a state of emergency, implementing priority preventive measures, and urging people to avoid the “Three Cs,” which refer to closed spaces, crowded places, and close-contact settings [8, 34].

The data obtained from observational research has revealed the features of the SARS-CoV-2 infection [22, 42, 43, 44, 64]. Nishiura et al. [43] reported that the serial interval of SARS-CoV-2 infection is close to or shorter than its median incubation period. This implies that transmission may occur before the onset of clinical symptoms or during asymptomatic infection. Such transmission may reduce the effectiveness of simple public measures, such as isolating symptomatic persons and tracing and quarantining their contacts [18]. In addition, it is important to estimate the exact number of infected persons in order to appropriately implement public health policies. Some studies assessed cases of unobserved infection and argued that the pandemic had been more broadly spread than the number of con rmed cases (e.g., [6, 7, 52, 63]).

Many researchers have proposed new epidemic models to describe the behavior of the novel coronavirus, extending and modifying the Susceptible-Infectious-Recovered (SIR) or Susceptible-Exposed-Infectious-Recovered (SEIR) models. The epidemic model was established to design a strategy for managing the pandemic and studying the impact of non-pharmaceutical interventions, such as lockdown [14, 47], testing [48], contact tracing, and isolation [23]. Senapati et al. [54] revealed that greater intervention effort is required to control the disease outbreak within a shorter period of time. Wood et al. [65] investigated the effectiveness of increasing healthcare capacity and extending the period of isolation. Some studies distinguish between and incorporate both asymptomatic and symptomatic persons, who play an important role in the COVID-19 pandemic (e.g., [3, 9, 19, 20, 25, 29, 40, 54, 62]). Moreover, the infectiousness of asymptomatic infected cases has been reported to be lower than that of symptomatically infected cases [22, 39]. Gevertz et al. [19], Kuniya and Inaba [29], and Senapati et al. [54] incorporated the differences into their epidemic models.

The increase in detection and isolation of asymptomatically infected persons appears to be effective as susceptible persons are prevented from being exposed to the virus from infected persons, including those that are asymptomatic. We divided the non-pharmaceutical interventions into two parts, namely: 1) the detection and isolation of asymptomatically infected persons and 2) behavioral restrictions, such as requesting restricted business hours and physical distancing. Some researchers use ”social” distancing; however, we use ”physical” distancing to emphasize in-person contact.

There is a trade-off between the negative impact on the economy and the reduction of infection-related deaths as a result of behavioral restrictions. Implementing behavioral restrictions contributes to reducing the reproduction number and preventing the spread of the virus; however, intense and prolonged restrictions decrease economic activities. To balance preventing the epidemic and maintaining economic activities is important for policymakers [9, 26, 30, 58]. Thunström et al. [58] conducted a bene t cost analysis of physical distancing measure to control the COVID-19 outbreak. Lasaulce et al. [30] found the optimal trade-off between economic and health impact by solving the optimization problem con ned to the number of Intensive Care Units patients with the SEIR model given the duration of interest for the epidemic is six months. Accordingly, we prepared the following indicators: the cumulative number of deaths by COVID-19, the socio-economic cost caused by the behavioral restrictions, the total number of isolated patients, and the total number of tests taken to detect infected persons.

This paper aims to reduce the damage caused by COVID-19 and provide some insights into the pandemic by utilizing mathematical modeling, taking Tokyo, Japan as an example. We recommend a feedback controller approach to decide the degree of behavioral restrictions to be undertaken during the epidemic management period, which policymakers can adjust based on observational data. The feedback control system is expected to be a robust and effective means against uncertainty. Dias et al. [13] proposed a control law of physical distancing within the SIR model, using the number of hospitalized persons as the feedback signal. Furthermore, during an epidemic, it is necessary to determine the proper timing during which to take preventive measures as well as establish the appropriate degree of behavioral restrictions. Di Lauro et al. [12] investigated the optimal timing of a one-time intervention using three indices, as follows: impact on attack rate, peak prevalence, and timing of infections. We conducted simulations of the feedback control of the degree of behavioral restrictions and demonstrated its effect and the timing at which to reduce the indicators by adjusting it. We also investigated the effects of detecting and isolating asymptomatically infected persons.

2 Methods

2.1 Model

Our basic model is the SEIIIR model, which is a modi ed version of the model that Kuniya and Inaba [29] proposed as an extended SEIR model. The infection spreads through asymptomatic and symptomatic persons. We assume that some infected persons recover without developing any symptoms, while others develop them later on in the course of their infection. Hereafter, the former and latter are described as asymptomatic and presymptomatically infected persons, respectively.

(1)

where , , , , , and represent the number of susceptible, exposed, asymptomatic, presymptomatically infected, symptomatically infected, and recovered persons, respectively. is the total population size, including the number of deaths. . is the transmission rate of asymptomatic persons, while is that of symptomatically infected persons. is the recovery rate of asymptomatic persons, while is that of symptomatically infected persons. is the reciprocal of the latent period. is the reciprocal of the difference between the incubation period and the latent period. is the proportion of infected persons who develop symptoms. In other words, refers to those who were infected and recovered without the onset of any symptoms. Note that those who are infected but do not have any symptoms are divided into and , but they cannot be distinguished by appearance. Figure 1 (a) shows a schematic diagram of Eq.1. The basic reproduction number is as follows (see Appendix A for the derivation):

(2)

, , and are not isolated and have the opportunity to infect susceptible persons. Let

$$— \quad —, \quad \text{and} \quad — \tag{3}$$

are the reproduction numbers for the asymptomatic and symptomatic infection, respectively. Note that . According to He, X. et al. [22], 44 percent of infection cases arise from the asymptomatic infection. Thus, in our context, we assume and . and are calculated using Eq.2 and these equations.

$$\overline{\qquad\qquad}, \quad \text{and} \quad \overline{\qquad\quad} \tag{4}$$

The SEIIIR model is modi ed and extended into the SEIIIHHHR model by incorporating three different compartments for isolation: , , and .

(5)

where . , and represent the number of isolated asymptomatic, isolated presymptomatically infected, and isolated symptomatically infected persons, respectively. A schematic of Eq.5. is shown in Figure 1 (b). The total population

is constant for any time ; is the degree of the behavioral restrictions. While represents the absence of behavioral restrictions, means that some policies, such as restriction of movement, are implemented. is the reciprocal of the time from onset to isolation. The parameter denotes the recovery rate. The reciprocals of and are the mean time periods from symptom onset to recovery and the average isolation period for those who are isolated at home or in hotels, respectively. People in compartment recover without the onset of symptoms, whereas people in develop some symptoms and are transferred to . Note that those in and cannot be distinguished in terms of appearance. The transition from compartment to means that an infected person is detected as a positive case and develops some symptoms later. The transition rate is assumed to be the same as . In this study, we assume that isolated persons without any symptoms stay at home or in hotels and do not occupy beds in hospitals or other healthcare facilities. The compartment includes death. Note that for simplicity, the loss of immunity is ignored in this model within the management period.

It is assumed that those who get sick die of infection at a rate. Let be the number of deaths by COVID-19 in those who are newly confirmed cases from time to . we calculate it as follows:

(6)

where is the case fatality rate, defined as the ratio of deaths to the number of confirmed infected persons. There is a time lag between infection and recovery or death, but the difference is negligible.

2.2 Feedback control of behavioral restrictions

This study explored the effectiveness of the feedback control of behavioral restrictions. The degree of behavioral restrictions is changed based on the number of isolated symptomatically infected persons and its trend of increasing or decreasing . Pataro et al. [50] introduced a framework for optimizing the required levels of public health policies and referred to the importance of finely tuning the level of restriction on the population s mobility. In this study, we assume that the intensity of the intervention, such as behavioral restrictions, can be divided into, at most, four levels. Hereafter, the feedback control which has levels of behavioral restrictions is referred to as " -level." We define as the mean degree of behavioral restrictions under the emergency state, which was executed in Tokyo from April 7 to May 25, 2020. In our simulation, let from the utilization ratio of major stations in the capital area [38]. We assume that the -level has situations and is discretely changed: , , , , , and . For example, the 1-level uses only two different situations: an emergency situation ( ) and its release ( ), whereas the 4-level uses , , , , and . The 1-level means the "bang-bang control" on the analogy of the control theory. The feedback control with is collectively denoted by "multilevel." Examples of dynamics of and different levels of feedback control are demonstrated in the supplementary le. To mimic the actual transition, the maximum behavioral restriction is initially implemented. In the multilevel feedback algorithm, , which is the increment and decrement of the degree of behavioral restrictions, is narrowed when is changed to execute the appropriate degree, while is constant in the algorithm of the 1-level. For example, if the 4-level is adopted, is at rst and changes to , , , and . The transition of with different levels of feedback control is demonstrated in the supplementary le.

Loewenthal et al. [33] argued that it is important to shorten the response time for initiating physical distancing, rather than extending the period of lockdown. We introduce and as the response and execution times, respectively. is the period from the time when reaches a criterion and to the time when is raised or lifted. We assume that days is a valid response time for administrative services in terms of feasibility and changeability. is the period from initiating the change in to restarting the monitoring of . We assume that days is a valid execution time.

refers to the capacity of healthcare facilities or the number of beds for infected persons who can receive suf cient healthcare treatment. We also introduce two thresholds and as parameters determined by policymakers, and they satisfy and . Decreasing lowers the thresholds to raise the degree of behavioral restrictions and prevents from exceeding . In contrast, increasing loosens the criteria to lower and shortens their duration. Hereafter, we de ne as the ratio of to , and let

$$ \tag{7} $$

Then the condition that the behavioral restriction changes depends on . This means the occupied rate of healthcare facilities at time . If , the capacity of healthcare facilities is overwhelmed. When exceeds and , the state of emergency is initiated days later, and . The state continues days after initiation, and then is lifted if falls below and . Then, is raised or lifted discretely in response to and . The detailed algorithm of feedback control is described in Appendix B.

2.3 Calculation of indicators

In 2020 (scal year), the Tokyo prefectural government budgeted about two trillion JPY for the measure against the novel coronavirus. The budget included four purposes: 1) to prevent the spread of the virus (1,174 billion JPY), 2) to reinforce a safety net to support economic activities and civic life (990 billion JPY), 3) to balance the prevention of spreading the virus and economic activities (20 billion JPY), and 4) to reform the social structure to adapt to the epidemic (55 billion JPY) [61]. The basis for calculation is not so clear, and the use is various. Thus, we established the following ve indicators which seem essentially important: the cumulative number of infected deaths by COVID-19 of during the management period , the total number of people isolated at home or in hotels , those who are hospitalized , those who undertake the reverse transcription-polymerase chain reaction (RT-PCR) or antigen tests , and the socio-economic cost caused by the behavioral restrictions .

is calculated as the sum of isolated persons without any symptoms during the management period. Symptomatically infected persons are hospitalized if . However, if the capacity of healthcare facilities is overwhelmed ( ), we assume that persons are also isolated at home or in hotels. Then they are added to .

(8)

is the sum of hospitalized persons during the management period and is calculated as follows:

(9)

is the sum of the number of people who take the tests during the management period and is calculated as follows:

$$-\qquad (10)$$

In reality, the rate of positive results uctuates daily and may increase with the identi cation of infection clusters. For simplicity, it is assumed that is based on the data obtained from [59].

indicates the intensity of implemented behavioral restrictions and is calculated as follows:

$$-\qquad ——\qquad (11)$$

This indicator is an abstract non-dimensional measure and satis es . means that the usual state is maintained and does that the state of emergency is executed during the management period . is the nonlinear effect. We assume that in the manuscript and discuss cases of in the supplementary le.

As two supplementary indicators, and are introduced to indicate the status of healthcare capacities. is the maximum ratio of the number of occupied beds to the number of available beds for healthcare treatment during the management period, and is de ned as follows:

$$ \qquad (12) $$

If , then the state of emergency is not declared and there are no behavioral restrictions within the management period. Moreover, if , then the capacity of the healthcare facilities is overwhelmed at least once during this period. is de ned as the number of days in which is true. Table 1 shows the list of variables, indicators and parameters.

2.4 Management parameter

We conduct the simulation, assuming our policy is implemented in Tokyo, Japan. Let , which supposes the population in Tokyo, Japan, on October 1, 2019, [55]. Parameters in Eq.5 are determined as follows. Let days [5] and days [35]. is calculated as the ratio of those discharged from the hospital to inpatients, including death, in one day based on the data by [36], and our simulation employs = 0.07. We assume that and . Let , and the sensitivity of and to is discussed in the supplementary le. The asymptomatic ratio has been estimated by proposing various methods and using different data (e.g., [4, 21, 42, 45]). The estimated values range from to ; therefore, we assume that ranges from to and let . The latent period days [51], and the incubation period was 5.1 days [31]. Thus, let days. We assume that the management period is 500 days ( ) from January 1, 2020, to May 14, 2021, as the vaccination for people over 64 years of age was issued in Japan on April 12, 2021, and the vaccine doses per capita have rapidly increased since the middle of May [46].

In reality, the fatality rate depends on symptoms, age, and access to appropriate medical care [64]. However, it is assumed to be a constant in this paper. According to the data [36], the number of con rmed cases is from June 1, 2020, to May 31, 2021, while that of fatalities in the same period is . Thus, we obtain .

Some studies report that the estimated value of the basic reproduction number, de ned as the average number of secondary cases generated by a typical primary case in an entirely susceptible population, varies widely from country to country [32, 53]. The basic reproduction number for the epidemic in Japan was also estimated (e.g., [28, 56]). Kuniya [28] reported that it was whose con dence interval was 2.4 to 2.8, and therefore, we adopt in this paper. Table 2 shows the list of parameters.

Table 3 shows the number of beds available for healthcare treatment in Tokyo, Japan. The number of beds available for healthcare treatment has increased [37]. Although data on the number of beds is missing from January 1, 2021, to April 30, 2021, we assume during this period.

2.5 Simulation

First, we investigated the behavior of the SEIIIHHHR model without feedback control over the degree of behavioral restrictions. The simulations were conducted under , and the sensitivities of and were analyzed in relation to . Second, we conducted simulations with different combinations of and and veri ed whether feedback control can be effective in reducing , , and . Third, based on the combinations of and , we considered three different scenarios: [A] to minimize , [B] to minimize , and [C] to minimize under and . Table 4 shows combinations of and which achieved the goal of the three scenarios when and . The strategic planning for achieving scenario A is to initiate behavioral restrictions early and maintain them until the occupied ratio of beds available for healthcare treatment is reduced. In contrast, behavioral restrictions in scenario B are reinforced when the number of hospitalized people increases while scenario C is an intermediate strategy. Using these arrangements, we investigated the level of feedback control that is more effective in reducing the indicators referred to in the previous subsection with different values of . Finally, we explored the performance of feedback control when is governed by a uniform distribution with different values ranging from to . varies on a daily basis and ranges from . Trials were carried out 1000 times and the statistical values were obtained.

The simulation starts from , , and . The rst deceased person due to COVID-19 was con rmed on February 26, 2020,

[60]. In Tokyo, 2035 people died of the infection, and the total period of the state of emergency was 147 days by May 14, 2021, [36].

3 Results

Figure 2 shows and with different detection rate for during the management period. Both and are monotonically decreasing with , and they are larger as the symptomatic rate becomes higher. For as shown in Figure 2 (a), if throughout the management period, will be lower than the actual data even without any behavioral restrictions. Moreover, according to Figure 2 (b), the capacity of health care capacity will be overwhelmed if for . This gure suggests that the detection of infected persons should be strengthened to contain the epidemic when is high.

Figure 3 demonstrates the results of simulations with and different combinations of and using three different indicators: , , and . Since these simulations were conducted under , the total number of those who take the test to detect infected persons, , is zero for any combinations. Decreasing and contribute to reducing , as shown in Figure 3 (a), (d), (g), and (j). When and are high, rises especially, in the 1-level.

When it comes to shown in Figure 3 (b), (e), (h), and (k), the same colored clusters radiate from the origin. The gures show a combination of high and is effective in reducing , especially in the lower level feedback control. When , is large in all the levels of the feedback control.

As shown in Figure 3 (c), (f), (i), and (l), a low reduces the risk that the capacity of health care facilities is overwhelmed. In the case of , is favorable for keeping the health care system with the exception of some combinations of the 1-level. In addition, the of the 1-level trends to be much longer than those in the other levels when .

Combinations of and are selected so that the indicators can be reduced. Table 4 shows the best combinations of and for each scenario when . Figures 4, 5, and 6 demonstrate the sensitivity analysis in relation to for three different scenarios. The combinations of and are xed regardless of the value of in the simulation. In each gure, panel (a), (b), (c), (d), (e), and (f) show , , , , , and , respectively.

For scenario A shown in Figure 4, the is under 100 persons in all the levels. The of the 1-level is lower than those of multilevel controls. In , behavioral restrictions are not implemented and corresponds to the line of of Figure 2. The and are increasing as is raised. The behaviors of and are similar and is about three times larger than . In addition, the behavior of the total number of hospitalized persons, , is also similar to that of . As becomes larger, the period of behavioral restrictions is shorter and its initiation is delayed. Thus, the and rise in . is maintained regardless of in all the levels and the capacity of health care facilities is enough for scenario A.

For scenario B shown in Figure 5, the is under in all the levels, and however, the other indicators are about 10 times larger than those of scenario A. In the 1-level, the is the lowest and the other indicators are the largest of all the levels. The of the 4-level is the same as those of the 2- and 3-level and overlaps with them in Figure 5 (f). When , is 83 days in the 1-level and is 31 days in the other levels. This implies that many symptomatically infected persons cannot be hospitalized and are isolated at home or in hotels. The is roughly decreasing with increasing , and however, should be maintained to achieve during the management period. The and of the 3-level surge and drop sharply in .

Figure 6 shows the result of scenario C. , , , and of the 4-level are the smallest in , while those of the 2-level are the smallest in . The of the 2-level exceeded 500 persons in . The of the 4-level slightly decreases in and keeps high, compared with the other levels. At , although the difference of of the 4- and 2-levels is just persons, their are and , respectively.

Figure 7 shows the sensitivity analysis in relation to for three different scenarios when uctuates on a daily basis. , , and are shown in the gure, and , , and are discussed in the supplementary le. For scenario A shown in Figure 7 (a), (b), and (c), means of are almost constant and differences between the maximum and the minimum of are small in all the level. Means of are increasing and those of are decreasing with increasing . The mean of in the 1-level is the smallest and the is the largest. In contrast, the 4-level resulted in the largest and the smallest .

For scenario B shown in Figure 7 (d), (e), and (f), means of in the 1- and 2-levels are increasing as becomes larger unlike scenario A. On the other hand, means of are increasing as becomes larger, like scenario A. Means of are also decreasing with increasing for multilevel feedback controls. However, the mean of in the 1-level rises at .

Panels (g), (h), and (i) in Figure 7 show the result of scenario C. Means of and for the 4-level are the smallest with the exception of . The is higher in the 4-level, and however, differences of the means between the 4-level and the other levels are decreasing with increasing . According to , , and , the 4-level is relatively effective when is high.

4 Discussion

We established the SEIIIHHHR model as a mathematical epidemic model of the COVID-19 and calculated indicators such as the socio-economic cost caused by the behavioral restrictions , the total number of those who are isolated at home or in hotels , the total number of hospitalized persons , and the total number of those who take the test to detect infected persons as well as the cumulative number of infected deaths . We conducted numerical simulations of implementing nonpharmaceutical interventions such as detecting infected persons in public spaces and restricting people s activities. The RT-PCR testing is not only a monitoring but also an intervention measure. As a result of simulations with different detection rate , and the burden on the health care system are reduced as becomes larger. To develop a measure against the virus with uncertain symptomatic rate, we proposed a feedback control of the degree of behavioral restrictions . The in the feedback control is adapted for how many infected persons occupy the health care facility and its trend. We concluded the feedback control of , rather than xing , can reduce and other costs to take countermeasures against the virus.

One of the simplest feedback controls is the bang-bang control (1-level) which repeats the state of emergency and the usual state. We explored a better way and suggested the multilevel feedback control in which the band of changing is narrowed. Three different scenarios were prepared for our simulations by exploring combinations of two parameters and . We came to some conclusions from the simulations. We found out that increasing and reduces , whereas decreasing and does . The number of days in which the capacity of health care facilities is overwhelmed depends on regardless of the number of levels for feedback control. The result of scenario A implied that early initiating and maintaining behavioral restrictions can be reasonable to decrease indicators except for . Furthermore, the in scenario A does not rise so much if the proportion of infected persons who develop symptoms is high. Gevertz et al. [19] investigated the best timing of initiating and canceling physical distancing and argued that it should start early and relax slowly. Our nding follows this research. According to Figures 4 and 5, scenario A reduced , , , and to about one tenth of those of scenario B. On the other hand, its is larger by than that of scenario B. From these two scenarios, the bang-bang control seemed to be better to reduce . However, it must be noted that is an abstract measure and the cost to raise is assumed to be linear. The cost to increase includes the monetary compensation for businesses damaged by the governmental interventions. A multilevel feedback control is preferable to reduce , , , and . In scenario C, the 4-level feedback control is effective when is high. As becomes higher, is increasing and is decreasing. The , , and can be converted into money by multiplying each cost per person. Depending on their unit costs, the favorable scenario may be changed.

Our analysis has several limitations. This paper assumed the distribution of population is homogeneous while that in reality is heterogeneous. We did not consider other important factors such as the time delay for aggravation of symptoms, the age group of patients, the increase of the number of suicides caused by recession, and the in uence of superspreading events reported in [44]. The Japanese government counts the number of deceased individuals who were positive for COVID-19 reported by jurisdictions, and de nes it as infected deaths by COVID-19 without specifying the cause of death. However, we calculated the number of infected deaths in those who are newly con rmed cases in the management period. We do not consider how or to what extent we can increase . The number of beds in health care facilities for infected persons with symptoms is assumed to be the same as the actual data during the management period in our simulation, but its increase may be also effective in reducing indicators [10, 65].

The timing of reinforcing or relaxing the behavioral restrictions might be more effective by using other indicators, such as the reduction in individual consumption due to the restrictions, the estimated number of uncon rmed infections, the number of severely ill persons, the number of deaths, or the positive rate of the test. Their combinations can be effective because indicators were sometimes unstable as shown in in Figures 4, 5, and 6. In addition, we assumed a time lag of one week because immediate executing or canceling behavioral restrictions may be impossible. If we could reduce the time lag of policy change, we would manage the situation more effectively.

We ignored a possibility that a successive long strong behavioral restriction causes the bankruptcy of business for which remote work cannot be substituted. The COVID-19 cases resurged in Japan from November, 2020 to January, 2021, [1, 27], and the number of infected deaths also increased in Tokyo

[60]. Karako et al. [27] argued that this was because people seemed accustomed to the situation of this epidemic and their level of activity was not reduced during the period. In Japan, no legal penalties are imposed for violating behavioral restrictions called for by the government. In this study, we didn t consider such people s spontaneous behavior change and assumed the degree of behavioral restrictions changes discretely and keeps constant during a certain period in the feedback control. However, people may reduce their mobility restrictions by themselves even though some governmental interventions are being implemented [41, 49]. From a point of view of behavioral science, Atkinson-Clement and Pigalle [2] argued that a lack of trust towards government measures reduces compliance. The management period of the simulation is from January 1, 2020 to May 14, 2021, but the outbreak of the SARS-CoV-2 Alpha variants, which has a higher transmissibility [57], was not considered.

The framework in the present study can be applied to another infectious disease against which vaccines and speci c medicines are not developed in the future. A feedback controller approach is an effective way even after vaccines and speci c medicines are developed because of the resurgence of infection cases caused by the loss of immunity. However, the knowledge provided by these models can only be understood in terms of the dynamical system. The structure of the model and its parameters need to be validated and improved in response to the appearance of variants which have different properties and the development of pharmaceutical interventions. Moreover, it must be stressed that if the value of statistical life is not converted to economic loss, then there is no objective optimal solution and that evaluations made during the decision-making process are arbitrary. The Japanese government was late to start administering the COVID-19 vaccination, but the vaccine doses per capita have been rapidly increasing since the middle of May, 2021 [46]. We will consider a better measure against the epidemic under insuf cient data and cost-effectiveness of a variety of anti-contagion measures including pharmaceutical interventions such as vaccination.

Appendix A. Derivation of basic reproduction number

The basic reproduction number is derived from Eq.1 as follows:

(1)

The linearized system at the disease-free steady state for Eq.1 is

(A1)

where , , , and denote the linearized forms of , , , and , respectively. And

(A2)

The next generation matrix with large domain is calculated as

— — — — — — —

(A3)

The basic reproduction number is equivalent to the spectral radius of .

— — — (A4)

Appendix B. Algorithm for the feedback control

```
, and denotes and at the th day. . , ,
, , , , and . denotes the oor function.

for to do
  if then
    if and then
      ,
    end if
  else if and then
    , , ,
  else if and then
    if , , and then
      ,
    else if , , and then
      ,
    end if
  else if and then
    , , ,
    if then

    end if
  else if and then
    , ,
    if then

    end if
  end if
  ,
end for
return
```

Declarations

Funding No funding was received for conducting this study.

Conflicts of interest The authors have no con icts of interest to declare that are relevant to the content of this article.

Availability of data and material Not applicable

Code availability The simulation code was available in the supplementary material.

Erratum

After the original article was published by Springer Nature, a few errata were found. Thus, errors and the corrections were given as follows: “shown in in” should be “shown in” at the fourth paragraph in the Discussion, “ oor” should be “ceiling” in the Appendix B, and “Number of those who are isolated into some health care facilities from time 0 to and die from infection” should be “the number of deaths by COVID-19 in those who are newly con rmed cases from time 0 to ” in Table 1.
and should be for the 4-level and the scenario C in Table 4. Results and gures are not changed.

References

[1] Arima, Y., Kanou, K., Arashiro, T., Ko, Y.K., Otani, K., Tsuchihashi, Y., Takahashi, T., Miyahara, R., Sunagawa, T., Suzuki, M., 2021. Epidemiology of Coronavirus Disease 2019 in Japan: Descriptive Findings and Lessons Learned through Surveillance during the First Three Waves. JMA Journal 4, 198–206. https://doi.org/10.31662/jmaj.2021-0043.

[2] Atkinson-Clement, C., Pigalle, E., 2021. What can we learn from Covid-19 pandemic's impact on human behaviour? The case of France's lockdown. Humanities and Social Sciences Communications 8. https://doi.org/10.1057/s41599-021-00749-2.

[3] Basnarkov, L., Chaos, Solitons and Fractals 142, 2021. SEAIR Epidemic spreading model of COVID-19. 110394. https://doi.org/10.1016/j.chaos.2020.110394.

[4] Byambasuren, O., Cardona, M., Bell, K., Clark, J., McLaws, M., Glasziou, P., 2020. Estimating the extent of asymptomatic COVID-19 and its potential for community transmission: systematic review and meta-analysis. Official Journal of the Association of Medical Microbiology and Infectious Disease Canada. https://doi.org/10.3138/jammi-2020-0030.

[5] Byrne, A.W., McEvoy, D., Collins, A.B., Hunt, K., Casey, M., Barber, A., Butler, F., Griffin, J., Lane, E.A., McAloon, C., O ' Brien, K., Wall, P., Walsh, K.A., More, S.J., 2020. Inferred duration of infectious period of SARS-CoV-2: rapid scoping review and analysis of available evidence for asymptomatic and symptomatic COVID-19 cases. BMJ Open 10. https://doi.org/10.1136/bmjopen-2020-039856.

[6] Bohk-Ewald, C., Dudel, C., Myrskylä, M., 2020. A demographic scaling model for estimating the total number of COVID-19 infections. International Journal of Epidemiology 49, 1963-1971. https://doi.org/10.1093/ije/d aa198.

[7] Böhning, D., Rocchetti, I., Maruotti, A., Holling, H., 2020. Estimating the undetected infections in the Covid-19 outbreak by harnessing capture-recapture methods. International Journal of Infectious Diseases 97, 197-201. https://doi.org/10.1016/j.ijid.2020.06.009.

[8] Cabinet Secretariat, Government of Japan 2021. https://corona.go.jp/en/emergenc / Accessed on 13 September 2022

[9] Choi, W., Shim, E., 2021. Optimal strategies for social distancing and testing to control COVID-19. Journal of Theoretical Biology 512, 110568. .

[10] Currie, C.S.M., Fowler, J.W., Kotiadis, K., Monks, T., Onggo, B.S., Robertson, D.A., Tako, A.A., 2020. How simulation modelling can help reduce the impact of COVID-19. Journal of Simulation 14. .

[11] Davies, N.G., Kucharski, A.J., Eggo, R.M., Gimma, A., Edmunds, W.J., 2020. Effects of non-pharmaceutical interventions on COVID-19 cases, deaths, and demand for hospital services in the UK: a modelling study. Lancet Public Health 5, e375-e385.
.

[12] Di Lauro, F., Kiss, I.Z., Miller, J.C., 2021. Optimal timing of one-shot interventions for epidemic control. PLOS Computational Biology 17, 1-25.
.

[13] Dias, S., Queiroz, K., Araujo, A., 2021. Controlling Epidemic Diseases Based only on Social Distancing Level. Journal of Control, Automation and Electrical Systems
.

[14] Flaxman, S., Mishra, S., Gandy, A., Unwin, H.J.T., Mellan, T.A., Coupland, H., Whittaker, C., Zhu, H., Berah, T., Eaton, J.W., Monod, M., Imperial College COVID-19 Response Team, Ghani, A.C., Donnelly, C.A., Riley, S., Vollmer, M.A.C., Ferguson, N.M., Okell, L.C., Bhatt, S., 2020. Estimating the effects of non-pharmaceutical interventions on COVID-19 in Europe. Nature 584, 257-261. .

[15] Ferguson, N.M., Cummings, D.A.T., Cauchemez, S., Fraser, C., Riley, S., Meeyai, A., Iamsirithaworn, S., Burke, D.S., 2005. Strategies for containing an emerging in uenza pandemic in southeast Asia. Nature 437, 209-214. .

[16] Ferguson, N.M., Cummings, D.A.T., Fraser, C., Cajka, J.C., Cooley, P.C., Burke, D.S., 2006. Strategies for mitigating an in uenza pandemic. Nature 442, 448-452.
.

[17] Ferguson, N.M., Laydon, D., Nedjati-Gilani, G., Imai, N., Ainslie, K., Baguelin, M., Bhatia, S., Boonyasiri, A., Cucunubá, Z., Cuomo- Dannenburg, G., Dighe, A., Dorigatti, I., Fu, H., Gaythorpe,

K., Green, W., Hamlet, A., Hinsley, W., Okell, L.C., van Elsland, S., Thompson, H., Verity, R., Volz, E., Wang, H., Wang, Y., Walker, P.G.T., Walters, C., Winskill, P., Whittaker, C., Donnelly, C.A., Riley, S., Ghani, A.C., 2020. Report 9: Impact of non-pharmaceutical interventions (NPIs) to reduce COVID-19 mortality and healthcare demand. .

[18] Fraser, C., Riley, S., Anderson, R.M., Ferguson, N.M., 2004. Factors that make an infectious disease outbreak controllable. Proceedings of the National Academy of Sciences 101, 6146-6151. .

[19] Gevertz, J.L., Greene, J.M., Sanchez-Tapia, C.H., Sontag, E.D., 2021. A novel COVID-19 epidemiological model with explicit susceptible and asymptomatic isolation compartments reveals unexpected consequences of timing social distancing. Journal of Theoretical Biology 510, 110539. .

[20] Giordano, G., Blanchini, F., Bruno, R., Colaneri, P., Filippo, A.D., Matteo, A.D., Colaneri, M., 2020. Modelling the COVID-19 epidemic and implementation of population-wide interventions in Italy. Nature Medicine 26, 855-860. .

[21] He, J., Guo, Y., Mao, R., Zhang, J., 2020. Proportion of asymptomatic coronavirus disease 2019 (COVID‐19): a systematic review and meta-analysis. Journal of Medical Virology. .

[22] He, X., Lau, E.H.Y., Wu, P., Deng, X., Wang, J., Hao, X., Lau, Y.C., Wong, J.Y., Guan, Y., Tan, X., Mo, X., Chen, Y., Liao, B., Chen, W., Hu, F., Zhang, Q., Zhong, M., Wu, Y., Zhao, L., Zhang, F., Cowling, B.J., Li, F., Leung, G.M., 2020. Temporal dynamics in viral shedding and transmissibility of COVID-19. Nature Medicine 26, 672-675. .

[23] Hellewell, J., Abbott, S., Gimma, A., Bosse, N.I., Jarvis, C.I., Russell, T.W., Munday, J.D., Kucharski, A.J., Edmunds, W.J., Sun, F., Flasche, S., Quilty, B.J., Davies, N., Liu, Y., Clifford, S., Klepac, P., Jit, M., Diamond, C., Gibbs, H., van Zandvoort, K., Funk, S., Eggo, R.M., 2020. Feasibility of controlling COVID-19 outbreaks by isolation of cases and contacts. The Lancet Global Health 8, e488-e496. .

[24] Hsiang, S., Allen, D., Annan-Phan, S., Bell, K., Bolliger, I., Chong, T., Druckenmiller, H., Huang, L. Y., Hultgren, A., Krasovich, E., Lau, P., Lee, J., Rolf, E., Tseng. J., Wu. J., 2020. The effect

of large-scale anti-contagion policies on the COVID-19 pandemic Nature 584, 262-267.

.

[25] Johansson, M.A., Quandelacy, T.M., S, K., Prasad, P.V., Steele, M., Brooks, J.T., Slayton, R.B., Biggerstaff, M., Butler, J.C., 2021. SARS-CoV-2 Transmission From People Without COVID-19 Symptoms. JAMA Network Open 4(1), e2035057.

.

[26] Kantner, M., Koprucki, T., 2020. Beyond just " attening the curve ": Optimal control of epidemics with purely non-pharmaceutical interventions. Journal of Mathematics in Industry 10.

.

[27] Karako, K., Song, P., Tang, W., Kokudo, N., 2021. Overview of the characteristics of and responses to the three waves of COVID-19 in Japan during 2020-2021. BioScience Trends 15(1), 1–8. .

[28] Kuniya, T., 2020. Prediction of the epidemic peak of coronavirus disease in Japan. Journal of Clinical Medicine 9, 789. .

[29] Kuniya, T., Inaba, H., 2020. Possible effects of mixed prevention strategy for COVID-19 epidemic: massive testing, quarantine and social distancing. AIMS Public Health 7(3), 490-503.

.

[30] Lasaulce, S., Varma, V., Morarescu, C., Lin, S. 2020. How ef cient are the lockdown measures taken for mitigating the Covid-19 epidemic? medRxiv

.

[31] Lauer, S.A., Grantz, K.H., Bi, Q., Jones, F.K., Zheng, Q., Meredith, H.R., Azman, A.S., Reich, N.G., Lessler, J., 2020. The Incubation Period of Coronavirus Disease 2019 (COVID-19) From Publicly Reported Con rmed Cases: Estimation and Application. Annals of Internal Medicine

.

[32] Liu, Y., Gayle, A.A., Wilder-Smith, A., Rocklöv, J., 2020. The reproductive number of COVID-19 is higher compared to SARS coronavirus. Journal of Travel Medicine

.

[33] Loewenthal, G., Abadi, S., Avram, O., Halabi, K., Ecker, N., Nagar, N., Mayrose, I., Pupko, T., 2020. COVID-19 pandemic-related lockdown: response time is more important than its strictness. EMBO Molecular Medicine 12, e13171. .

[34] Ministry of Health, Labor, and Welfare, 2020a. Accessed on 13 September 2022

[35] Ministry of Health, Labor, and Welfare, 2020b. Accessed on 13 September 2022

[36] Ministry of Health, Labor, and Welfare, 2021a. Accessed on 13 September 2022

[37] Ministry of Health, Labor, and Welfare, 2021b. Accessed on 13 September 2022

[38] Ministry of Land, Infrastructure, Transport and Tourism, 2020. Accessed on 13 September 2020

[39] Nakajo, K., Nishiura, H., 2021. Transmissibility of asymptomatic COVID-19: Data from Japanese clusters. International Journal of Infectious Diseases 105, 236-238. .

[40] Nakamoto, I., Zhang, J., 2021. Modeling the underestimation of COVID-19 infection. Results in Physics 25, 104271. .

[41] Nakanishi, M., Shibasaki, R., Yamasaki, S., Miyazawa, S., Usami, S., Nishiura, H., Nishida, A., 2021. On-site Dining in Tokyo During the COVID-19 Pandemic: Time Series Analysis Using Mobile Phone Location Data. JMIR Mhealth and Uhealth 9, .

[42] Nishiura, H., Kobayashi, T., Miyama, T., Suzuki, A., Jung, S., Hayashi, K., Kinoshita, R., Yang, Y., Yuan, B., Akhmetzhanov, A.R., Linton, N.M., 2020. Estimation of the asymptomatic ratio of novel coronavirus infections (COVID-19). International Journal of Infectious Diseases 94, 154-155. .

[43] Nishiura, H., Linton, N.M., Akhmetzhanov, A.R., 2020. Serial interval of novel coronavirus (COVID-19) infections. International Journal of Infectious Diseases 93, 284-286.

.

[44] Nishiura, H., Oshitani, H., Kobayashi, T., Saito, T., Sunagawa, T., Matsui, T., Wakita, T., MHLW COVID-19 Response Team, Suzuki, M., 2020. Closed environments facilitate secondary transmission of coronavirus disease 2019 (COVID-19). medRxiv

.

[45] Oran, D.P., Topol, E.J., 2020. Prevalence of Asymptomatic SARS-CoV-2 Infection: A Narrative Review. Annals of Internal Medicine .

[46] Our World in Data, 2021.

Accessed on 13 September 2022

[47] Pachetti, M., Marini, B., Giudici, F., Benedetti, F., Angeletti, S., Ciccozzi, M., Masciovecchio, C., R., I., D., Z., 2020. Impact of lockdown on Covid-19 case fatality rate and viral mutations spread in 7 countries in Europe and North America. Journal of Translational Medicine 18.

.

[48] Paltiel, A.D., Zheng, A., Sax, P.E., 2021. Clinical and Economic Effects of Widespread Rapid Testing to Decrease SARS-CoV-2 Transmission. Annals of Internal Medicine

.

[49] Pan, Y., Darzi, A., Kabiri, A., Zhao, G., Luo, W., Xiong, C., Zhang, L., 2020. Quantifying human mobility behaviour changes during the COVID-19 outbreak in the United States. Scienti c Reports 10. .

[50] Pataro, I.M.L., Oliveira, J.F., Morato, M.M., Amad, A.A.S., Ramos, P.I.P., Pereira, F.A.C., Silva, M.S., Jorge, D.C.P., Andrade, R.F.S., Barreto, M.L., da Costa, M.A., 2021. A control framework to optimize public health policies in the course of the COVID-19 pandemic. Scienti c Reports 11.

.

[51] Peirlinck, M., Linka, K., Costabal, F.S., Kuhl, E., 2020. Outbreak dynamics of COVID-19 in China and the United States. Biomechanics and Modeling in Mechanobiology 19, 2179-2193. https://doi.org/10.1007/s10237-020-01332-5.

[52] Perkins, T.A., Cavany, S.M., Moore, S.M., Oidtman, R.J., Lerch, A., Poterek, M., 2020. Estimating unobserved SARS-CoV-2 infections in the United States. Proceedings of the National Academy of Sciences 117, 22597-22602. https://doi.org/10.1073/pnas.2005476117.

[53] Rahman, B., Sadraddin, E., Porreca, A., 2020. The basic reproduction number of SARS‐CoV‐2 in Wuhan is about to die out, how about the rest of the World? Review in Medical Virology, e2111 https://doi.org/10.1002/rmv.2111.

[54] Senapati, A., Rana, S., Das, T., Chattopadhyay, J., 2021. Impact of intervention on the spread of COVID-19 in India: A model based study. Journal of Theoretical Biology 523, 110711. https://doi.org/10.1016/j.jtbi.2021.110711.

[55] Statistics Division, Bureau of General Affairs, Tokyo Metropolitan Government, 2020. https://www.toukei.metro.tok o.lg.jp/tnenkan/2019/tn19q3e002.htm Accessed on 13 September 2022

[56] Sugishita, Y., Kurita, J., Sugawara, T., Yasushi Ohkusa, Y., 2020. Preliminary evaluation of voluntary event cancellation as a countermeasure against the COVID-19 outbreak in Japan as of 11 March, 2020. medRxiv https://doi.org/10.1101/2020.03.12.20035220.

[57] Tanaka, H., Hirayama, A., Nagai, H., Shirai, C., Takahashi, Y., Shinomiya, H., Taniguchi, C., Ogata, T., 2021. Increased Transmissibility of the SARS-CoV-2 Alpha Variant in a Japanese Population. International Journal of Environmental Research and Public Health 18. https://doi.org/10.3390/ijerph18157752.

[58] Thunström, L., Newbold, S. C., Finnoff, D., Ashworth, D., Shogren, J. F., 2020. The Benefits and Costs of Using Social Distancing to Flatten the Curve for COVID-19. J. Benefit Cost Anal. 11, 179-195. https://doi.org/10.1017/bca.2020.12.

[59] Tokyo Metropolitan Government, 2020. https://stopcovid19.metro.tok o.lg.jp/en/ Accessed on 13 September 2022

[60] Tokyo Metropolitan Government, 2021a.
https://stopcovid19.metro.tok o.lg.jp/en/cards/deaths-b -death-date Accessed on 13 September 2022

[61] Tokyo Metropolitan Government, 2021b.
https://www.zaimu.metro.tok o.lg.jp/s ukei1/zaisei/20210129_reiwa3nendo_tok oto osanangai ou/3 osanangai ou.pdf Accessed on 13 September 2022

[62] Tsay, C., Lejarza, F., Stadtherr, M.A., Baldea, M., 2020. Modeling, state estimation, and optimal control for the US COVID-19 outbreak. Scientific Reports 10. https://doi.org/10.1038/s41598-020-67459-8.

[63] Tuite, A.R., Ng, V., Rees, E., Fisman, D., 2020. Estimation of COVID-19 outbreak size in Italy. The Lancet Infectious Diseases 20, 537. https://doi.org/10.1016/S1473-3099(20)30227-9.

[64] Verity, R., Okell, L.C., Dorigatti, I., Winskill, P., Whittaker, C., Imai, N., Cuomo-Dannenburg, G., Thompson, H., Walker, P.G.T., Fu, H., Dighe, A., Griffin, J.T., Baguelin, M., Bhatia, S., Boonyasiri, A., Cori, A., Cucunubá, Z., FitzJohn, R., Gaythorpe, K., Green, W., Hamlet, A., Hinsley, W., Laydon, D., Nedjati-Gilani, G., Riley, S., van Elsland, S., Volz, E., Wang, H., Wang, Y., Xi, X., Donnelly, C.A., Ghani, A.C., Ferguson, N.M., 2020. Estimates of the severity of coronavirus disease 2019: a model-based analysis. Lancet Infect Diseases 20, 669-677. https://doi.org/10.1016/S1473-3099(20)30243-7.

[65] Wood, R.M., McWilliams, C.J., Thomas, M.J., Bourdeaux, C.P., Vasilakis, C., 2020. COVID-19 scenario modelling for the mitigation of capacity-dependent deaths in intensive care. Health Care Management Science 23, 315-324. https://doi.org/10.1007/s10729-020-09511-7.

Table 1: The list of variables, indicators, and parameters

Symbol	De nition
	Number of susceptible persons at time
	Number of those who are exposed to the virus at time
	Number of asymptomatically infected persons (without being isolated) at time
	Number of presymptomatically infected persons (without being isolated) at time
	Number of symptomatically infected persons (without being isolated) at time
	Number of recovered persons at time
	Number of isolated persons without any symptoms at time
	Number of isolated presymptomatic persons at time
	Number of isolated symptomatic persons at time
	Number of those who are isolated into some health care facilities from time to and die from infection
	Degree of behavioral restrictions, such as the restriction of movement and shortening business hours at time
	Socio-economic cost caused by the behavioral restrictions
	Total number of isolated persons at home or in hotels
	Total number of hospitalized persons
	Total number of those who take the test to detect infected persons
	Occupied rate of health care facilities at time , de ned as
	The maximum occupied rate in the management period, de ned as
	Number of days in which the occupied rate of health care facilities is over 1
	Coef cient to increase the degree of behavioral restrictions
	Coef cient to decrease the degree of behavioral restrictions

Table 2: The list of parameters (The blank in the Reference column means that the value is an assumption.)

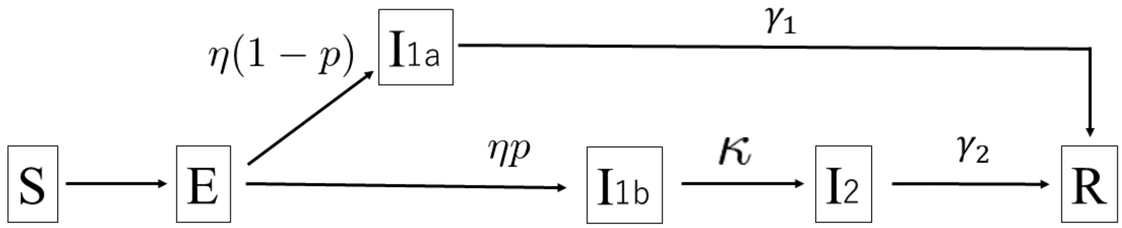
Symbol	De nition	Value	Reference
	Total population in Tokyo on October 1, 2019		[55]
	Asymptomatic infection rate		(derived from Eq.4)
	Symptomatic infection rate		(derived from Eq.4)
	Recovery rate of asymptomatically infected persons		
	Mean time from symptom onset to recovery		[5]
	Average isolated period		[35]
	Discharge rate from hospital		[36]
	Proportion of asymptomatically infected persons in all the infected persons		[4, 21, 42, 45]
	Median of latent period		[51]
	Difference between the incubation period and the latent period	2.54	[31, 51]
	the time from the onset to hospitalization	2	
	Detection rate of those who are exposed or asymptomatically infected		
	Basic reproduction number		[28, 56]
	Number of beds for infected persons to receive suf cient health care treatment at time in Tokyo		[37]
	Case fatality rate		[36]
	Positive rate per RT-PCR test		[59]
	during the emergency regulations of April-May in 2020 in Tokyo		[38]
	the maximum degree of behavioral restrictions		
	Management period from January 1, 2020 to May 14, 2021	days	
	Response time	days	
	The shortest execution time	days	
	Nonlinear effect for		

Table 3: The number of beds for infected persons to receive suf cient health care treatment in Tokyo, [37]

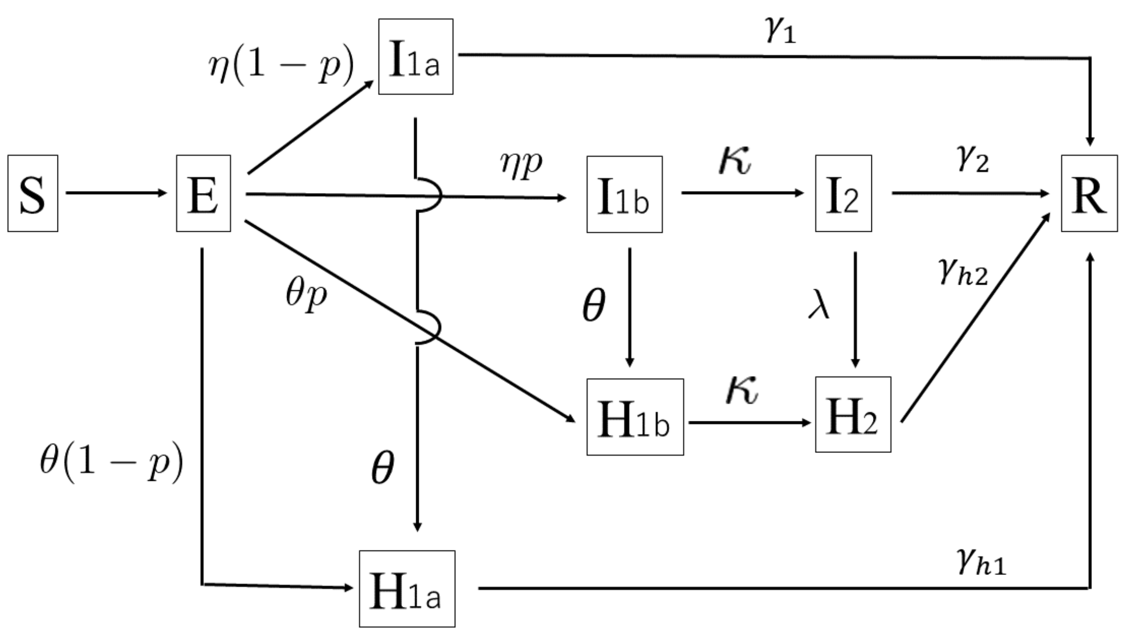
Day		Date (yyyy/mm/dd)		The number of beds
1	121	2020/01/01	2020/04/30	no data (assumed to be 3300)
122	245	2020/05/01	2020/09/01	3300
246	399	2020/09/02	2021/02/02	4000
400	413	2021/02/03	2021/02/16	4900
414	434	2021/02/17	2020/03/09	5000
435	483	2021/03/10	2021/04/27	5048
484	500	2021/04/28	2021/05/14	5594

Table 4: Combinations of and for three scenarios: [A] To minimize the number of deaths , [B] To minimize the socio-economic cost , [C] To minimize under and

Scenario	[A]		[B]		[C]	
Level						
1	0.05	0.05	0.95	0.60	0.45	0.25
2	0.05	0.05	1.00	0.95	0.35	0.70
3	0.05	0.05	1.00	0.60	0.65	0.35
4	0.05	0.05	1.00	0.65	0.95	0.15

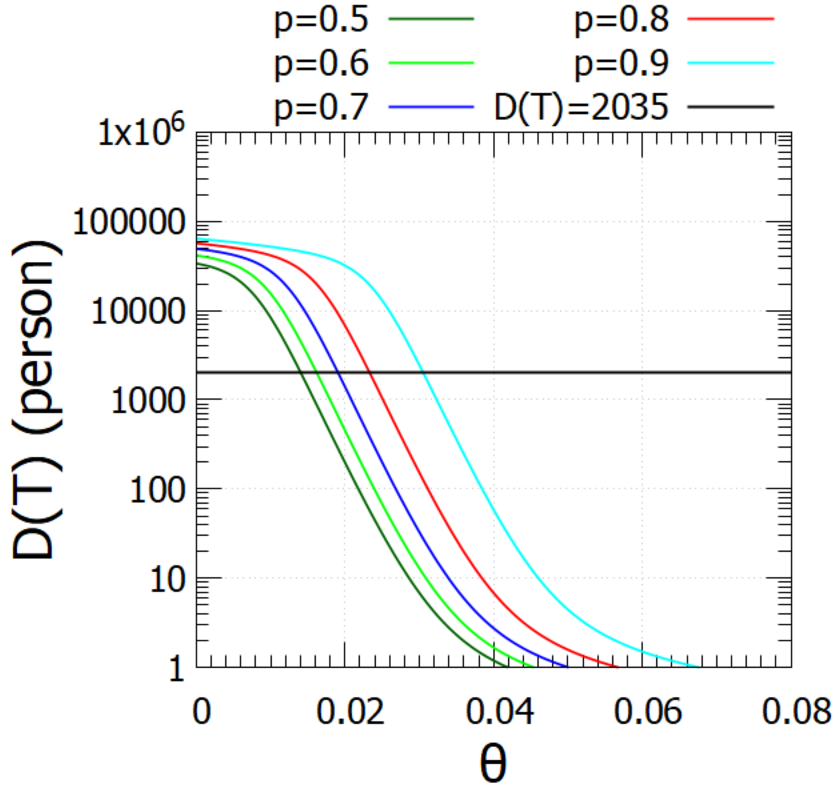


(a) The SEIIIR model: no isolation and

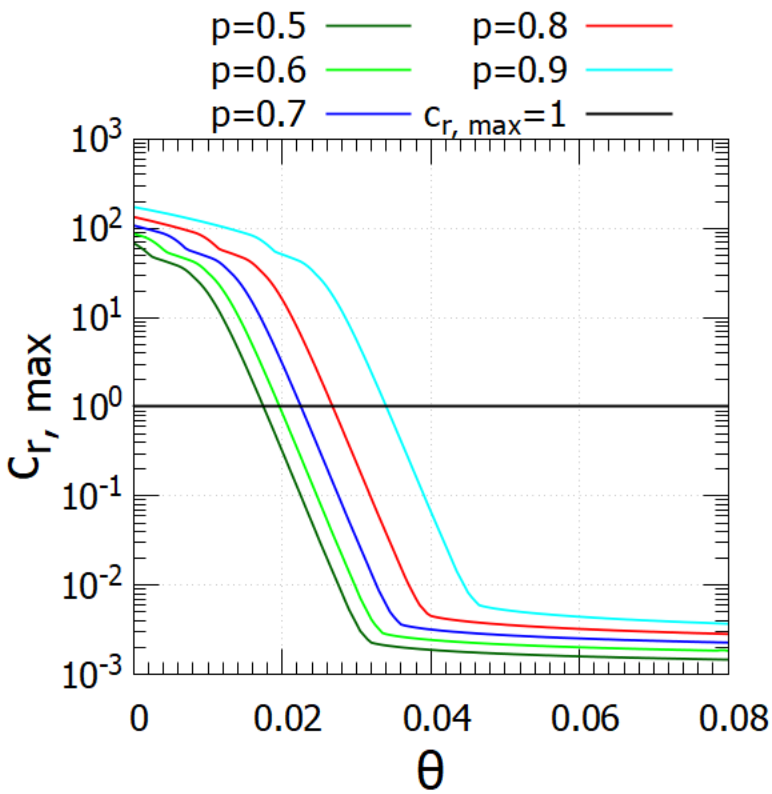


(b) The SEIIIHHHR model: and

Figure 1: The epidemic model

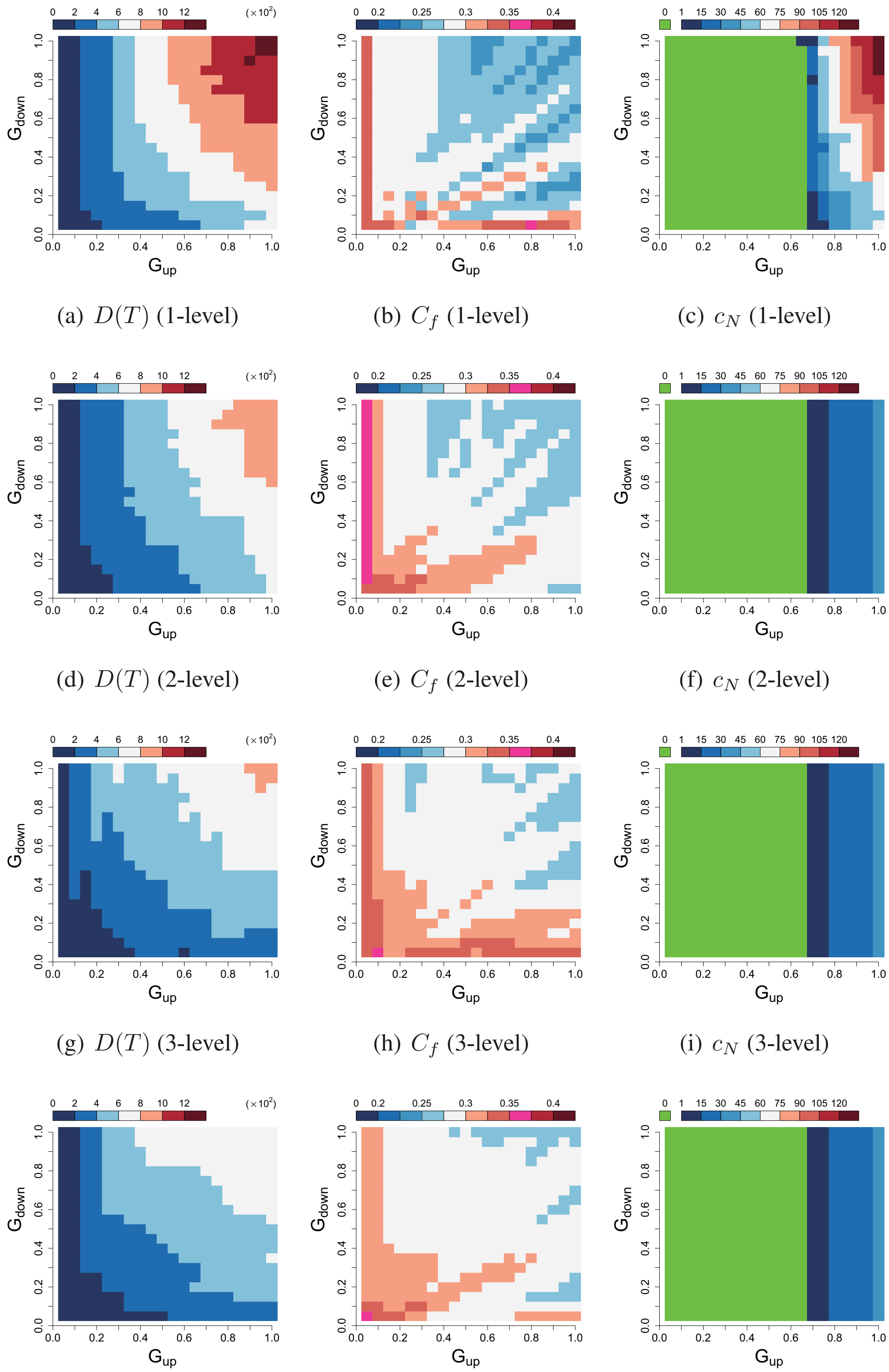


(a)



(b)

Figure 2: (a) The number of cumulative deaths by COVID-19 and (b) with different when and at any time



(a) $D(T)$ (1-level) (b) C_f (1-level) (c) c_N (1-level)

(d) $D(T)$ (2-level) (e) C_f (2-level) (f) c_N (2-level)

(g) $D(T)$ (3-level) (h) C_f (3-level) (i) c_N (3-level)

(j) $D(T)$ (4-level) (k) C_f (4-level) (l) c_N (4-level)

Figure 3: Heat maps of the cumulative number of deaths by COVID-19 $D(T)$, the socio-economic cost caused by the behavioral restrictions C_f, and the number of days in which the capacity of health care facilities is overwhelmed c_N when $p = 0.7$ and $\theta = 0$. Their units are person, no dimension, and day, respectively.

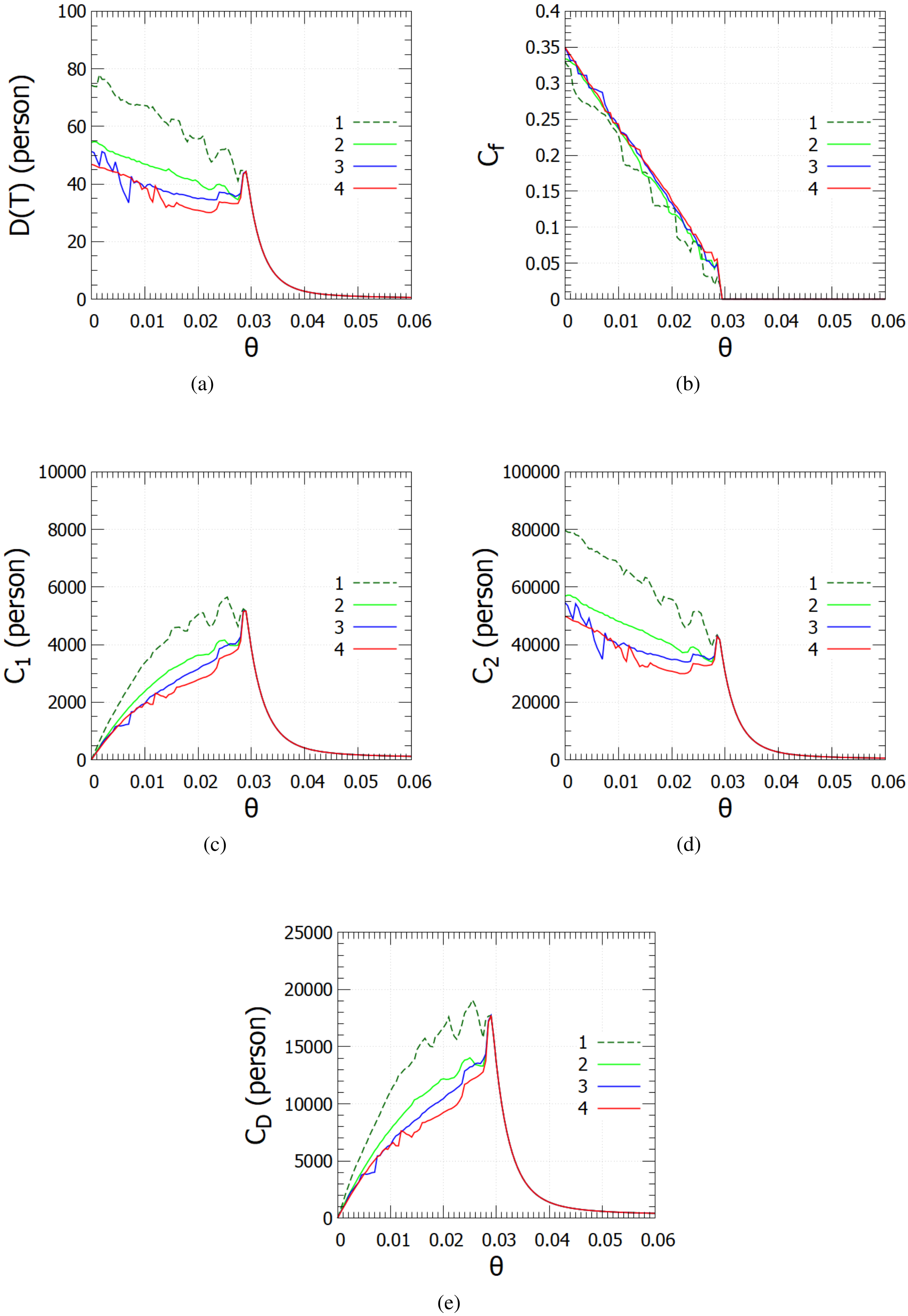


Figure 4: Sensitivity of indicators for scenario A in relation to when . , regardless of , in all feedback controls.

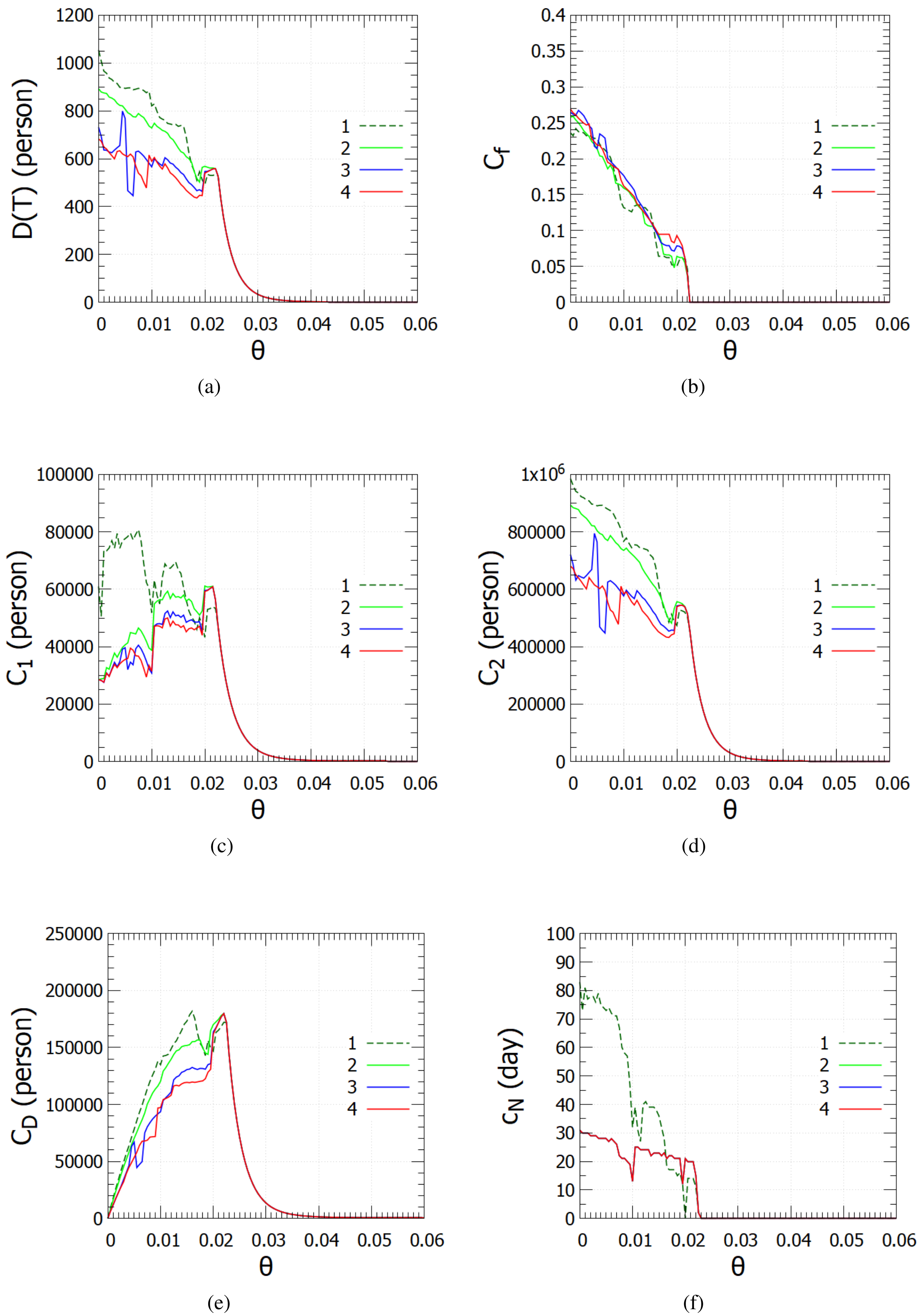
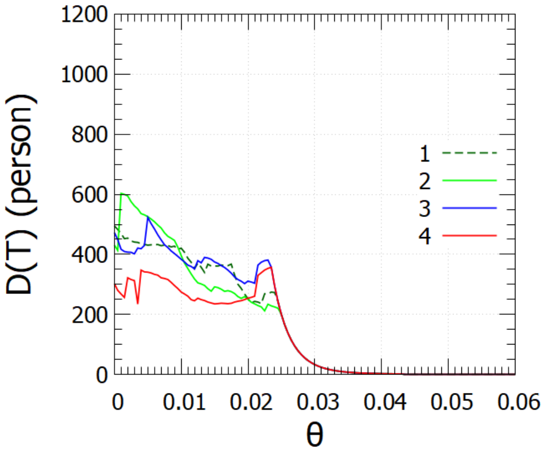
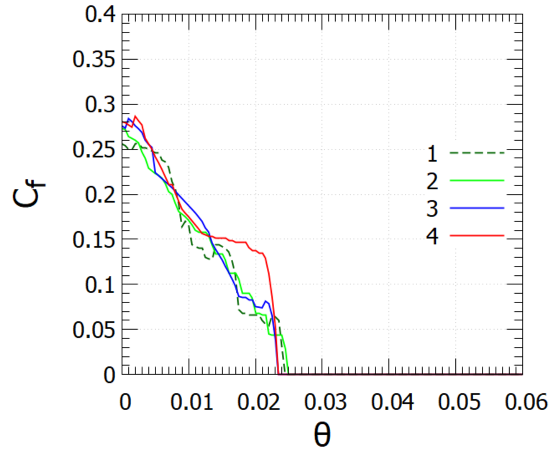


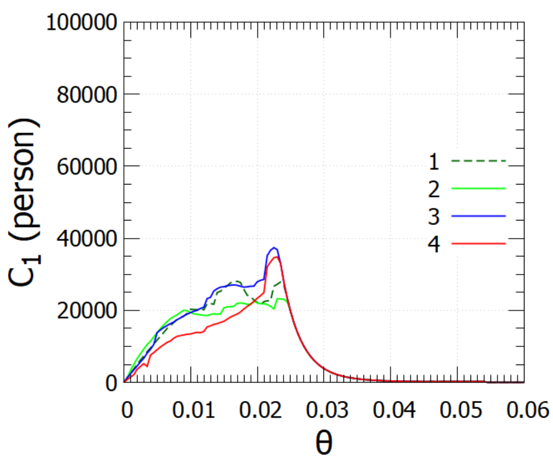
Figure 5: Sensitivity of indicators for scenario B in relation to when . The result of in the 4-level overlaps with those in the 2- and 3-level.



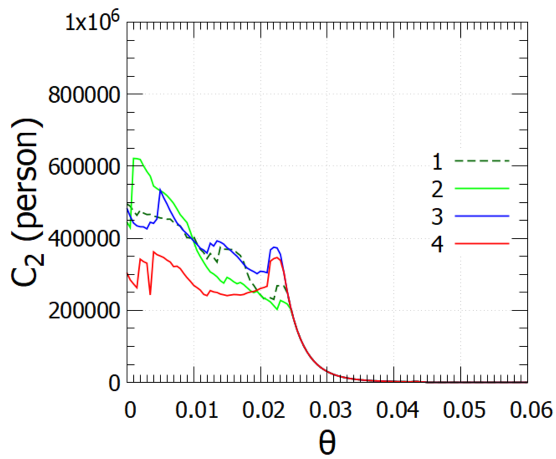
(a)



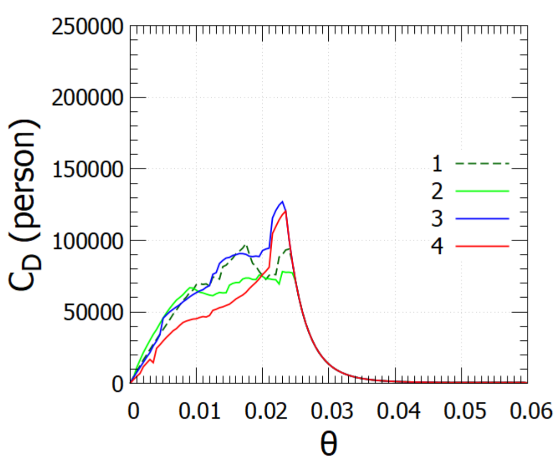
(b)



(c)



(d)



(e)

Figure 6: Sensitivity of indicators for scenario C in relation to when . , regardless of , in all feedback controls.

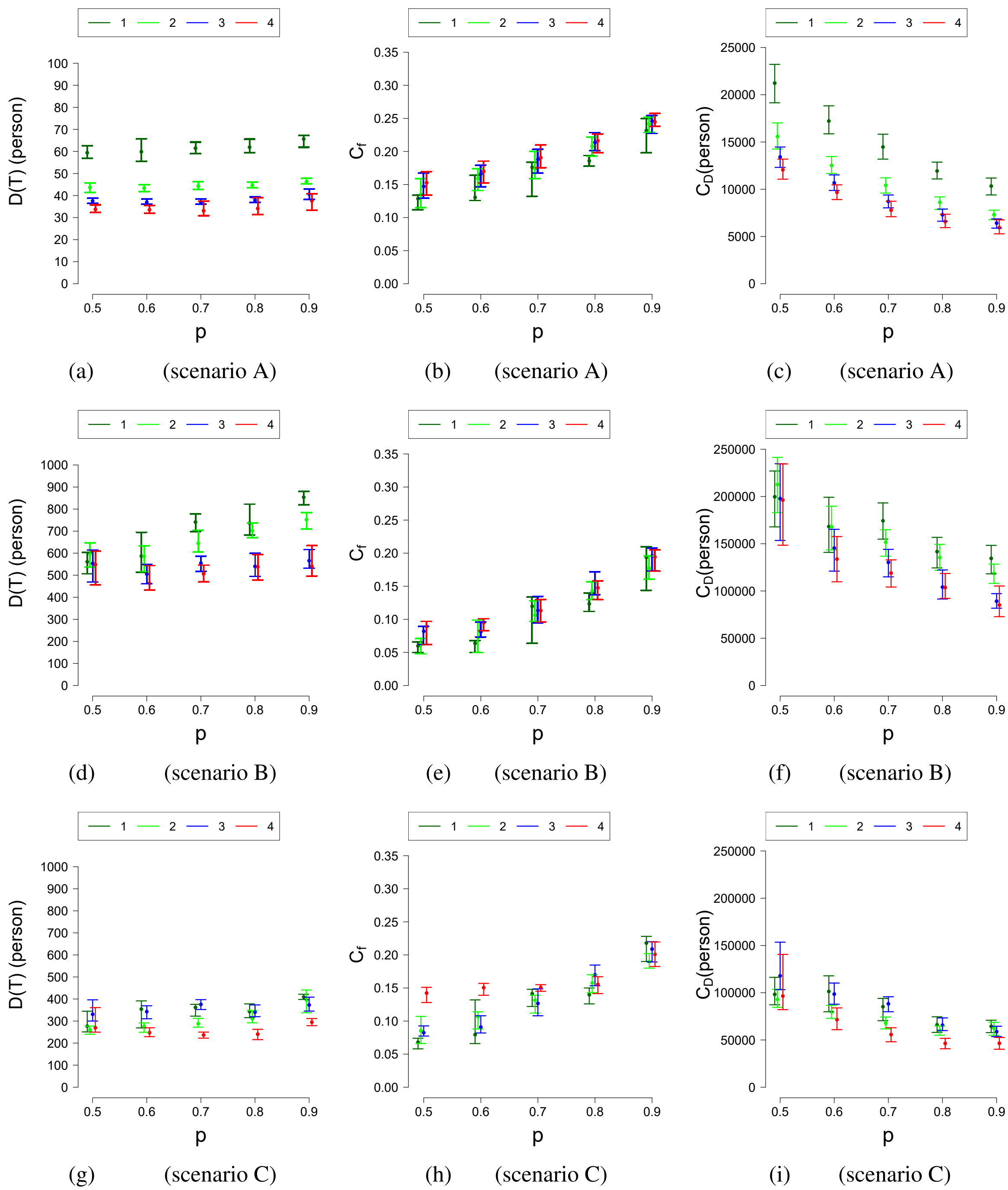


Figure 7: Sensitivity of indicators for scenario A (panels (a), (b), and (c)), B (panels (d), (e), and (f)), and C (panels (g), (h), and (i)) in relation to . Point indicates the mean value. The upper and lower bars show the maximum and minimum values, respectively.

Supplementary materials

S1. Feedback control

Table 1 shows that the change of with different levels of the feedback control. is narrowed down as the degree of behavioral restrictions changes. Figure 1 demonstrates examples of the feedback control and the number of isolated symptomatic persons at time , .

S2. The time from the onset to hospitalization

Figure 2 shows and with different time from the onset to the isolation . According to Figure 2 (a), shortening is effective in reducing . By isolating symptomatically infected persons, the spread of infection can be prevented and the number of deaths becomes smaller. Figure 2 (b) indicates is also reduced by shortening . This gure implies that the herd immunity is acquired earlier in a longer and a higher because more symptomatically infected people contribute to the spread of the infection. The early acquisition of herd immunity can make short, and however, becomes larger then.

S3. Nonlinear effect for

We did not consider the nonlinear effect for Eq.11 and assumed in the main manuscrpt, although it is a important factor for decision-making. In Figure 3, panels (a), (c),and (e) show the for , and panels (b), (d), and (f) do for . Compared with panels (b), (e), (h), and (k) in Figure 3 in the main manuscript, these results imply that the effectiveness of the multilevel feedback controls may depends on the value of . The number of combinations of and for increases, as the level of feedback controls becomes high. On the other hand, that for increases in a higher level of feedback control. The multilevel feedback controls is more effective when , whereas the bang-bang control (1-level) is better when .

S4. Sensitivity in relation to

Figure 4 shows the result of , , and for scenarios A, B, C. For scenario A shown in panels (a), (b), and (c), means of are decreasing and those of are increasing with increasing . They become smaller in a higher level of feedback controls. is always zero regardless of different . Increasing didn t enhance the risk of overwhelming the capacity of health care in this scenario, according to Panel (c) ( ).

For scenario B shown in panels (d), (e), and (f), qualitative results of and with increasing are roughly similar to scenario A. However, unlike scenario A, means of are also increasing as becomes larger. That in 1-level becomes the largest of all the levels in . The increase in the mean of in the 1-level resulted in the increase in its at .

Panels (g), (h), and (i) show the result of scenario C. It results in the increase in , and however, the difference of means of between the 4- and 2-levels is decreasing with increasing with the exception of . Similarly, that of between the 4- and 2-levels also decreases from persons at to persons at .

Table 1: The change of with different levels of the feedback control.

Level					
1	0.6	0.6			
2	0.6	0.3	0.3		
3	0.6	0.4	0.2	0.2	
4	0.6	0.3	0.15	0.15	

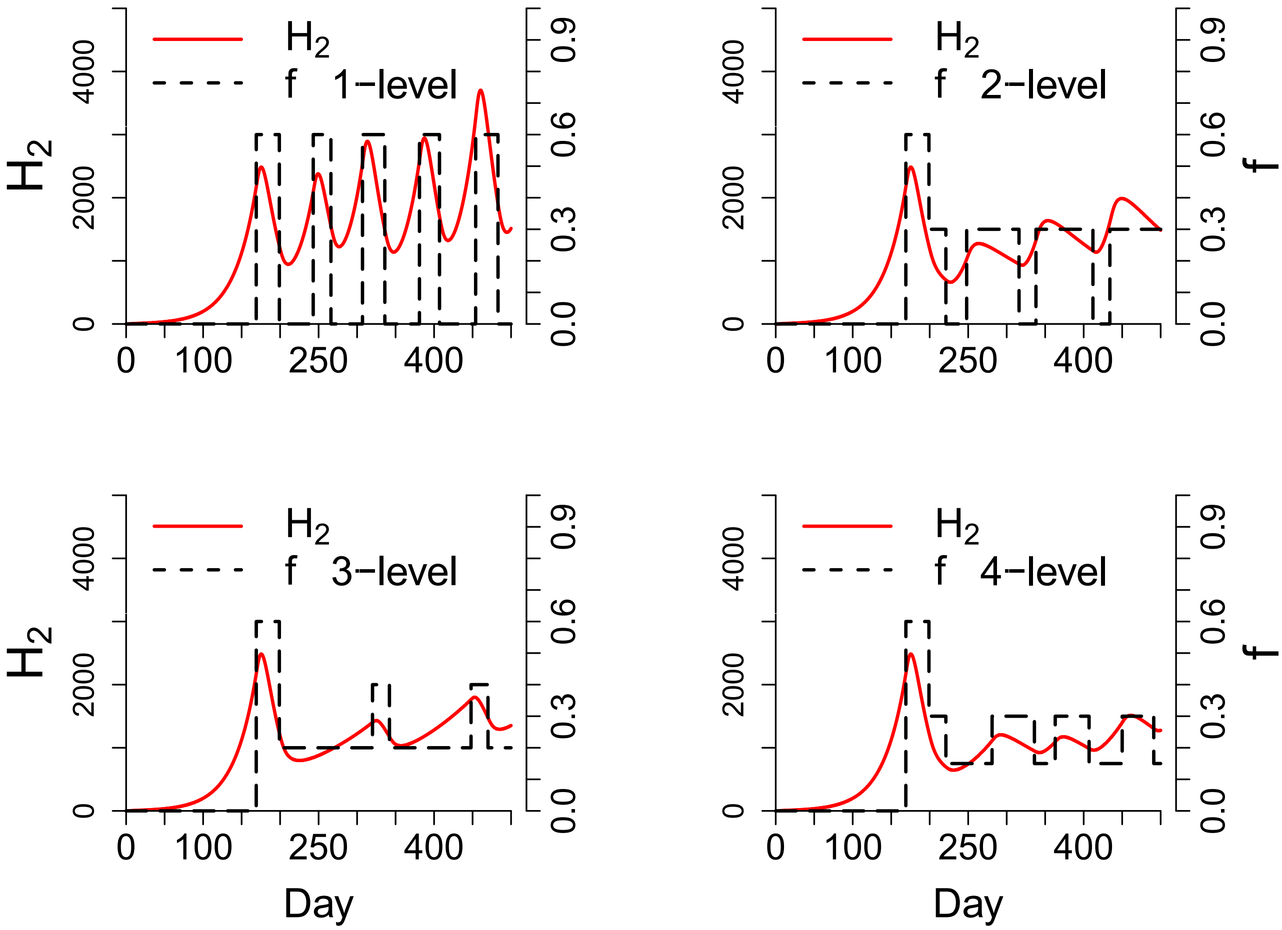
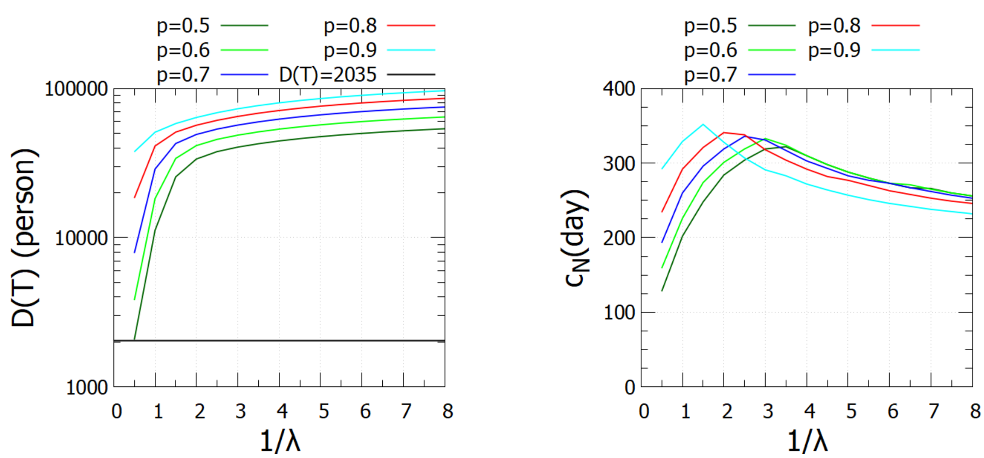
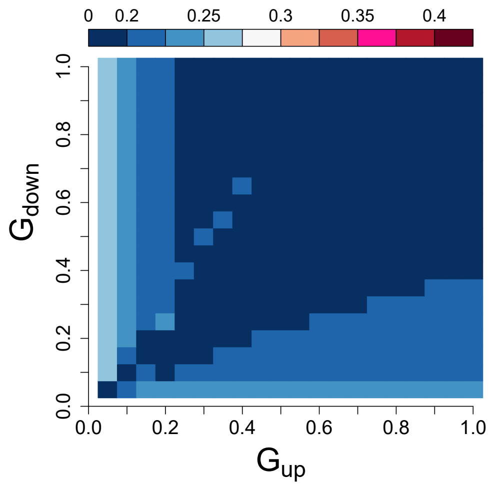


Figure 1: Dynamics of and with different levels of feedback control. ,
, , ,

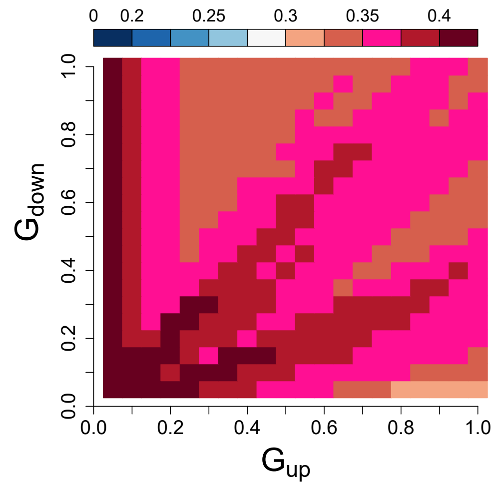


(a) (b)

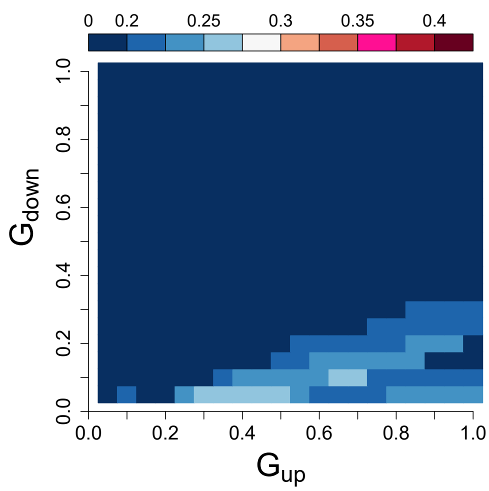
Figure 2: (a) The number of cumulative deaths by COVID-19 and (b) with different when and at any time



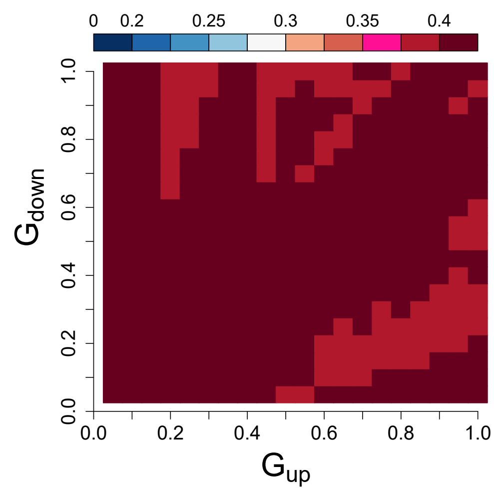
(a) 2-level ( )



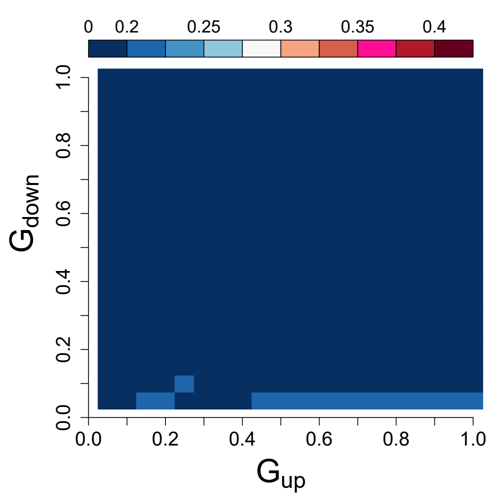
(b) 2-level ( )



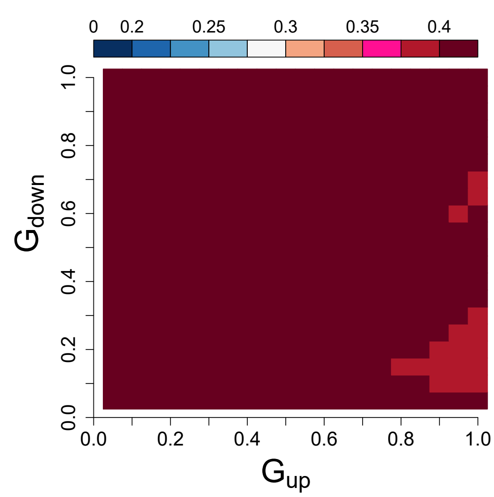
(c) 3-level ( )



(d) 3-level ( )



(e) 4-level ( )



(f) 4-level ( )

Figure 3: Heat maps of the socio-economic cost caused by the behavioral restrictions when and .

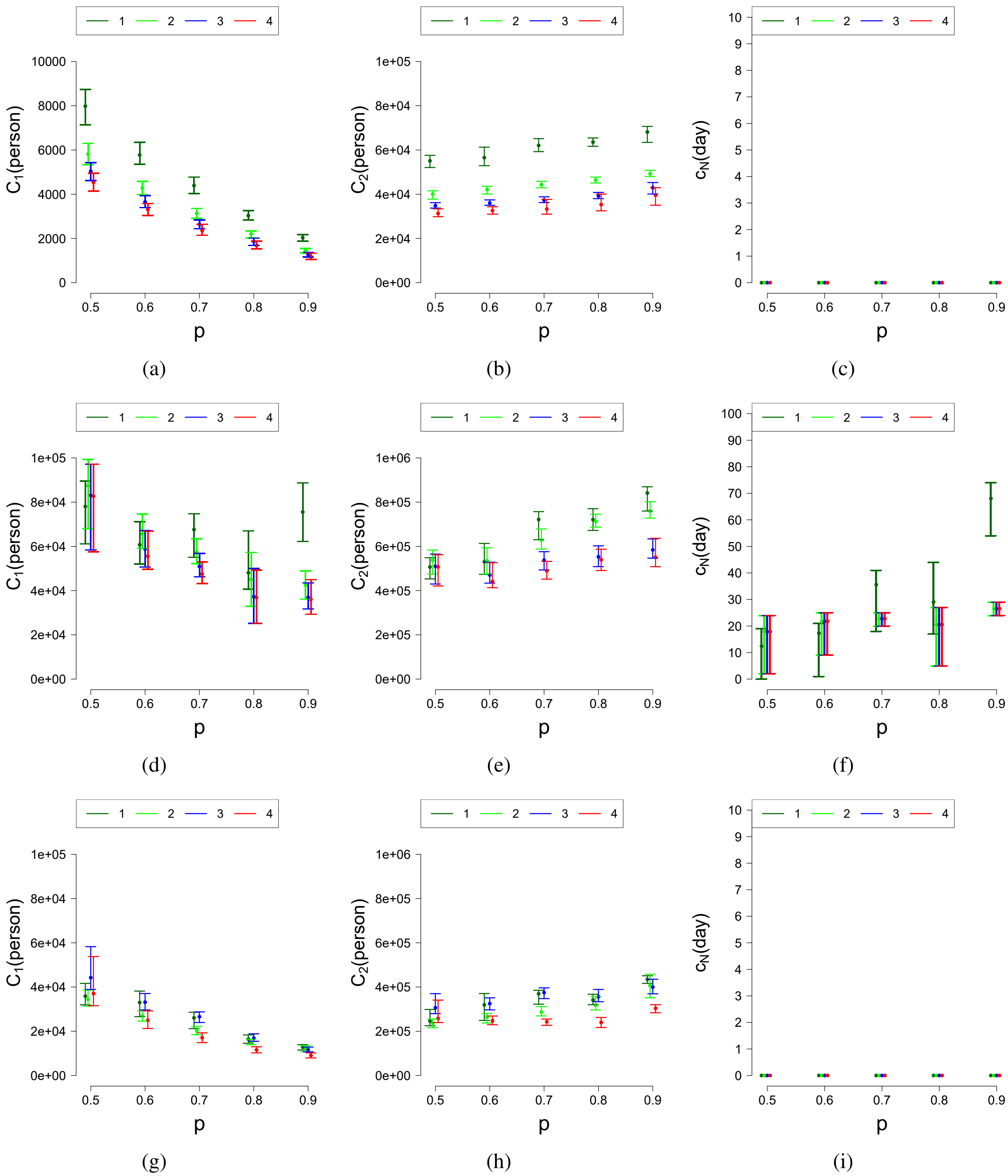


Figure 4: Sensitivity of indicators for scenario A (panels (a), (b), and (c)), B (panels (d), (e), and (f)), and C (panels (g), (h), and (i)) in relation to . The point shows the mean value. The upper and lower bars show the maximum and minimum, respectively

Chapter III

出口管理と漁獲圧制限の組み合わせによるマイワシ（*Sardinops melanostictus*）の漁獲管理の改善

Combining output control and   shing pressure limitations improves the management of the Japanese sardine *Sardinops melanostictus*

Abstract

The stock biomass of the Japanese sardine *Sardinops melanostictus* in the Paci c Ocean shows large uctuations in response to environmental variations and shing activities; this is re ected in annual catch amounts. Harvest policy in Japan determines the current allowable biological catch (ABC) by using catch data and marine resource indices. The total allowable catch (TAC) for sardine is based on the ABC, but there is a time delay from the collection and analysis of data to its implementation. We have developed a new harvest control rule (HCR) into which shing pressure limitations are incorporated. The rule calls for shing to stop when sh landings reach the TAC or the shing effort and the catchability of shing instruments reach the limit. We have validated the performance of the proposed HCR against the implementation error for shing pressure and the observation error for shing mortality. We conducted simulations using two stock recruitment relationships and three historic starting years to investigate the effects of rule initiation timing. The results indicate that this HCR could help to facilitate a recovery of the stock biomass and improve annual catches of the Japanese sardine. Especially when the observation error is large, the HCR is effective in maintaining stock biomass, increasing the average annual catch, and stabilizing the overall annual catch.

Keywords: Japanese sardine; Harvest control rule; Allowable biological catch; Total allowable catch; Fishing pressure

1 Introduction

Forage sh such as sardines, anchovies, and herring are used for sh oil and meal as well as direct human consumption. Konar et al. [19] assessed the values of forage sh resources in terms of the environment, society, using qualitative and quantitative methods. They estimated the global economic bene t provided by forage sh to be 18.7 billion USD per annum although they stated that their data were limited. The abundance of forage sh uctuates greatly under the effect of environmental conditions, and the management has been an important topic [3, 4, 9].

The stock biomass of the Japanese sardine *Sardinops melanostictus* in the Paci c Ocean reached its peak in the 1980s and was estimated to be over million tons in 1987 as shown in Figure 1, with data obtained from the Japan Fisheries Research and Education Agency (FRA) [14]. After this peak, the biomass declined to below million tons in the 1990s. This was in part because the sh aged 0 years had a small population, which was due to the environmental conditions at the time [13, 23, 28, 31]. The recruit per spawning (RPS) was extremely low from 1988 to 1991 despite the stock biomass being large (Figure 1). Nishikawa [23] noted that the spawning ground clearly shifted and the spawning season was extended in the low stock period from 1995 to 2010, when compared with the high stock period. Moreover, the stock abundance did not recover from the high shing mortality in the early 1990s, and consequently, the stock biomass was approximately million tons in the 2000s. According to Katsukawa [17], controlled shing could have prevented this stock collapse.

Fishing regulations are classi ed into three parts: technical measures, input controls, and output controls [8]. Hereafter, we refer to the intensity of shing which is determined by technical measures and input controls as shing pressure. The output control, which establishes a catch limit for a speci ed period, has been adopted as the harvest policy for the Japanese sardine. The total allowable catch (TAC) was legislated in 1996 in Japan and is based on the allowable biological catch (ABC). Previous studies have identi ed the necessity of appropriate shery management and proposed improved harvest control rules (HCRs) [11, 16, 32]. The current harvest policy in Japan determines the ABC to achieve a maximum sustainable yield (MSY) through feedback control based on the amount of spawning stock biomass (SSB) [35]. However, the SSB is forecasted using stock assessments obtained two years prior in the management of the Japanese sardine. The time delay for the ABC calculation is recognized as a problem in ABC decision making [2, 36], as the forecast may not actually be suitable based on the most recent environmental conditions.

In the present study, we aimed to develop an effective HCR to achieve the following three objectives de ned by FRA [15].

1. Take uncertainty into consideration and conserve the stock biomass to avoid aggravating the reproduction ability of resources.
2. Maximize the long-term (10-100 years) average catch.
3. Minimize annual catch uctuations.

We have developed the new HCR by combining the output control and shing pressure limitations. We ran numerical simulations, considering the time delay from the stock assessment to the implementation of the calculated ABC. To evaluate the performance, we observed the dynamics of the stock biomass, the annual catch, and the average annual variability in catch.

2 Methods

2.1 Prerequisite

This section describes the population dynamics of the Japanese sardine, the detail of our new HCR, and the design of numerical simulations. In simulations, we compared the performance of our proposed HCR with the current rule. Hereafter, ”historical” data refer to the historical stock biomass, annual catch, and shing mortality coef cients estimated by the FRA, while ”simulated” values refer to the values obtained by changing the HCR retrospectively. In this study and are the abundance and the shing mortality of the Japanese sardine at age in year , respectively. In addition, and denote their stock biomass and SSB, respectively, in year . Hereafter, we distinguished between their estimated, forecasted, and true values in the simulation, using the asterisk, prime, and tilde, respectively. For example, , , and mean the estimated stock abundance, the forecasted SSB, and the true shing mortality, respectively. Unmarked variables represent estimated, forecasted, or true values. Note that we do not know the true values but use their estimated and forecasted values when we consider the dynamics of stock management in the simulation. Throughout this article, the starting point of a year is de ned as being immediately after the spawning season (spring). Variables and parameters are shown in Table 1.

2.2 Simulation

2.2.1 General approach

Figure 3 illustrates the fishery management in the simulation. The flow in one time step is as follows:

1. Plan regulates fishing based on HCRs.
2. Doing corresponds to fish landings, and the annual catch and the true fishing mortality are determined.
3. Estimation corresponds to the stock assessment. The estimated stock abundance and fishing mortality are obtained.
4. Forecast calculates the stock abundance and fishing mortality in the future.
5. Calculation determines the ABC.
6. Update renews the true value of the stock abundance and the time step in the simulation.

2.2.2 Population dynamics

The population dynamics are described as follows:

$$N_{a+1,t+1} = N_{a,t} \exp\left(-M - F_{a,t}\right) \qquad (0 \leq a \leq 3) \tag{1}$$

$$N_{5,t+1} = N_{\ ,t} \exp\left(-M - F_{\ ,t}\right) + N_{5,t} \exp\left(-M - F_{5,t}\right) \tag{2}$$

where M is the natural mortality; $N_{5,t}$ and $F_{5,t}$ are the abundance in number and the fishing mortality coefficient at ≥ 5 years of age in year t, respectively [14]. Eqs.1 and 2 are utilized when forecasted values are calculated by using $N^*_{a,t}$ and $F^*_{a,t}$. Furthermore, we assume that the true stock abundance is updated by these equations with $\tilde{N}_{a,t}$ and $\tilde{F}_{a,t}$ in the simulation.

The stock biomass in year t is the total weight for all fish, including all ages, and is calculated as follows:

$$B_t = \sum_{a=0}^{5} w_{a,t} N_{a,t} \tag{3}$$

where $w_{a,t}$ is the average weight at age a in year t. The SSB in year t is the total weight for all spawners and is calculated as follows:

$$S_t = \sum_{a=1}^{5} m_a w_{a,t} N_{a,t} \tag{4}$$

where m_a is the maturity rate at age a. By definition, $\tilde{F}_{a,t}$ satisfies the following equation:

$$C_{a,t} = \tilde{N}_{a,t} \left(1 - \exp\left(-\tilde{F}_{a,t}\right)\right) \exp\left(-\frac{M}{2}\right) \tag{5}$$

where $C_{a,t}$ is the (true) catch-in-number at age a in year t.

2.2.3 Current HCR

The current Japanese harvest policy for the Japanese sardine is based on the output control, which establishes the upper limit of the annual catch. It uses data for the annual catch and marine resource indices in year t to estimate the stock abundance and fishing mortality in year t. The ABC in year t, denoted by ABC_t, is forecasted two years prior, namely in year $t-2$. In other words, even though the current true value is unknown, we need to forecast the stock abundance in year $t+1$ and in $t+2$ at the time of year t, in order to determine the ABC in year $t+2$ by using Eqs.1 and 2. The fishing mortality coefficient in year $t+1$ is assumed to be the mean of the previous five years and is then given by:

$$F'_{a,t+1} = \frac{1}{5} \sum_{i=0} F^*_{a,t-i} \tag{6}$$

When the abundance of the fish at age 0 in year $t + j$ ($j = 1, 2$) is forecasted, the RPS is assumed to be the median of the previous data from the past 30 years [14]. In our simulation, we assume the forecasted RPS is $24.0(kg^{-1})$, according to the historical data. The average weight of fish at age a in year $t + j$ is assumed to be the same as that in year t, namely, $w_{a,t+j} = w_{a,t}$.

$$S'_{t+j} = \sum_{a=1}^{5} m_a w_{a,t} N'_{a,t+j} \qquad (j = 1, 2) \tag{7}$$

The ABC in year is determined using the feedback control of and the forecasted with Eqs.8 and 9, as follows:

(if)

(if) (8)

(if)

where , , and denote the reference point of SSB for shery closure, the limit reference point of SSB, and the shing pressure achieving MSY, respectively [14, 15]. We then obtain the following:

(9)

It is assumed that .

We de ne as the annual catch in year , and it corresponds to the TAC in year , denoted by , under the current policy for the management of the Japanese sardine.

(10)

We assume in the simulation. In the simulation process of the stock assessment, it is necessary to estimate the shing mortality. The true shing mortality at age in year , , is determined implicitly so that it can satisfy Eq.11 (see Appendix A).

(11)

2.2.4 New HCR

We propose a new HCR under which shing is suspended in the rest of the year when sh landings reach the TAC or the shing effort and the catchability of shing instruments reach the limit. The new HCR prepares the upper limit of the operating time, the number and size of vessels, the gear type, and mesh sizes for the sardine shery as well as the TAC, at the beginning of the management period. The manager monitors sh landings and the operation record and stops shing when either of them is exhausted. For the numerical simulation, the upper limit of the shing effort and catchability is converted into that of the shing pressure denoted by . We de ne as the expected yield when the shing pressure reaches in year . By operating in year , the is determined as follows:

— (12)

(13)

where is the limit of shing pressure disturbed by the implementation error; is an independent random number governed by the normal distribution , in which the average of is 1. We then assume .

Our proposed HCR stops shing when either or reaches their limit. In other words, under the new rule, is determined by

(14)

remains constant during the management period regardless of the environmental variation and the status of the stock.

2.2.5 Stock assessment

The stock abundance and shing mortality are estimated from the annual catch and the marine resource indices in reality. In simulation processes of the current and new rules, the stock assessment is reproduced by utilizing the estimated shing mortality and the annual catch in number. The estimated shing mortality, , is determined as follows:

(if)
(if) (15)

where is an independent random number governed by the normal distribution . We consider the observation error that occurs when the shing mortality data are collected every year. is estimated in the simulation process by using , , and . The equation to nd is derived from Eq.5:

(16)

When , we assume .

2.3 Study design

2.3.1 Stock Recruitment Relationship scenarios

Figure 2 demonstrates the SRR and implies that the productivity was high from 1976 to 1987 and decreased since then. Many previous studies pointed out that a regime shift occurred in the late 1980s in the Paci c Ocean [20, 33]. The change in the climate and the ocean in uenced the recruitment of the Japanese sardine. Thus, we divided historical data into two ages: the high productivity period (1976-1987) and the low productivity period (1988-2019). In addition, we prepared two different scenarios of SRRs: scenario A and scenario B.

Scenario A uses three representative SRR models such as the Beverton Holt (BH), Ricker (RI), and Hockey Stick (HS) models by tting them into the historical data (see Appendix B). Using the Akaike Information Criterion (AIC), we selected appropriate models and parameters to reproduce the plausible SRR in our simulation. Table 3 shows the AIC and parameters obtained by tting. We adopted the RI model (Eq.17) for periods of high and low productivity with different parameters.

(17)

The parameters are during the high productivity period and during the low productivity period, respectively (Fig.4 (a)).

Scenario B uses the method that Kawai et al. [18] proposed for the simulation of the SRR of the chub mackerel. This method is based on the BH model and the coef cient is assumed to be a time-dependent variable (Eq.18).

(18)

where is the magnitude of the density effect. We interpreted the regime shift as the change in the carrying capacity of the recruitment of Japanese sardine . We assumed that during the high productivity period and during the low productivity period, respectively. Figure 4 (b) shows the change of and over time. The detail of the method is described in the Appendix C.

In the supplementary le, we assumed and explored the three productivity ages: the high productivity period (1976-1987), the low productivity period (1988-1991), and the middle productivity period (1992-2019).

2.3.2 Design

We rst compared the historical data to the results obtained from our proposed HCR and the current rule without implementation and observation errors ( ). Simulations were conducted in cases of the current rule and our new HCR for and . The following relationship is given instead of Eq.15:

(if)
(19)
(if)

Next, we conducted the simulation in which the implementation error and observation error of the shing mortality were incorporated. By incorporating these errors in the simulation, the effectiveness of the new HCR is validated. We examined the sensitivity of the current rule and our new HCRs with different from 0.1 to 1.0. We considered four different cases of error: [#1] , [#2] , [#3] , and [#4] . Table 4 shows gures and the corresponding scenarios and parameters.

Simulations started in three different historic years: 1976, 1996, and 2005. Fishing data were available from 1976 onward. Although the biomass and the annual catch were small in the 1990s, the historical RPS was comparably high in 1996 (Figure 1). In 2005, the stock biomass was the smallest in the historical data (Figure 1). The stock biomass, the annual catch, and the shing mortality in the rst and second year of the simulation are the same as those of the historical data. The simulation was carried out 1000 times for each combination of errors and starting year . Note that the current rule corresponds to the case without input regulation, i.e., when is suf ciently large. The maturity rate, average weight, and natural mortality data were obtained from FRA [14]. The maturity rate is assumed to be constant from 1976 to 2019 (Table 2). Let for any age and time.

2.3.3 Indicators

The performance was evaluated using three measures: the average stock biomass, , the average annual catch, , and the average annual variability (AAV). The and are the 10-year means from 2010 to 2019.

$$— \quad (20)$$

$$— \quad (21)$$

The AAV is given as:

$$——————— \quad (22)$$

where is the starting year of the simulation. The calculation starts two years later because the historical data are used in the simulation until year .

3 Results

We applied the proposed HCR and the current rule in simulations using two different SRRs and three starting years. The changes in stock biomass and annual catch without implementation and observation errors are shown in Figure 5. The expected yield is often adopted as the is larger, and the simulated result for a higher is similar to that of the current rule.

Management with the control rules started in 1976, as seen in Figure 5 (a) and (b). The qualitative behaviors of the stock biomass and the annual catch for scenario A were similar to scenario B during the high productivity period from 1976 to 1987. During the period, annual catches with the simulated current rule greatly varied for both scenarios. They exceeded 4 million tons in 1981 and 1982 and were reduced to no more than 2 million tons in 1986. For scenario B, the simulated annual catch with the new HCR for was limited, and its maximum was million tons in 1986 (Figure 5 (b)). The stock biomass in 1986 was the largest during the management period at 25.5 million tons (Figure 5 (a)). The simulation for showed an intermediate result. For both scenarios, the reduction in simulated annual catches in the early 1990s helped to prevent the collapse of stock biomass, when compared with the historical data. After the middle 1990s, the simulated biomass became almost stable in scenario A. In contrast, in scenario B, it was reduced until 2006 and recovered thereafter.

The results from the cases in which the stock biomass was very small in the starting years are shown in Figure 5 (c-f). Starting in 1996, the new HCR reduced the simulated annual catches when compared with that of the historical data from 1998 (Figure 5 (d)). However, Figure 5 (c) and (d) imply that keeping the stock biomass above a certain level contributed to its recovery. Scenario A showed a quick recovery of the stock biomass and the annual catch because of its SRR, whereas the increases for scenario B were gradual. The variation over time in annual catches with the current rule was larger than that for in both scenarios.

For the simulation that started in 2005, shing was banned under the new HCR and the current rule in 2007 and 2008 (Figure 5 (e), and (f)). The annual catches in 2009 were very small with the new and current rules (3.0 kilotons for scenario A and 0.75 kilotons for scenario B). However, the shery closure contributed to the recovery of the stock biomass, when compared with the historical data.

Next, we conducted simulations for our proposed HCR and the current rule including the implementation and observation errors. The sensitivity of the average simulated biomass and annual catches from 2010 to 2019 with different are shown in Figures 6 and 7, as well as the results with the current rule and the historical data. The upper and lower bars indicate the 97.5 and 2.5 percentiles of the results, respectively. The qualitative results for scenario B were like those for scenario A, whereas its quantitative values of and were smaller because of the SRR. Moreover, for starting year 2005, they were smaller when compared with the other starting years.

The results of case [#1] for scenario A are shown in Figure 6 (a), (b), and (c). The implementation and observation errors of this case are the lowest in all cases. Accordingly, differences between the upper and lower bars of and were the smallest of the four different cases. For case [#2], the differences between the upper and lower bars were larger with a lower because the was often adopted and the implementation error was large (Figure 6 (d-f)). For cases [#1] and [#2], means of and approached stability in (Figure 6 (a-f)). For cases [#3] and [#4] with a large observation error, the shape of the mean of seemed convex, whereas is decreasing with different (Figure 6 (g-l)). In , and with the new HCR were improved when compared to the current rule. Means of and with the new HCR at were larger than those with the current rule regardless of the starting year. However, when the starting year was 2005, the difference of between the new HCR and the current rule was small. For example, the mean of at was 457 kiloton and that with the current rule was 449 kiloton for case [#3] (Figure 6 (i)).

Figure 7 shows the performance of our proposed HCR for scenario B. The maximum values of the mean of for scenario B were smaller than those for scenario A because of different SRRs. They 438 kilotons starting from 1976 ( ), 435 kilotons from 1996 ( ), and 368 kilotons from 2005 ( ), respectively (Figure 7 (a-c)). When compared with the results for the simulated current rule, the means of and improved with the new HCR. The shape of the mean for also seemed convex and its peak was reached in for all the starting years, whereas means of decreased with increasing . The observation error is large in cases [#3] and [#4], and their results are shown in Figure 7 (g-l). The variance of and became larger as increased, and was maximized with the simulated current rule.

The AAV is shown in Figure 8. Qualitative results were similar for both scenarios although their quantitative results were different. The mean and the difference between the upper and lower bars were the largest when the starting year is 2005 for both scenarios. When the implementation error was large, the mean of AAV is large at a lower (Figure 8 ((c), (d), (g), and (h)). In addition, when the observation error was large, the mean of AAV is large at a higher (Figure 8 (e), (f), (g), and (h)). For cases [#1] and [#3] for both scenarios, the AAV gradually increased and was nearly stabilized (Figure 8 (a), (b), (e), and (f)). For cases [#2] and [#4] for both scenarios, the mean of the AAV is minimized at or (Figure 8 (c), (d), (g), and (h)). In . the mean for case [#2] increased and was stabilized, whereas that for case [#4] was increasing in a higher .

4 Discussion

We proposed a new HCR and conducted numerical simulations using two SRR scenarios and three historic starting years. In the simulation, we distinguished between estimated, forecasted, and true values to consider the time delay from the ABC calculation to its execution. Our HCR calls for shing to stop when sh landings reach the TAC or the shing effort and the catchability of shing instruments reach the limit. The results showed that the new HCR could satisfy the management objectives for the Japanese sardine. They indicated that the new rule could have been used to stabilize the annual catch as well as recover previous stock biomass and improve the average annual catches. Bastardie et al. [1] evaluated a management plan that combined the total allowable effort (TAE) with TAC and argued that shing control regulations based on the TAC provided an ef cient strategy for Baltic cod stock recovery. The present study suggests that this combination would also be effective for the management of the small pelagic fish such as the Japanese sardine stocks.

An important lesson implied from Figure 5 is that the stock biomass should be recovered and maintained to some extent for sustainable fishery management. The early reduction of the annual catch in the low RPS age contributed to the recovery of the biomass. The ABC determined by the current harvest policy was implemented in Japan in 1996, when the United Nations Convention on the Law of the Sea [30] came into effect. Its aim was to control fisheries and maintain a relatively higher stock biomass. Ichinokawa et al. [12] identified the great potential of Japanese fisheries to exhibit quick recoveries and therefore increase their yields if they adjust fishing intensities to appropriate levels. Suda et al. [27] argued that the sardine stock decline in the 1990s could not have been halted by catch regulations; however, the slope of the decline could have been mitigated by a reduction in fishing mortality, as shown by their simulation. Our results suggest the importance of maintaining the stock biomass and were thus in agreement with previous findings.

We considered the implementation error of the fishing pressure and the observation error of the fishing mortality. The results indicated that the fluctuations in average stock biomass and annual catch could be small if these errors were small. Using a new HCR where could effectively help to address the uncertainty, especially when the observation error was large (Figures 6 and 7). These results imply that fishing pressure limitations can prevent overfishing if the stock abundance or the TAC is overestimated. The limitations contribute to enhance and stabilize the annual catch in a long run. The simulations were also conducted with three different starting years to investigate when the new HCR should be initiated. The performance of the simulation was good for the new HCR with the earlier starting years, 1976 and 1996. The results from 2005 showed the smallest average stock biomass and annual catch among the three different cases.

There are some limitations. We assumed Eqs.1 and 2 could describe the population dynamics in the simulation. We also assumed the natural mortality is constant; however, real natural mortality can also be a function of predation [29], density dependence [26], and body length [6]. We also did not take into account annual changes in age-specific body maturity rate. Limiting the fishing effort and catchability is the essence of the new HCR, but we did not discuss how they should be adjusted so that can be optimized. This study focused on single species management, and consequently, we have not considered the influence of predators and competitors on the Japanese sardine. Previous studies have proposed fishing management strategies that consider the dynamics of the ecosystem [21, 25]. Matsuda and Katsukawa [21] proposed a switching fishery that depends on the abundance of the dominant sh species, focusing on three competitive pelagic species. Punt et al. [25] developed a model of intermediate complexity for ecosystem assessment model including the Paci c sardine (*Sardinops sagax*) and evaluated the impacts of variable forage availability on adult predator reproductive success and survival.

Both the current rule and our new HCR use only the abundance of the target sh species. The virtual population analysis used in Japan s current harvest policy utilizes other marine resource indices to estimate stock abundance as well as shing mortality [10, 14]. We utilized some parameters from reports of FRA, such as biological reference points and shing mortalities at different ages to achieve the MSY, and these values were not unique or trivial [16]. The new HCR assumes that remains constant during the management period, but it is also thought that is determined by the state of the resource [34].

Our proposed HCR worked well in the simulation; however, it does not always mean the rule is accepted by stakeholders. Matsuda et al. [22] identi ed that the TAC of the Japanese sardine was often much larger than the ABC in the 1990s and 2000s. In current practice in Japan, a target shing mortality is used in the ABC decision rule and is set to be smaller than the shing mortality achieving the MSY. However, the target shing mortality is only a means by which to calculate the TAC and not a means of regulating the shing pressure before the TAC is reached. In addition to the TAC, there are other sh species for which the TAE is set in Japan, but there are no penalties when this is exceeded. This situation implies that stakeholders such as shers, scientists, and political leaders have not reached a consensus on an optimal management system for sustainable sheries.

5 Conclusions

In the marine food web, forage sh transfer energy from lower trophic levels to valued predators [7, 24]. The stock biomass of the Japanese sardine in the Paci c Ocean is important for Japanese sheries and society and shows large uctuations in response to environmental variations and shing activities. We developed a new HCR to provide a stable and sustainable annual catch and validated it under two different SRR scenarios caused by the environmental variation. We found that considering the output control and shing pressure limitations contributed to stock conservation and annual catch improvements. This rule is a feasible solution to achieve objectives of shing management established by the FRA. Future work will incorporate decision making among stakeholders into the management framework as well as developing the HCR based on shery science.

Appendix A

According to FRA [14], the selection probability at different ages varies from year to year. The range of estimated shing mortality is assumed to be [14]. We assumed that this range holds for in our simulations. When in the simulation, shing mortalities at different ages are generated at random unless otherwise noted. We generate independent random numbers ( ) from a uniform distribution between 0 to 1. We then determine a real number such that satis es Eqs.A.1 and A.2.

( ) (A.1)

— (A.2)

Finally, we can obtain . If exceeds by Eq.15 in the simulation, we assume .

Appendix B

To reproduce the plausible recruitment, we used the BH model (Eq.B.1), RI model (Eq.B.2), and HS model. However, for simplicity, we utilized a proxy for the HS model (Eq.B.3) which Froese [5] proposed.

——— (B.1)

(B.2)

—— (B.3)

Data for the SSB and recruitment were tted using the least square method, and obtained parameters are shown in Table 3.

Appendix C

The method Kawai et al. [18] proposed is based on the Beverton Holt model (Eq.C.1). We tted the equation into historical data for periods of high (1976-1987) and low (1988-2019) productivity, respectively. We used the least square method between the historical data and the function value and estimated parameters: for the high productivity period and for the low productivity period. We then xed the values of and made a time-dependent variable. denotes in year and is calculated as follows:

— (C.1)

Using two estimated s and the historical SSB and recruitment from 1976 to 2019, we determined during the management period (Fig.4 (b)). By substituting into Eq.C.1, the recruitment in the simulation is determined.

References

[1] Bastardie, F., Vinther, M., Nielsen, J.R., Ulrich, C., Paulsen, M.S., 2010. Stock-based vs. eet-based evaluation of the multi-annual management plan for the cod stocks in the Baltic Sea. Fisheries Research 101, 188-202.

[2] Brown, C.J., Fulton, E.A., Possingham, H.P., Richardson, A.J., 2012. How long can sheries management delay action in response to ecosystem and climate change? Ecological Applications 22, 298-310.

[3] Engelhard, G.H., Peck, M.A., Rindorf, A., C. Smout, S., van Deurs, M., Raab, K., Andersen, K.H., Garthe, S., Lauerburg, R.A., Scott, F., Brunel, T., Aarts, G., van Kooten, T., Dickey-Collas, M., 2013. Forage sh, their sheries, and their predators: who drives whom? ICES Journal of Marine Science 71, 90–104.

[4] Essington, T.E., Moriarty, P.E., Froehlich, H.E., Hodgson, E.E., Koehn, L.E., Oken, K.L., Siple, M.C., Stawitz, C.C., 2015. Fishing ampli es forage sh population collapses. Proceedings of the National Academy of Sciences 112, 6648–6652.

[5] Froese, R., 2008. The continuous smooth hockey stick: a newly proposed spawner-recruitment model. Journal of Applied Ichthyology 24, 703–704.

[6] Gislason, H., Daan, N., Rice, J.C., Pope, J.G., 2010. Size, growth, temperature and the natural mortality of marine sh. Fish and Fisheries 11, 149-158.

[7] Hannesson, R., Herrick, S.F., 2010. The value of paci c sardine as forage sh. Marine Policy 34, 935-942.

[8] Hilborn, R., Maguire, J.J., Parma, A.M., Rosenberg, A.A., 2001. The Precautionary Approach and risk management: can they increase the probability of successes in shery management? Canadian Journal of Fisheries and Aquatic Sciences 58, 99–107.

[9] Hilborn, R., Amoroso, R.O., Bogazzi, E., Jensen, O.P., Parma, A.M., Szuwalski, C., Walters, C.J., 2017. When does shing forage species affect their predators? Fisheries Research 191, 211-221.

[10] Hiramatsu, K., 2009. Evaluation of the reliability of VPA used for stock assessment for the Paci c stock of Japanese sardine. (in Japanese) Nippon Suisan Gakkaishi 75(4), 661-665.

[11] Hurtado-Ferro, F., Hiramatsu, K., Shirakihara, K., 2010. Allowing for environmental effects in a management strategy evaluation for Japanese sardine. ICES Journal of Marine Science 67, 2012-2017.

[12] Ichinokawa, M., Okamura, H., Kurota, H., 2017. The status of Japanese sheries relative to sheries around the world. ICES Journal of Marine Science 74, 1277-1287.

[13] Itoh, S., Yasuda, I., Nishikawa, H., Sasaki, H. and Sasai, Y. 2009, Transport and environmental temperature variability of eggs and larvae of the Japanese anchovy (*Engraulis japonicus*) and Japanese sardine (*Sardinops melanostictus*) in the western North Paci c estimated via numerical particle-tracking experiments. Fisheries Oceanography, 18: 118-133.

[14] Japan Fisheries Research and Education Agency (FRA), 2020a. Stock assessment of the Japanese sardine in the Paci c in 2020 (scal year) (in Japanese) (Accessed on 8 January 2023)

[15] Japan Fisheries Research and Education Agency (FRA), 2020b. Basic policy for the harvest control rule and the calculation of ABC and in 2020 (scal year) (in Japanese) (Accessed on 8 January 2023)

[16] Katsukawa, T., 2004. Numerical investigation of the optimal control rule for decision-making in sheries management. Fisheries Science 70, 123-131.

[17] Katsukawa, T., 2007. Fisheries impact on Japanese sardine. (in Japanese) Nippon Suisan Gakkaishi 73(4), 763-766.

[18] Kawai, H., Yatsu, A., Watanabe, C., Mitani, T., Katsukawa, T., Matsuda, H., 2002. Recovery policy for chub mackerel stock using recruitment-per spawning. Fisheries science 68(5), 963-971.

.

[19] Konar, M., Qiu, S., Tougher, B., Vause, J., Tlusty, M., Fitzsimmons, K., Barrows, R., Cao, L., 2019. Illustrating the hidden economic, social and ecological values of global forage sh resources. Resources, Conservation and Recycling 151, 104456.

.

[20] Lees, K., Pitois, S., Scott, C., Frid, C., Mackinson, S., 2006. Characterizing regime shifts in the marine environment. Fish and Fisheries 7, 104-127.

[21] Matsuda, H. and Katsukawa, T. 2002, Fisheries management based on ecosystem dynamics and feedback control. Fisheries Oceanography 11, 366-370.

.

[22] Matsuda, H., Makino, M., Tomiyama, M., Gelcich, S., Castilla, J.C., 2010. Fishery management in Japan. Ecological Research 25, 899-907.

.

[23] Nishikawa, H., 2019. Relationship between recruitment of Japanese sardine (*Sardinops melanostictus*) and environment of larval habitat in the low-stock period (1995-2010). Fisheries Oceanography 28, 131-142. .

[24] Pikitch, E.K., Rountos, K.J., Essington, T.E., Santora, C., Pauly, D., Watson, R., Sumaila, U.R., Boersma, P.D., Boyd, I.L., Conover, D.O., Cury, P., Heppell, S.S., Houde, E.D., Mangel, M., Plagányi, É., Sainsbury, K., Steneck, R.S., Geers, T.M., Gownaris, N., Munch, S.B., 2014. The global contribution of forage sh to marine sheries and ecosystems. Fish and Fisheries 15, 43-64. .

[25] Punt, A.E., MacCall, A.D., Essington, T.E., Francis, T.B., Hurtado-Ferro, F., Johnson, K.F., Kaplan, I.C., Koehn, L.E., Levin, P.S., Sydeman, W.J., 2016. Exploring the implications of the harvest control rule for Paci c sardine, accounting for predator dynamics: A MICE model. Ecological Modelling 337, 79–95. .

[26] Siple, M.C., Koehn, L.E., Johnson, K.F., Punt, A.E., Canales, T.M., Carpi, P., de Moor, C.L., De Oliveira, J.A.A., Gao, J., Jacobsen, N.S., Lam, M.E., Licandeo, R., Lindegren, M., Ma, S., Oskarsson, G.J., Sanchez-Marono, S., Smolinski, S., Surma, S., Tian, Y., Tommasi, D., Gutierrez T., M., Trenkel, V., Zador, S.G., Zimmermann, F., 2021. Considerations for management strategy evaluation for small pelagic shes. Fish and Fisheries 22,
.

[27] Suda, M., Akamine, T., Kishida, T., 2005. In uence of environment factors, interspeci c-relationships and shing mortality on the stock uctuation of the Japanese sardine, *Sardinops melanostictus*, off the Paci c coast of Japan. Fisheries Research 76, 368-378.
.

[28] Takasuka, A., Oozeki, Y., Kubota, H., Lluch-Cota, S.E., 2008. Contrasting spawning temperature optima: Why are anchovy and sardine regime shifts synchronous across the North Paci c? Progress in Oceanography 77, 225-232.
.

[29] Tyrrell, M., Link, J., Moustah d, H., 2011. The importance of including predation in sh population models: Implications for biological reference points. Fisheries Research 108, 1-8.
.

[30] United Nations, 1982. (Accessed on 8 January 2023)

[31] Watanabe, Y., Zenitani, H., Kimura, R., 1995. Population decline off the Japanese sardine *Sardinops melanostictus* owing to recruitment failures. Canadian Journal of Fisheries and Aquatic Sciences 52, 1609-1616. .

[32] Yagi, T., Yamakawa, T., 2020. Optimal shape of the harvest control rule for different shery management objectives. ICES Journal of Marine Science 77, 3083-3094.
.

[33] Yasunaka, S., Hanawa, K., 2002. Regime Shifts Found in the Northern Hemisphere SST Field. Journal of the Meteorological Society of Japan 80, 119-135.
.

[34] Yatsu, A., Watanabe, T., Ishida, M., Sugisaki, H. and Jacobson, L. D. 2005, Environmental effects on recruitment and productivity of the Japanese sardine *Sardinops melanostictus* and chub mackerel *Scomber japonicus* with recommendations for management. Fisheries Oceanography, 14: 263-278. .

[35] Yatsu, A., 2019. Review of population dynamics and management of small pelagic shes around the Japanese Archipelago. Fishery Science 85, 611-639.
.

[36] Yoda, M., Watanabe, C., Yukami, R., Fukuwaka, M., 2016. Effects of the time schedule on a stock management process. (in Japanese) Nippon Suisan Gakkaishi 82(5), 676-685.
.

Table 1: Parameters and variables.

	Stock biomass of sh in year	
	Spawning stock biomass (SSB) in year	
	Abundance of sh at age in year	
	Fishing mortality at age in year	
	Annual catch of sh at age in year	
	Maturity rate of sh at age	Table 2
	Average weight of sh at age in year	[14]
	Natural mortality of the Japanese sardine	0.4 [14]
	Reference point of SSB for shery closure	g [14]
	Limit reference point of SSB	g [14]
	Fishing mortality achieving the MSY at age	Table 2
	Limit of shing pressure	
	Limit of shing pressure at age in year disturbed by the implementation error	
	Random number at age in year	
	Annual catch of sh in year	
	Expected yield determined by operating in year	
	Total allowable catch (TAC, expected yield determined by the output control) in year	
	Random number governed by the normal distribution at age in year	
	Random number governed by the normal distribution at age in year	
	Average stock biomass from 2010 to 2019	—
	Average annual catch from 2010 to 2019	—
	Starting year of the simulation	1976, 1996, or 2005
, ,	parameters for RI, HS, and BH models	
	Carrying capacity of the recruitment for the BH model	—
	Estimated value of	
	Forecasted value of	
	True value of . This value is unknown in reality	

Table 2: Maturity rate and fishing mortality at different ages [14].

Age	0	1	2	3	4	5
m_a	0	0.2	1	1	1	1
$F_{MSY,a}$	0.18	0.18	0.24	0.50	0.50	0.50

Table 3: The AIC and parameters. The units of α, β, and R_∞ are kg^{-1}, kg^{-1}, and million, respectively.

	BH			RI			HS		
	AIC	α	β	AIC	α	β	AIC	α	R_∞
1976 to 1987	302.859	70.0	2.27×10^{-10}	302.226	56.7	1.00×10^{-10}	302.585	60.4	227952
1988 to 2019	691.223	70.0	2.56×10^{-9}	682.586	44.7	$.9 \times 10^{-10}$	687.162	48.8	25780

Table 4: Figures and the corresponding scenarios and parameters (see Appendix A and Eqs. 13 and 15).

Figure	Scenario	$\gamma_{a,t}$	$\Theta_{a,t}^{imp}$	$\Theta_{a,t}^{obs}$
5	A and B	1 (for any a and t)	0	0
6	A	random	$N(-0.5\theta_1^2, \theta_1^2)$	$N(-0.5\theta_2^2, \theta_2^2)$
7	B	random	$N(-0.5\theta_1^2, \theta_1^2)$	$N(-0.5\theta_2^2, \theta_2^2)$
8	A and B	random	$N(-0.5\theta_1^2, \theta_1^2)$	$N(-0.5\theta_2^2, \theta_2^2)$

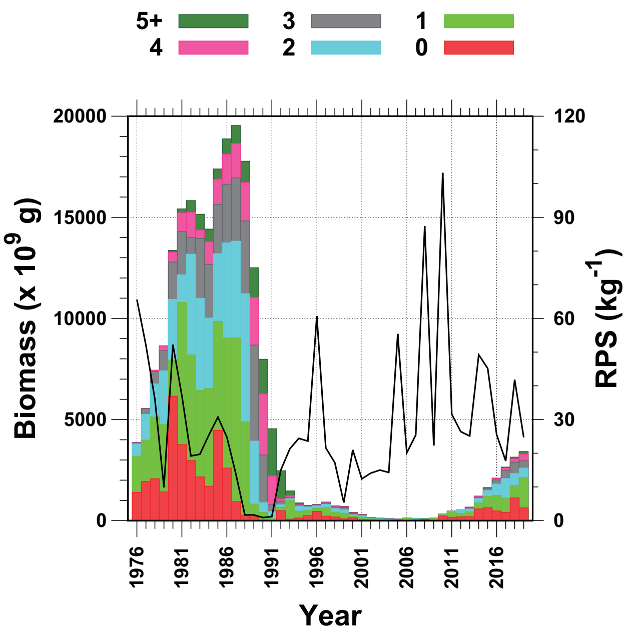


Figure 1: The historical data for stock biomass at different ages and the RPS from 1976 to 2019 [14]. Bar represents the stock biomass, whereas line represents the RPS.

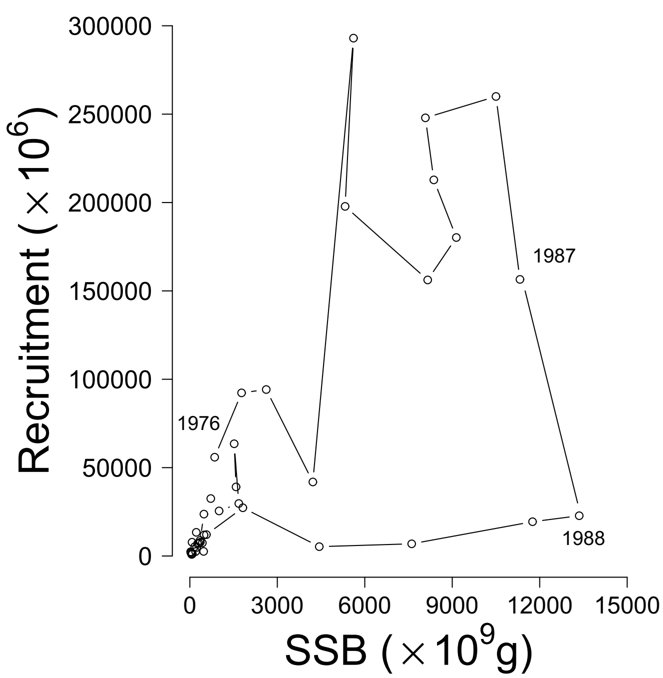


Figure 2: Scatter plot of the spawning stock biomass and the recruitment of the Japanese sardine [14].

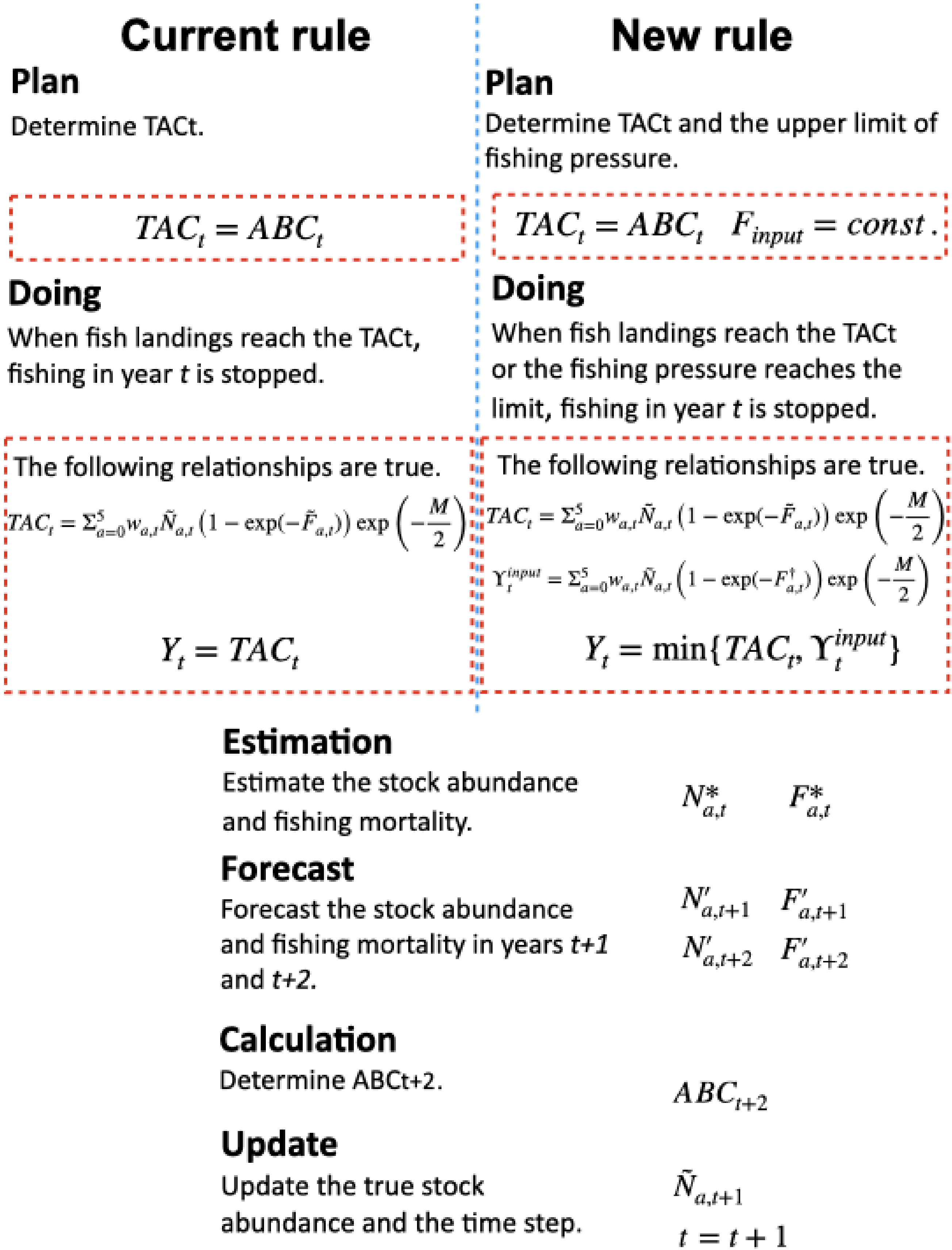
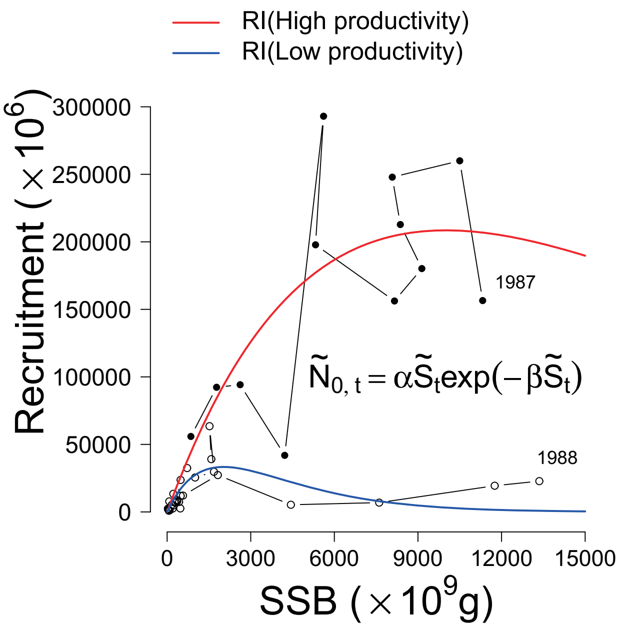
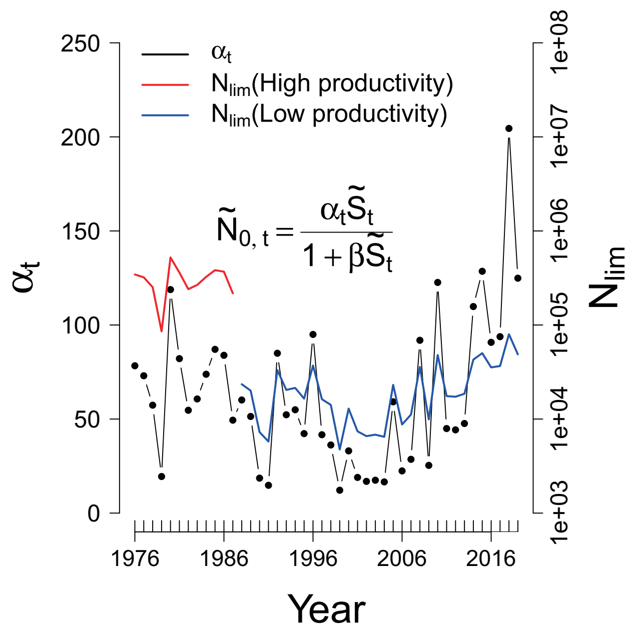


Figure 3: Illustration of the fishery management in the simulation. Assumptions of current and new HCRs are surrounded by red broken line rectangles.

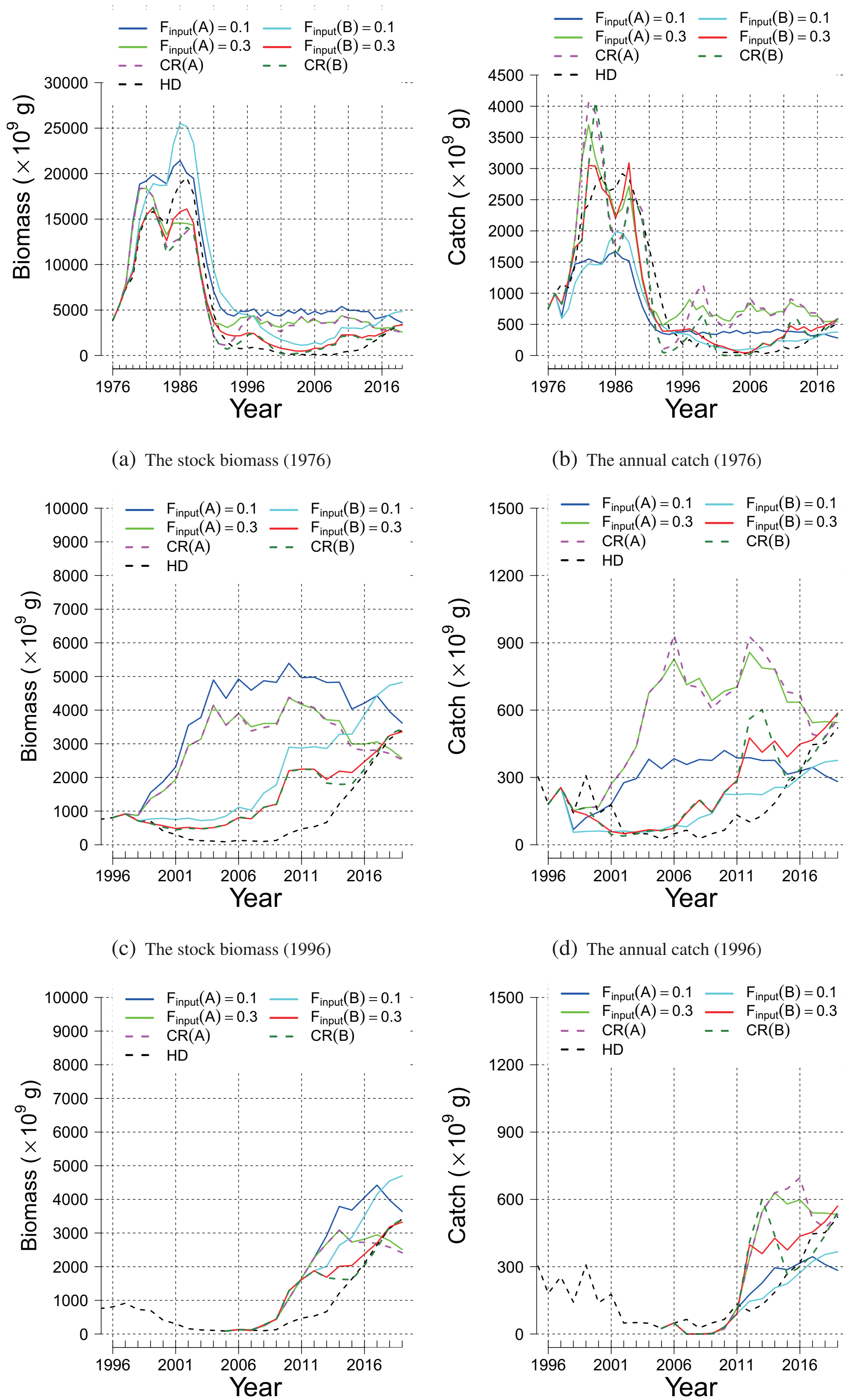


(a) Scenario A



(b) Scenario B

Figure 4: SRR scenarios of the Japanese sardine. The red line represents the high productivity period (1976-1987), while the blue line represents the low productivity period (1988-2019). Panel (a) is a scatter plot of the spawning stock biomass and the recruitment of the Japanese sardine [14] for scenario A. The RI model is shown, and the parameters are $(\alpha, \beta) = (56.7(kg^{-1}), 1.00 \times 10^{-10}(kg^{-1}))$ (red) and $(\alpha, \beta) = (44.7(kg^{-1}), 4.94 \times 10^{-10}(kg^{-1}))$ (blue), respectively. Panel (b) is the time series of parameters for the BH model for scenario B. The black line represents α_t, while red and blue lines represent $N_{lim}(= \alpha_t/\beta)$. $\beta = 2.27 \times 10^{-10}(kg^{-1})$ during the high productivity period (red) and $\beta = 2.56 \times 10^{-9}(kg^{-1})$ during the low productivity period (blue).



(a) The stock biomass (1976)

(b) The annual catch (1976)

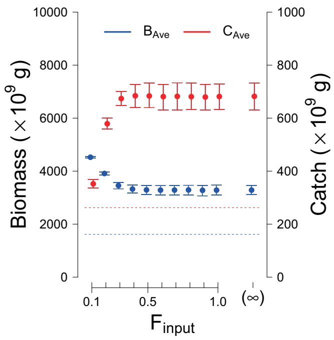
(c) The stock biomass (1996)

(d) The annual catch (1996)

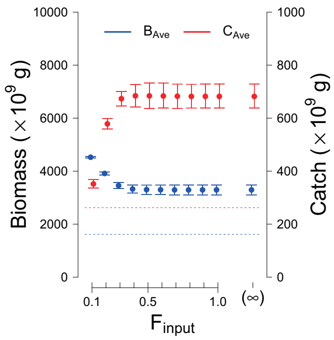
(e) The stock biomass (2005)

(f) The annual catch (2005)

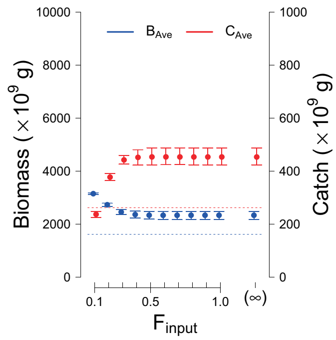
Figure 5: Performance of the new rule (solid lines) with no implementation and observation errors from different starting years in the past. The broken lines represent the current rule (CR) and the historical data (HD).



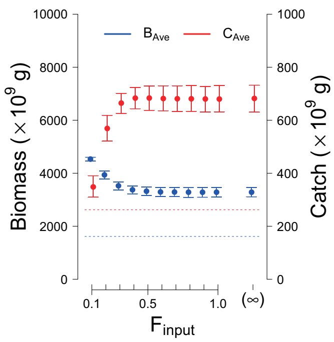
(a) [A-#1]1976



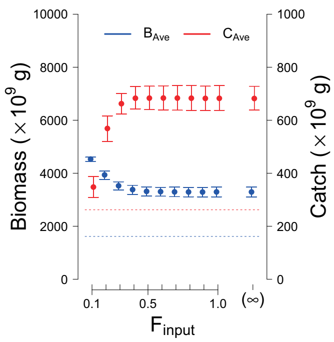
(b) [A-#1]1996



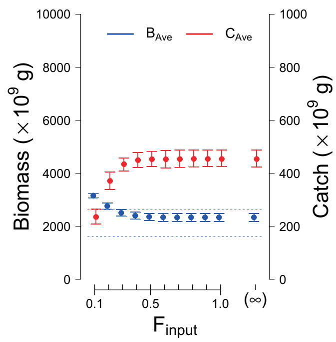
(c) [A-#1]2005



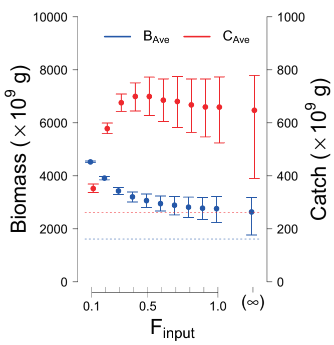
(d) [A-#2]1976



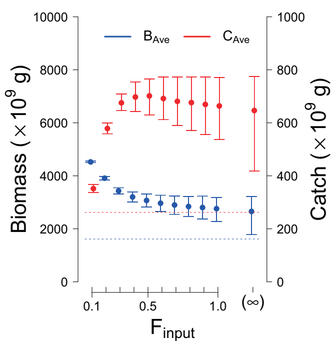
(e) [A-#2]1996



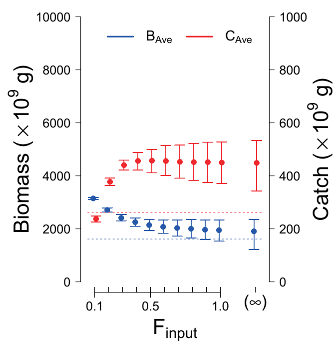
(f) [A-#2]2005



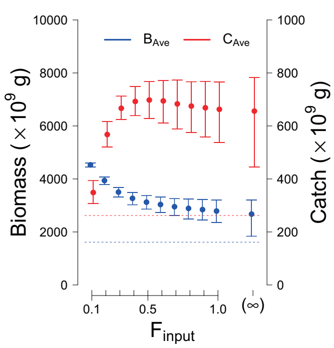
(g) [A-#3]1976



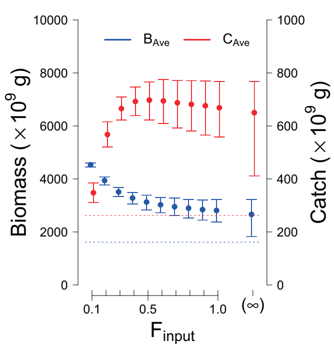
(h) [A-#3]1996



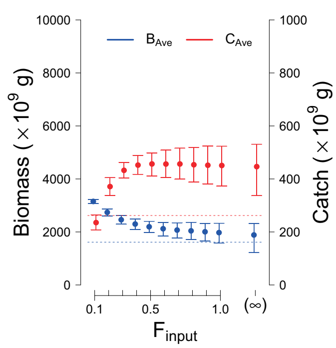
(i) [A-#3]2005



(j) [A-#4]1976

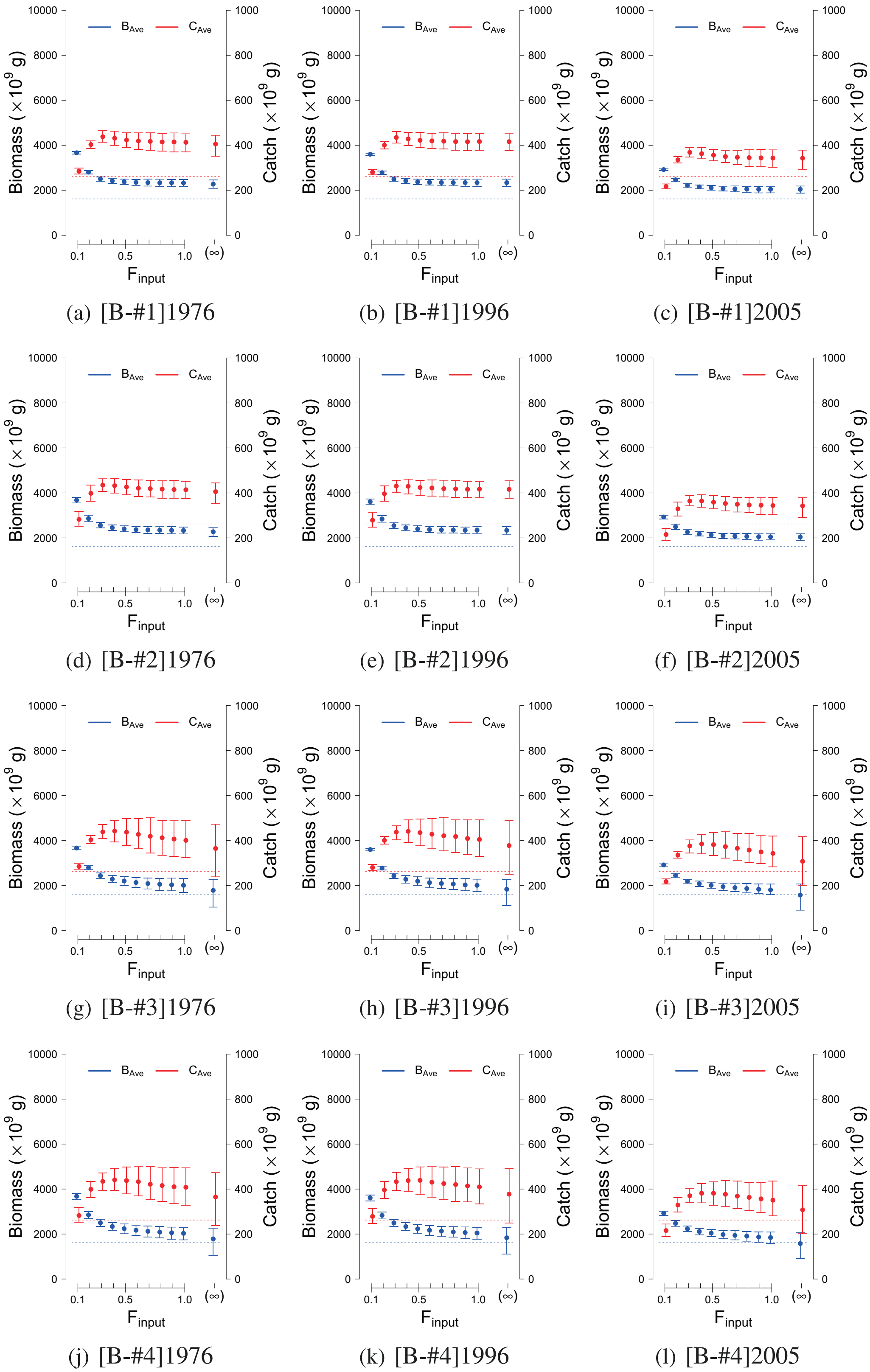


(k) [A-#4]1996



(l) [A-#4]2005

Figure 6: Sensitivity of the average stock biomass and annual catch from 2010 to 2019 with different F_{input} for scenario A. Each caption means '[scenario-case] starting year'. Point represents the mean of results. Upper and lower bars indicate the 97.5 and 2.5 percentiles of results, respectively. Broken lines represent the 10-year mean of the historical data.



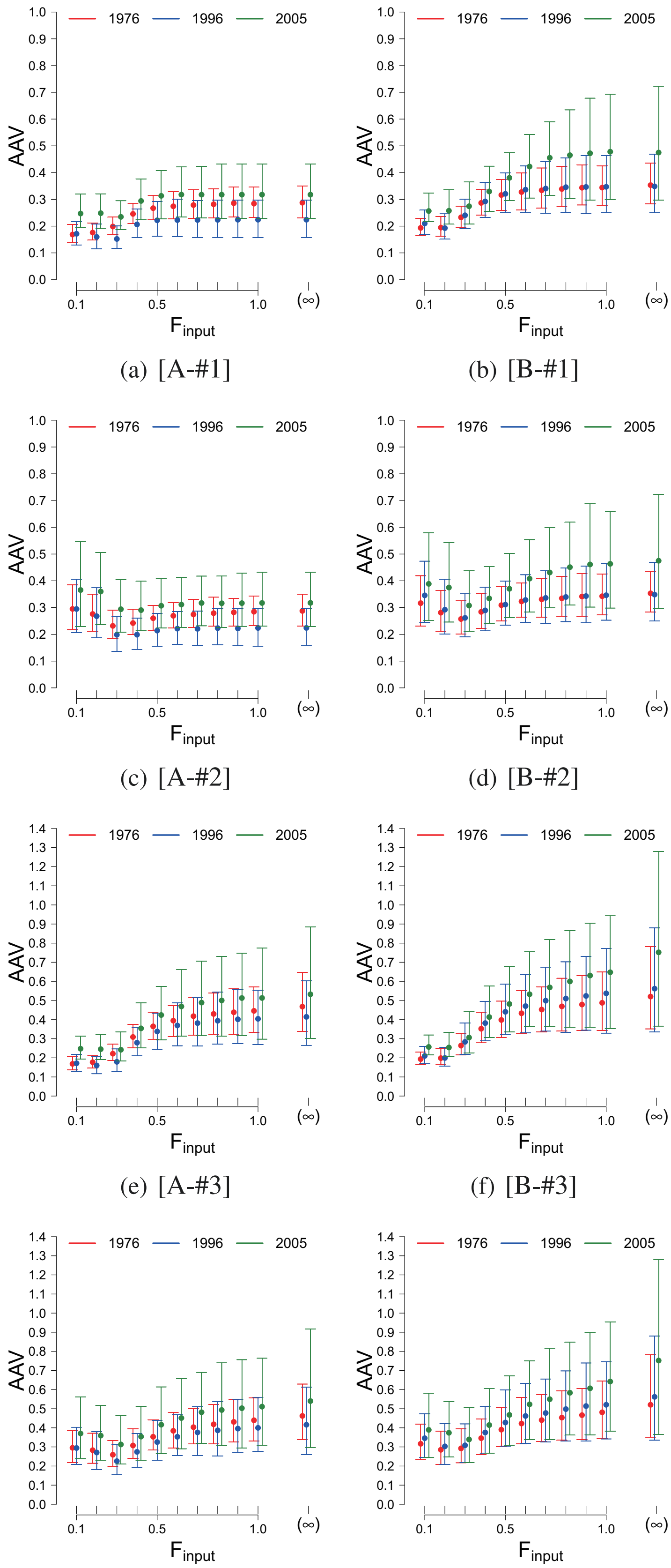
(a) [B-#1]1976 (b) [B-#1]1996 (c) [B-#1]2005

(d) [B-#2]1976 (e) [B-#2]1996 (f) [B-#2]2005

(g) [B-#3]1976 (h) [B-#3]1996 (i) [B-#3]2005

(j) [B-#4]1976 (k) [B-#4]1996 (l) [B-#4]2005

Figure 7: Sensitivity of the average stock biomass and annual catch from 2010 to 2019 with different F_{input} for scenario B. Each caption means '[scenario-case] starting year'. Point represents the mean of results. Upper and lower bars indicate their 97.5 and 2.5 percentiles of results, respectively. Broken lines represent the 10-year mean of the historical data.



(a) [A-#1] (b) [B-#1]

(c) [A-#2] (d) [B-#2]

(e) [A-#3] (f) [B-#3]

(g) [A-#4] (h) [B-#4]

Figure 8: The AAV. Each caption means '[scenario-case]'. Point represents the mean of results. Upper and lower bars indicate their 97.5 and 2.5 percentiles of results, respectively.

Supplementary materials

S1. Stock Recruitment Relationship scenarios

We divided historical data into three ages: the high productivity period (1976-1987), the low productivity period (1988-1991), and the high productivity period (1992-2019). We prepared two different scenarios of stock recruitment relationships (SRRs): scenario C and scenario D.

Scenario C is the counterpart of scenario A and uses three representative SRR models such as the Beverton Holt (BH), Ricker (RI), and Hockey Stick (HS) models by tting them into the historical data. Using the Akaike Information Criterion (AIC), we selected appropriate models and parameters to reproduce the plausible SRR in our simulation. Table 1 shows the AIC and parameters obtained by tting. We adopted the RI model for high and middle productivity ages with different parameters and the HS model for the low productivity age. The parameters are during the high productivity period, during the low productivity period, and during the middle productivity period, respectively (Figure 1 (a)).

Scenario D is the counterpart of scenario B and uses the method that Kawai et al. (2002) proposed for the simulation of the SRR of the chub mackerel. This method is based on the BH model and the coef cient is assumed to be a time-dependent variable. We assumed that during the high productivity period, during the low productivity period, and during the middle productivity period, respectively. Figure 1 (b) shows the change of and over time.

We rst compared the historical data to the results obtained from our proposed HCR and the current rule without implementation and observation errors ( ). Simulations were conducted in cases of the current rule and our new HCR for and . Next, we conducted the simulation in which the implementation error and observation error of the shing mortality were incorporated. By incorporating these errors in the simulation, the effectiveness of the new HCR is validated. We examined the sensitivity of the current rule and our new HCRs with different from 0.1 to 1.0. We considered four different cases of error: [#1] , [#2] , [#3] , and [#4] . Table 2 shows gures and the corresponding scenarios and parameters.

S2. Simulation Results

Figure 2 demonstrates the changes in stock biomass and annual catch without implementation and observation errors. The stock biomass and annual catch greatly recovered after the low productivy period (Figure 2 (a)) or starting years when the stock biomass was very small in both scenarios (Figure 2 (c) and (e)). When the starting year was 1976 or 1996, the stock biomass declined from 2010 or 2011, according to Figure 2 (a) and (c). This was re ected in annual catches in 2010s; however, they remained larger than results for scenarios A and B in the same period (Figure 2 (b) and (d)).

Figures 3 and 4 show and with implementation and observation errors. The performance at or is better than that of the current rule for both scenarios, especially when the observation error was large. For scenario D, means of and at were improved as the starting year was earlier (4), regardless of any combinations of implementation and observation errors.

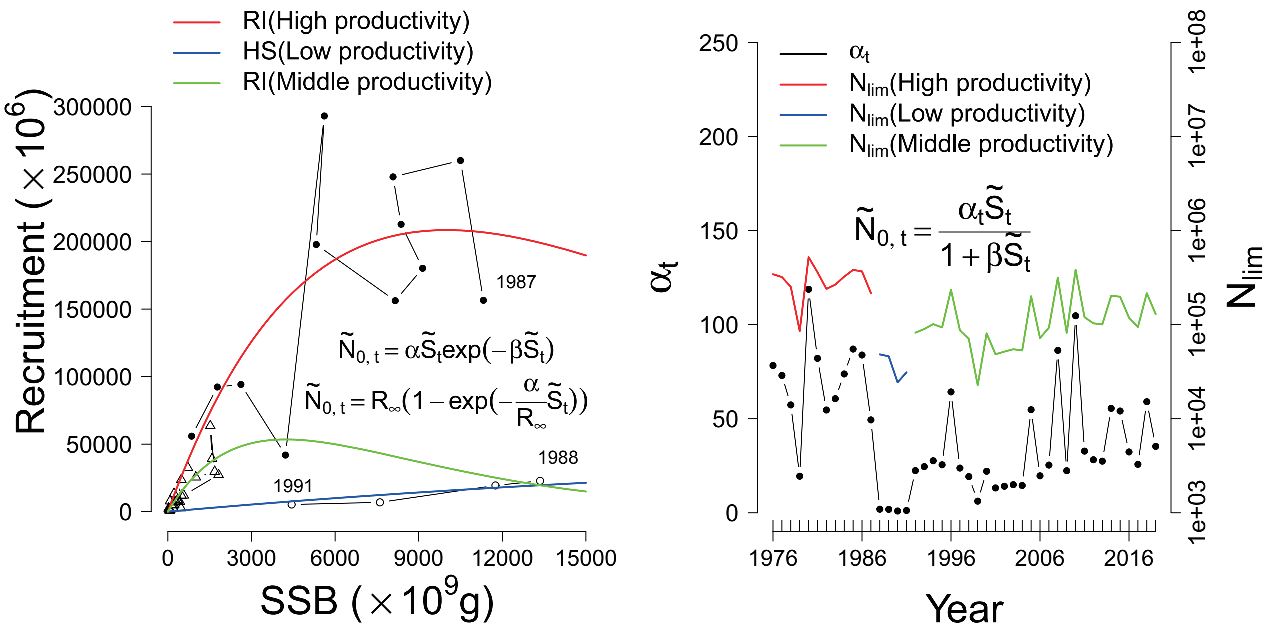
Figure 5 demonstrates the average annual variability. Qualitative results were similar to those of scenarios A and B with exception of cases [#1] and [#2] for scenario D.

Table 1: The AIC and parameters. The units of α, β, and R_∞ are kg^{-1}, kg^{-1}, and million, respectively.

	BH			RI			HS		
	AIC	α	β	AIC	α	β	AIC	α	R_∞
1976 to 1987	302.859	70.0	2.27×10^{-10}	302.226	56.7	1.00×10^{-10}	302.585	60.4	227952
1988 to 1991	81.9715	2.00	$.00 \times 10^{-11}$	83.3459	1.92	2.00×10^{-11}	80.8417	1.86	50000
1992 to 2019	584.994	33.9	2.73×10^{-10}	584.706	34.3	2.36×10^{-10}	584.832	34.1	69127

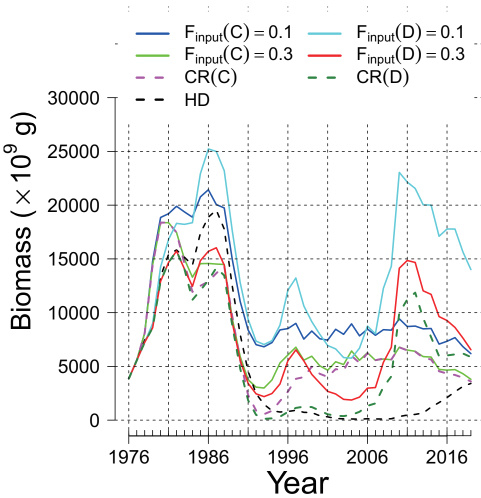
Table 2: Figures and the corresponding scenarios and parameters.

Figure	Scenario	$\gamma_{a,t}$	$\Theta_{a,t}^{imp}$	$\Theta_{a,t}^{obs}$
2	C and D	1 (for any a and t)	0	0
3	C	random	$N(-0.5\theta_1^2, \theta_1^2)$	$N(-0.5\theta_2^2, \theta_2^2)$
4	D	random	$N(-0.5\theta_1^2, \theta_1^2)$	$N(-0.5\theta_2^2, \theta_2^2)$
5	C and D	random	$N(-0.5\theta_1^2, \theta_1^2)$	$N(-0.5\theta_2^2, \theta_2^2)$

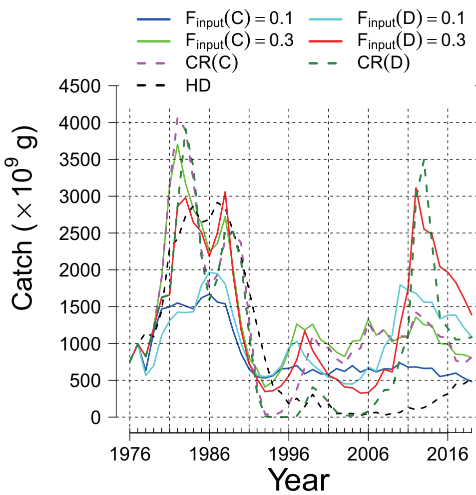


(a) Scenario C (b) Scenario D

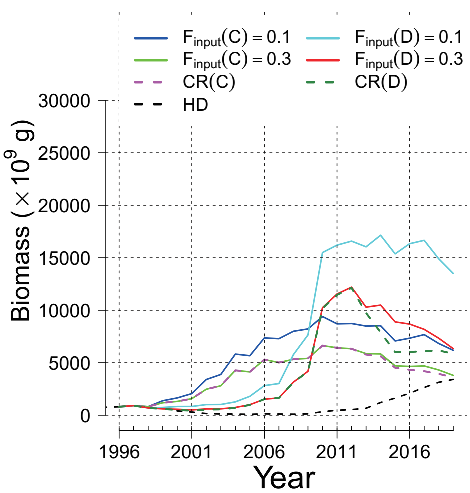
Figure 1: SRR scenarios of the Japanese sardine. The red line represents the high productivity period (1976-1987), the blue line represents the low productivity period (1988-1992), and the green line represents the middle productivity period (1992-2019). Panel (a) is a scatter plot of the spawning stock biomass and the recruitment of the Japanese sardine for scenario C. The RI and HS models are shown, and the parameters are $(\alpha, \beta) = (56.7(kg^{-1}), 1.00 \times 10^{-10}(kg^{-1}))$ (red), $(\alpha, R_\infty) = (1.86(kg^{-1}), 50000(million))$ (blue), and $(\alpha, \beta) = (34.3(kg^{-1}), 2.36 \times 10^{-10}(kg^{-1}))$ (green), respectively. Panel (b) is the time series of parameters for the BH model for scenario D. The black line represents α_t, while red and blue lines represent β. $\beta = 2.27 \times 10^{-10}(kg^{-1})$ during the high productivity period (red), $\beta = 4.00 \times 10^{-11}(kg^{-1})$ during the low productivity period (blue), and $\beta = 2.73 \times 10^{-10}(kg^{-1})$ during the middle productivity period (green). $N_{lim} = \alpha_t/\beta$.



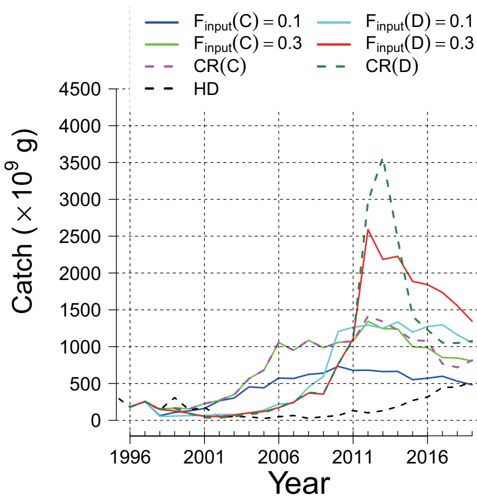
(a) The stock biomass (1976)



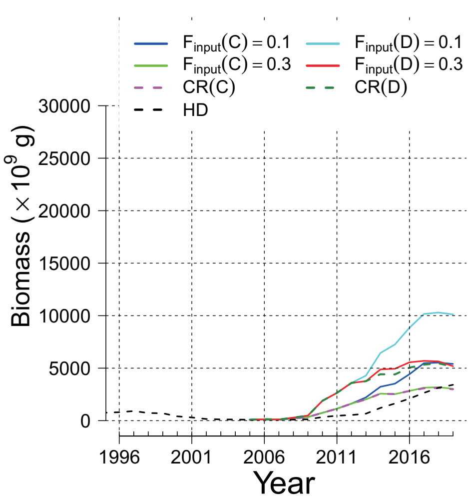
(b) The annual catch (1976)



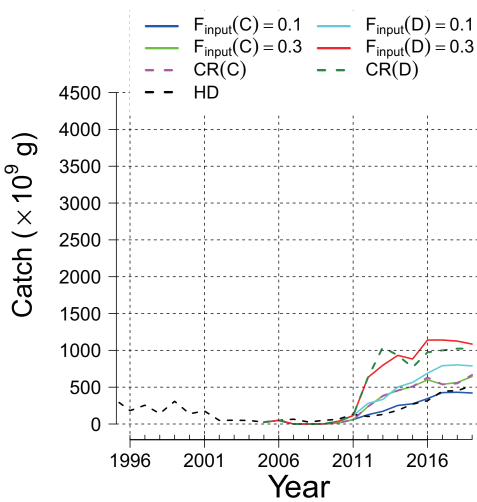
(c) The stock biomass (1996)



(d) The annual catch (1996)

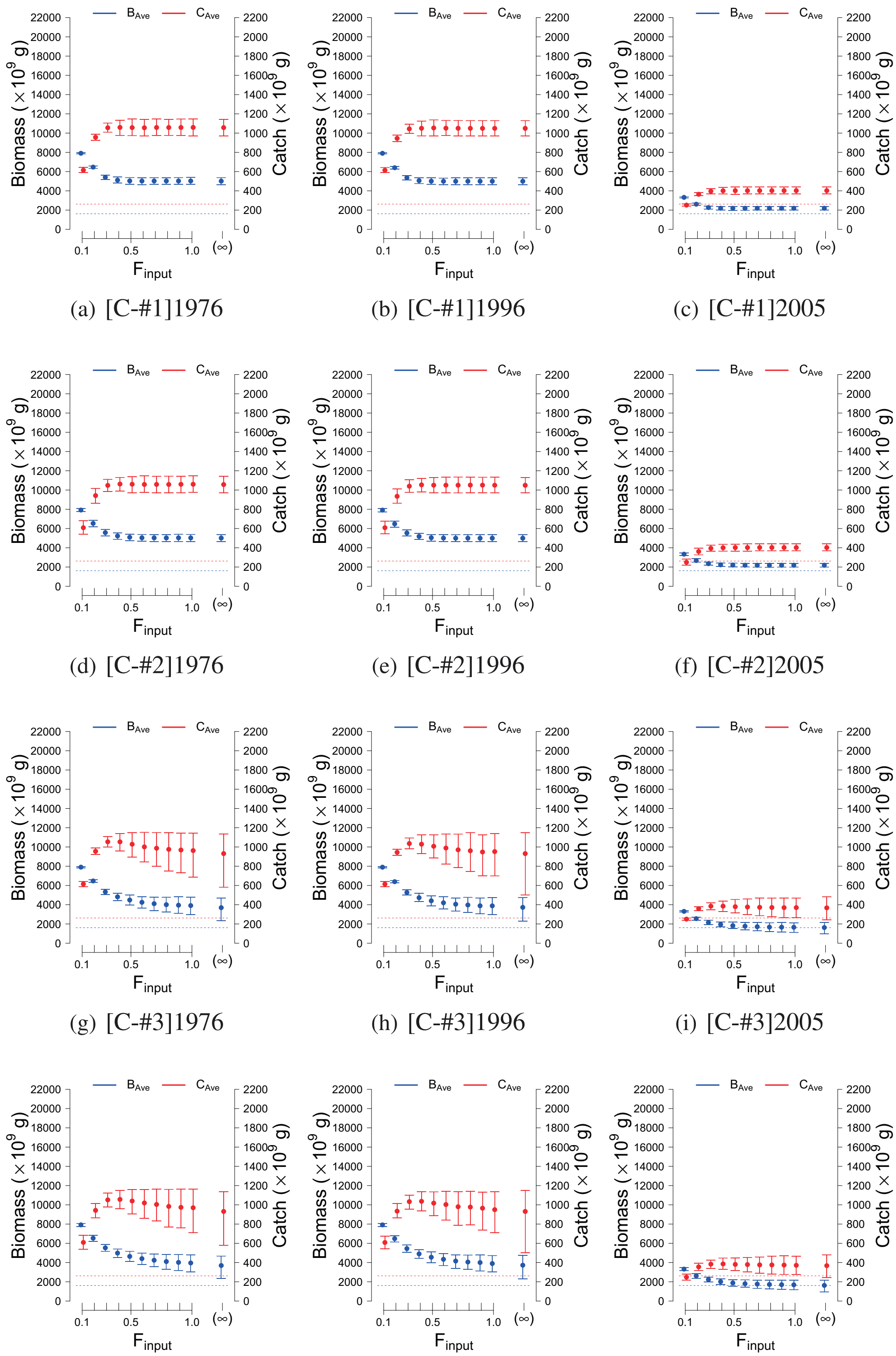


(e) The stock biomass (2005)



(f) The annual catch (2005)

Figure 2: Performance of the new rule (solid lines) with no implementation and observation errors from different starting years in the past. The broken lines represent the current rule (CR) and the historical data (HD).



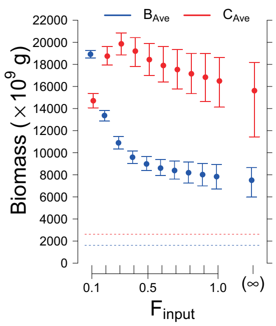
(a) [C-#1]1976 (b) [C-#1]1996 (c) [C-#1]2005

(d) [C-#2]1976 (e) [C-#2]1996 (f) [C-#2]2005

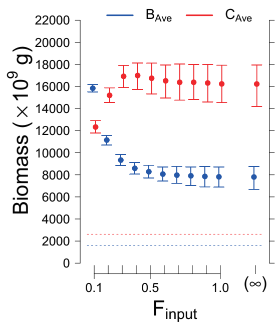
(g) [C-#3]1976 (h) [C-#3]1996 (i) [C-#3]2005

(j) [C-#4]1976 (k) [C-#4]1996 (l) [C-#4]2005

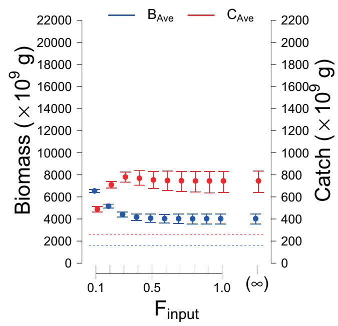
Figure 3: Sensitivity of the average stock biomass and annual catch from 2010 to 2019 with F_{input} for scenario C. Each caption means '[scenario-case] starting year'. Point represents the mean of results. Upper and lower bars indicate the 97.5 and 2.5 percentiles of results, respectively. Broken lines represent the 10-year mean of the historical data.



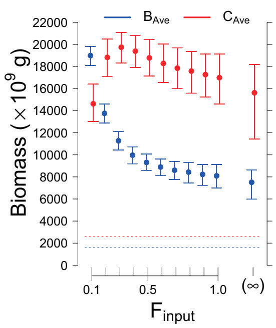
(a) [D-#1]1976



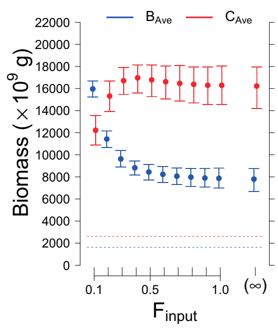
(b) [D-#1]1996



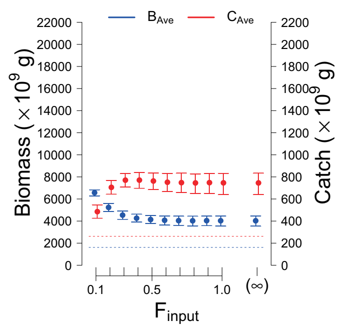
(c) [D-#1]2005



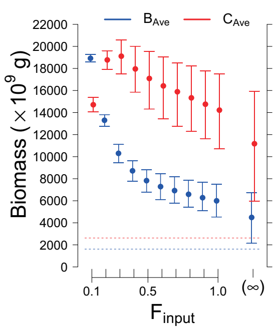
(d) [D-#2]1976



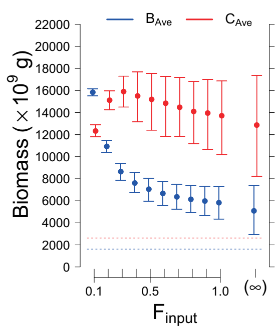
(e) [D-#2]1996



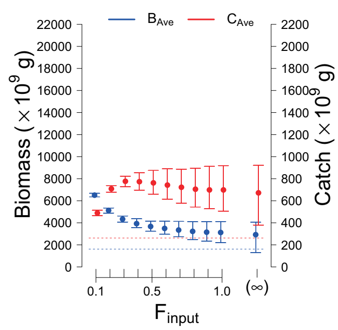
(f) [D-#2]2005



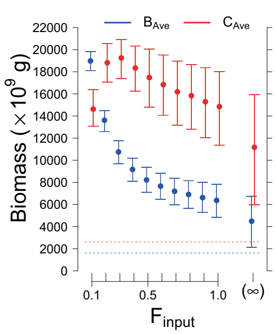
(g) [D-#3]1976



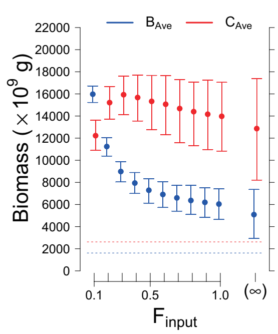
(h) [D-#3]1996



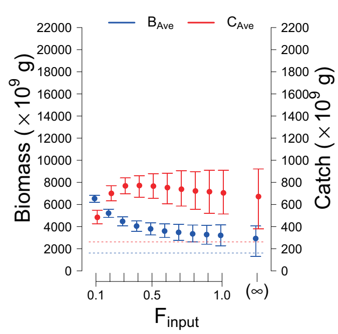
(i) [D-#3]2005



(j) [D-#4]1976

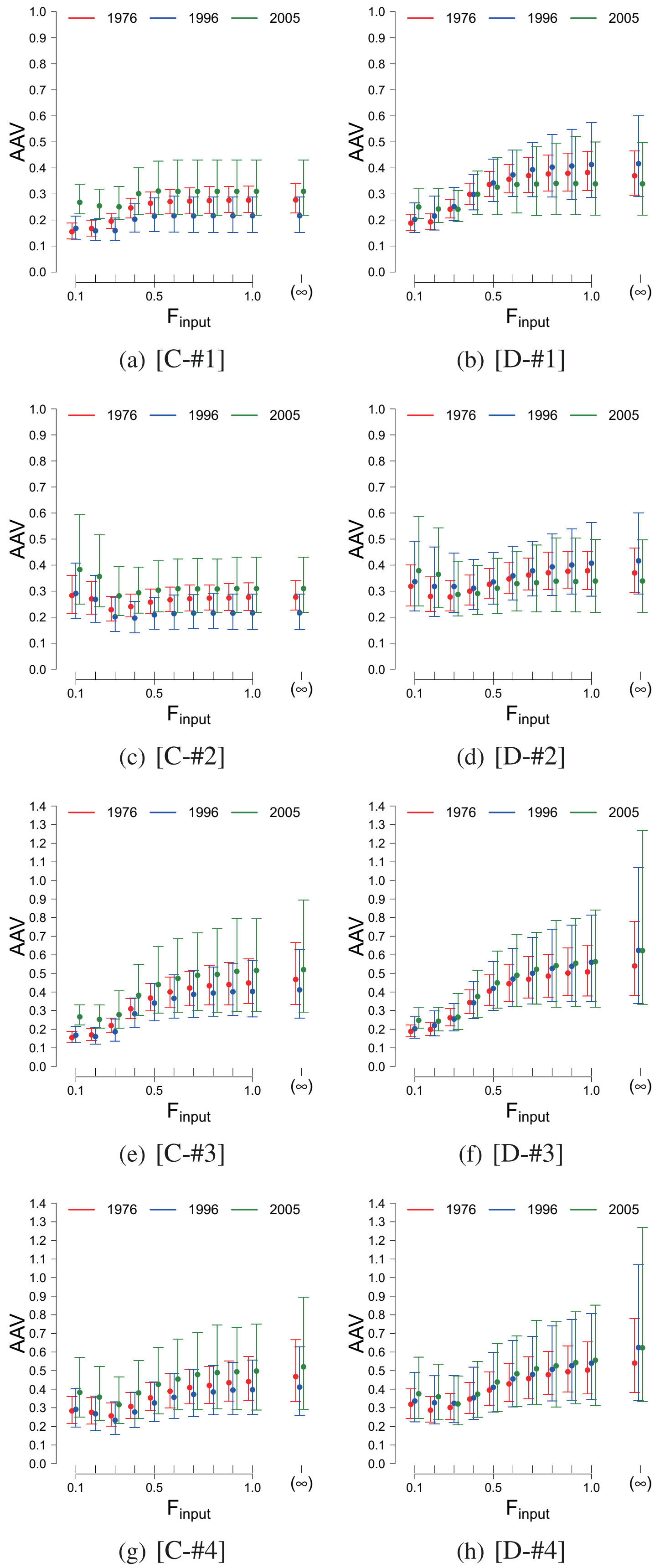


(k) [D-#4]1996



(l) [D-#4]2005

Figure 4: Sensitivity of the average stock biomass and annual catch from 2010 to 2019 with F_{input} for scenario D. Each caption means '[scenario-case] starting year'. Point represents the mean of results. Upper and lower bars indicate their 97.5 and 2.5 percentiles of results, respectively. Broken lines represent the 10-year mean of the historical data.



(a) [C-#1] (b) [D-#1]
(c) [C-#2] (d) [D-#2]
(e) [C-#3] (f) [D-#3]
(g) [C-#4] (h) [D-#4]

Figure 5: The AAV. Each caption means '[scenario-case]'. Point represents the mean of results. Upper and lower bars indicate their 97.5 and 2.5 percentiles, respectively.

Chapter IV

新型コロナウイルスSARS-CoV-2対策への総合的評価

1 Introduction

2019 年 12 月から感染拡大が起こった新型コロナウイルス SARS-CoV-2 による感染症（COVID-19）に対し、世界中で多数の感染死者が計上された。厚生労働省（以下 MHLW）[11] によると、日本国は 2022 年 12 月末までに 57272 人の感染死者を出した。感染者数がある期間に渡って大きく増加し極大値に到達してその後減少することを感染の波と呼ぶことにすると、2022 年末までに 8 つの波があったと数えることができる（Figure 1）。Table 1 に各波の期間とその期間内の一日の新規陽性者の最大値と考えられる原因を示す。夏と冬の季節的な要因として、夏休みやお盆又は正月の帰省による接触機会の増加、外気温に対する冷暖房の使用による換気回数の減少が挙げられ、さらにワクチン接種又は感染により獲得した免疫の減衰も波の原因とされている [14]。その一方で、政府は 2020（令和 2）年度補正予算、2021（令和 3）年度当初予算、同年度補正予算にて対策費用を計上した。財務省（以下 MOF）[13] で公開されている日本国の国家予算から新型コロナウイルス対策のために計上された予算とそのうち医療体制の整備及び拡充に使われた金額を Table 2 にまとめた。そのうち感染制御のために直接使われた予算と、企業経営支援など間接的に使われた予算、感染症対策の広報のために使われた予算もある。経済や財政を無視するなら感染症制御は行動抑制の継続と検査体制の常設をすればよいが、公衆衛生を含む公共政策に対して事後の政策評価の必要性も主張されている [21]。費用対効果の高い政策の実施が求められるが、一定期間に投じた費用に対しての効果を測定することは困難が多く、一年あるいはそれ以上の期間が測定のために必要になる場合もある。今回の新型コロナウイルス対策のように複数の施策を実行した場合は、結果との因果関係の特定も難しい [6, 25]。本章では公衆衛生、経済の二つの視点から新型コロナウイルス対策の総合的な評価を行う。以下の調査で対象期間は暦年換算の 2020 年と 2021 年とした。

2 Review of countermeasures against SARS-CoV-2

2.1 Public health

公衆衛生分野の評価指標として COVID-19 感染死者数と超過死亡数（Excess mortality）を利用する。超過死亡数は、ある期間の実際の全死亡者数から例年の死亡者数を基に推定される死亡数を引いた値と定義される。COVID-19 感染死者数は、別の死因で亡くなった人が COVID-19 に陽性だった場合も感染死者数に計上されている場合があり、 COVID-19 が実際の死因になった人のみを計上している保証はない。よって超過死亡数がより包括的で頑健な指標となる [24]。

超過死亡数には、COVID-19 による直接的な死亡、COVID-19 による医療体制の収容力超過による死亡、インフルエンザなど自然要因による超過死亡、交通事故や自殺など自然要因でない超過死亡、戦争や災害など特別な事故による超過死亡が含まれる [9, 10]。ここでは 2020 年以前と以降による死因の変化を探究する。超過死亡数のデータは国立感染症研究所 (以下 NIID) で公開されているものを利用した [15]。さらに日本人の全死亡数と死因を MHLW の人口動態調査のデータ [12] から入手し、以下のことを調べた。

1. 過去 5 年間の死亡者数平均値が一定数以上でかつ 2020 年と 2021 年の死亡者数が共に増加もしくは減少した死因

2. 過去 5 年間の死亡者数の変化率の平均値と 2020 年の変化率が増加もしくは減少した死因

具体的には、1 は 2015 年から 2019 年までの死亡者数平均値が一万人以上でかつ 2020 年と 2021 年の死亡者数が共に平均値に対し、　倍以上もしくは　倍以下になっている死因を調べた。さらに 2 について、2020 年の死亡者数の変化率が 2015 年から 2019 年までの死亡者数の変化率の　% 信頼区間の外にある死因を調べた。ここで　年の死亡者数の変化率　は以下の式で定義される。

$$ \frac{\quad}{\quad} \tag{1} $$

ただし　は　年の死亡者数を表す。

日本国における 2020 年と 2021 年の超過死亡数を計算した結果、それぞれ　人と　人となった。各年の 10 月 1 日時点の全人口で除算することで人口百万人当たりの超過死亡数を計算すると、それぞれ　人と　人となった。それに対して同期間の COVID-19 による感染死者数は、それぞれ　人と　人であった（Table 3)。日本人の全死亡数と 2020 年における死因上位５つ（悪性新生物＜腫瘍＞、高血圧性を除く心疾患、老衰、脳血管疾患、肺炎）の死亡数の 2012 年から 2021 年までの移り変わりを Figure 2 に示す。日本人の全死亡数は 2020 年を除き 2012 年から増加し続けており、特に老衰による死亡数の増加が顕著である。ただし脳血管疾患と肺炎の死亡数は減少傾向である。死因上位５つの死亡数が全体の死亡数の 6 割以上を占めているが、割合は減少傾向である。

過去 5 年間の死因別死亡者数と 2020 年及び 2021 年の死因別死亡者数を比べた結果を Table 4 と 5 に示す。死因分類コードの下 3 桁が 0 になっているものは大分類を表し、上 2 桁が同じ分類コードの死因を合計したものである。大分類を除くと、2020 年及び 2021 年に増加したのは、膵の悪性新生物＜腫瘍＞、悪性リンパ腫、血管性及び詳細不明の認知症、アルツハイマー病、そ

の他の神経系の疾患、慢性腎臓病、老衰、その他の症状，徴候及び異常臨床所見・異常検査所見で他に分類されないもの、であった。また、減少したのは、急性心筋梗塞、肺炎であった。

過去 5 年間の死亡者数の変化率の平均値と 2020 年の変化率比べた結果を Table 6 と 7 に示す。変化率が増加した死因は、悪性リンパ腫、その他の高血圧性疾患[1]、ヘルニア及び腸閉塞、自殺であった。前の三つの死因は過去 5 年間上昇傾向にあったが、自殺は過去 5 年間は減少傾向であった。ただし 2020 年と 2021 年の自殺による死亡者数は過去 5 年の平均値よりは低かった（Table 6）。変化率が減少した死因は、大分類を除いて、食道の悪性新生物＜腫瘍＞、喉頭の悪性新生物＜腫瘍＞、乳房の悪性新生物＜腫瘍＞、インフルエンザ、急性気管支炎、喘息、胃潰瘍及び十二指腸潰瘍、循環器系の先天奇形、その他の先天奇形及び変形、交通事故であった。過去 5 年間増加傾向であったが 2020 年に減少に転じた死因は、食道の悪性新生物＜腫瘍＞、乳房の悪性新生物＜腫瘍＞、インフルエンザ、その他の先天奇形及び変形であった。とりわけインフルエンザは 2020 年に 274% と大幅な減少が見られ、死亡者数は 956 人（2020 年）、22 人（2021 年）であった。

医療機関へのアクセスのしやすさの指標として救急搬送困難事案が「救急隊による「医療機関への受入れ照会回数 4 回以上」かつ「現場滞在時間 30 分以上」の事案として、各消防本部から総務省消防庁に報告があったもの」と定義され、総務省消防庁（以下 FDMA）から公開されている [5]。Figure 3 は日本全国の一週間当たりの救急搬送困難事案数と一日当たりの新規陽性者数の時系列データを表している。救急搬送困難事案は全事案と全事案のうち非コロナ疑いの両方の件数を図示した。これによると、COVID-19 の新規陽性者数が増えて感染の波が起こるとき、同時に救急搬送困難事案数も増加することが分かる。全事案のうち非コロナ疑いの件数は、2021 年 3 月 29 日月曜日の週以前は集計されていないが、2022 年以降のデータ（Figure 3 (b)）も参照すると、COVID-19 の感染の波と同時に増加していることが推測される。

2.2 Economics

新型コロナウイルスの流行による社会経済分野の指標として一人当たりの名目 GDP と国債発行残高と失業率のデータを利用し、他国と比較する [17, 18, 19]。比較対象は、日本国以外の G7 諸国に加え、百万人当たりの COVID-19 感染死者数が日本と同水準と思われるオーストラリアと韓国を設定した（Figure 4）。

Figure 5 は一人当たりの名目 GDP を示しており、各国すべてが 2012 年から 2019 年まで増加傾向にあった。2020 年には、SARS-CoV-2 の流行により、米国、カナダ、フランス、英国、イタ

[1]高血圧性心疾患及び心腎疾患（9101）以外

リアで下落、ドイツと日本で微減、オーストラリアと韓国で増加となった。2021 年はすべての国で一人当たりの名目 GDP が増加となったが、日本のみほぼ横ばいで金額は USD と比較国の間では最低であり、2021 年の変化率は約 %であった。

四半期ごとの日本の名目 GDP とその内訳を Figure 6 に示すと、民間最終消費支出が名目 GDP の半分以上を占めていることが分かる（Figure 6 (a)）。民間最終消費支出は 2020 年の第二四半期（4 月から 6 月）に大きな落ち込みがあり、同年第一四半期（1 月から 3 月）から約 25 兆円減少した。その後 2021 年の第四四半期（10 月から 12 月）に 兆円まで回復したが、2019 年第四四半期の 兆円にまでは届いていない。他にも 2020 年の第二四半期には輸出と輸入がともに下落し、輸出から輸入を引いた純輸出も同年第一四半期から約 16 兆円減少した（Figure 6 (b)）。

対 GDP 比国債発行残高（Figure 7） は各国ともに 2012 年から 2019 年までほぼ横ばいであり、ドイツが微減、オーストラリアが微増傾向であった。2020 年には微増した韓国を除くすべての国で増加が見られたが、2021 年は日本と韓国以外の国では減少した。日本の対 GDP 比国債発行残高は 2019 年以前から 220% を上回っていたが、2020 年（257%）の増加を 2021 年（258%）も引き継ぐ形となった。

Figure 8 は四半期ごとの失業率を示す。2015 年から韓国を除き減少傾向であったが、2020 年から 2021 年までの 1 年間にすべての国で上昇が見られた。特にカナダと米国で顕著な増加があったが一時にピークに達してその後は減少している。日本は 2015 年以降失業率が比較国の間では最小であり続け、2020 年以降に上昇した際も 3% （2020 年第 4 四半期）が最大であり、増加幅を小さく留められている。

3 Discussion

新型コロナウイルス対策の評価として、医療と公衆衛生分野の指標として COVID-19 感染死者数と超過死亡数を挙げ、社会経済分野の指標として一人当たりの名目 GDP と国債発行残高と失業率を挙げた。

2020 年には COVID-19 感染死者数が 3459 人に上ったが、超過死亡は負であった。2020 年は肺炎のような呼吸器系の疾患が過去 5 年間に比べ大幅に減り、インフルエンザによる死者数も 1000 人を下回った。行動抑制や外出規制のような新型コロナウイルス対策による接触機会の減少が要因として考えられる。Nomura et al. [16] によると、47 都道府県で 2020 年 1 月から 9 月までの交通事故死を調べたところ、過去の同じ時期に比べ減っていた。ただし減少はわずかなの

で、COVID-19 流行期のすべての死因を含む超過死亡の変化にそれほど大きな影響を与えたわけではないと結論付けている。

日本における感染の第四波以降は感染力の強い変異株の流行が観測された [2, 7, 26]。その影響で感染者数と感染死者数は増加し、2021 年内の日本の COVID-19 感染死者数は 14926 人に上り、超過死亡は 48005 人と正の値に転じた。Table 4 と 6 に増加した死因をまとめたが、悪性リンパ腫による死者数は過去 5 年間の平均の　倍、さらに変化率も大幅に上昇していた。また、人々の接触機会の減少の副次的な影響として自殺率の増加が見込まれることから、精神的な健康に危機を抱える個人への配慮措置の必要性も主張されている [22]。Figure 3 から新型コロナウイルスによる医療資源の逼迫が示唆される。COVID-19 感染死者数のような直接な影響だけでなく、病床逼迫や持病持ちの患者の受診控えのような間接的な健康状態の悪化リスクも含めて考えて医療資源の割り当てをする必要があった。今後の新興感染症発生時への教訓としては、感染者数そのものを減らすことと、場合によっては感染者への対応の簡素化による医療資源の節約と確保が挙げられる。

日本は他の G7 諸国やオーストラリアと韓国と同様に 2020 年の拡大期に国債発行残高を増やして対策予算に充て、2021 年もさらに国債発行残高を増やした。しかし 2021 年は他国のように一人当たり名目 GDP を伸ばすことはできず、2019 年以前と同様横ばいまたは微増にとどまっている。2020 年初めから 2021 年終わりまでを総合してみると、日本は超過死亡数 11925 人と COVID-19 感染死者数 18385 人に留め、一人当たりの名目 GDP と失業率を SARS-CoV-2 流行以前程度に戻した引き換えに、対 GDP 比国債発行残高を約 25%（約 134 兆円）程度引き上げたと見ることもできる。

この研究では超過死亡数を用いたが、超過死亡数で異なる国々を比べる際は、死亡の定義に注意し、死亡理由にも区別をつけて行うことが望ましいという指摘がある [1]。その理由は、COVID-19 で亡くなることがなかったとしても症状が長く続いたり、肺や心臓などに余病や合併症ができてしまうことがあるため、それがその後の生活の質や働く能力に支障をきたすこともあるからである。また、Our World in Data [20] によると人口百万人あたりの感染死者数は、2022 年 2 月 3 日にオーストラリアが、同年 3 月 16 日に韓国がそれぞれ日本を上回った。よって 2020 年から 2021 年にかけて感染死者数を抑えていた国ですら変異株の出現や世界的な流行拡大からの時間経過による人々の意識や行動の変化、免疫を獲得した人の多寡で感染状況が悪化しうることが示唆される。

Danger eld et al. [4] は、感染症の流行の際のウイルスの特性や感染制御行動の不確実さから、政策による介入の間接的な利益と不利益の評価に課題があることを指摘した。COVID-19 への対

策による COVID-19 以外の医療利用の減少のような間接的な影響は、例えば慢性疾患の患者に数年掛かりで表出する可能性もある [23]。さらに Kanda et al. [8] は三重県の被保険者及び扶養者 80 万人のデータベースから、新型コロナウイルス流行期間に性感染症の症例数が増加したことを明らかにし、その潜在的な要因として人々の行動変容の影響を示唆した。今回の新型コロナウイルスの流行では、病床の確保のために医療機関に補償が支払われた。ここで支払われた金額は将来の感染症の流行の際にも参考になる。今後も個々の政策の費用対効果と妥当性の検証や、出生率の低下など新型コロナウイルスの流行とその対策による副次的な影響を調べる必要がある。

References

[1] Beaney, T., Clarke, J.M., Jain, V., Golestaneh, A.K., Lyons, G., Salman, D., Majeed, A., 2020. Excess mortality: the gold standard in measuring the impact of COVID-19 worldwide? Journal of the Royal Society of Medicine 113, 329-334.

.

[2] Campbell, F., Archer, B., Laurenson-Schafer, H., Jinnai, Y., Konings, F., Batra, N., Pavlin, B., Vandemaele, K., Van Kerkhove, M.D., Jombart, T., Morgan, O., le Polain de Waroux, O., 2021. Increased transmissibility and global spread of SARS-CoV-2 variants of concern as at June 2021. Eurosurveillance 26. .

[3] 内閣府（CAO）, 2022. 国民経済計算（GDP 統計）

(Accessed on 8 January 2023)

[4] Danger eld, C., Fenichel, E.P., Finnoff, D., Hanley, N., Hargreaves Heap, S., Shogren, J.F., Toxvaerd, F., 2022. Challenges of integrating economics into epidemiological analysis of and policy responses to emerging infectious diseases. Epidemics 39, 100585.

.

[5] 総務省消防庁（FDMA）新型コロナウイルス感染症関連

. (Accessed on 8 January 2023)

[6] Flaxman, S., Mishra, S., Gandy, A., Unwin, H.J.T., Mellan, T.A., Coupland, H., Whittaker, C., Zhu, H., Berah, T., Eaton, J.W., Monod, M., Imperial College COVID-19 Response Team, Ghani, A.C., Donnelly, C.A., Riley, S., Vollmer, M.A.C., Ferguson, N.M., Okell, L.C., Bhatt, S., 2020. Estimating the effects of non-pharmaceutical interventions on COVID-19 in Europe. Nature 584, 257–261. .

[7] Furuse, Y., 2022. Properties of the Omicron Variant of SARS-CoV-2 Affect Public Health Measure Effectiveness in the COVID-19 Epidemic. International Journal of Environmental Research and Public Health 19. .

[8] Kanda, N., Hashimoto, H., Imai, T., Yoshimoto, H., Goda, K., Mitsutake, N., Hatakeyama, S., 2023. Indirect impact of the COVID-19 pandemic on the incidence of non-COVID-19 infectious

diseases: a region-wide, patient-based database study in Japan. Public Health 214, 20-24. https://doi.org/10.1016/j.puhe.2022.10.018.

[9] Karlinsky, A., Kobak, D. 2021 Tracking excess mortality across countries during the COVID-19 pandemic with the World Mortality Dataset eLife. https://doi.org/10.7554/eLife.69336.

[10] Kawashima, T., Nomura, S., Tanoue, Y., Yoneoka, D., Eguchi, A., Ng, C., Matsuura, K., Shi, S., Makiyama, K., Uryu, S., Kawamura, Y., Takayanagi, S., Gilmour, S., Miyata, H., Sunagawa, T., Takahashi, T., Tsuchihashi, Y., Kobayashi, Y., Arima, Y., Kanou, K., Suzuki, M., Hashizume, M., 2021. Excess All-Cause Deaths during Coronavirus Disease Pandemic, Japan, January–May 2020. Emerging Infectious Diseases 27(3), 789–795. https://doi.org/10.3201/eid2703.203925.

[11] 厚生労働省（MHLW）, 2022a. データからわかる新型コロナウイルス感染症情報
https://covid19.mhlw.go.jp/
(Accessed on 8 January 2023)

[12] 厚生労働省（MHLW）, 2022b. 人口調査動態
https://www.mhlw.go.jp/toukei/list/81-1a.html
(Accessed on 8 January 2023)

[13] 財務省（MOF）, 2022.
https://www.mof.go.jp/polic /budget/budger_workflow/budget/index.html
(Accessed on 8 January 2023)

[14] 国立感染症研究所（NIID）, 2022a. 新型コロナウイルス感染症（COVID-19）関連情報
https://www.niid.go.jp/niid/ja/diseases/ka/corona-virus/covid-19.html
(Accessed on 8 January 2023)

[15] 国立感染症研究所（NIID）, 2022b. 日本の超過および過少死亡数ダッシュボード
https://exdeaths-japan.org/ (Accessed on 8 January 2023)

[16] Nomura, S., Kawashima, T., Yoneoka, D., Tanoue, Y., Eguchi, A., Gilmour, S., Hashizume, M., 2020. Trends in deaths from road injuries during the COVID-19 pandemic in Japan, January to September 2020. Injury Epidemiology 7. https://doi.org/10.1186/s40621-020-00294-7.

[17] OECD, 2022. Gross domestic product (GDP) (indicator). https://doi.org/10.1787/dc2f7aec-en (Accessed on 8 January 2023)

[18] OECD, 2022. General government debt (indicator). https://doi.org/10.1787/a0528cc2-en (Accessed on 8 January 2023)

[19] OECD, 2022. Unemployment rate (indicator). https://doi.org/10.1787/52570002-en (Accessed on 8 January 2023)

[20] Our World in Data, 2022. https://ourworldindata.org/explorers/coronavirus-data-explorer (Accessed on 8 January 2023)

[21] Oxmán, A.D., Bjorndal, A., Becerra-Posada, F., Gibson, M., Block, M.A.G., Haines, A., Hamid, M., Odom, C.H., Lei, H., Levin, B., Lipsey, M.W., Littell, J.H., Mshinda, H., Ongolo-Zogo, P., Pang, T., Sewankambo, N., Songane, F., Soydan, H., Torgerson, C., Weisburd, D., Whitworth, J., Wibulpolprasert, S., 2010. A framework for mandatory impact evaluation to ensure well informed public policy decisions. The Lancet 375, 427-431. https://doi.org/10.1016/S0140-6736(09)61251-4.

[22] Reger, M.A., Stanley, I.H., Joiner, T.E., 2020. Suicide Mortality and Coronavirus Disease 2019-A Perfect Storm? JAMA Psychiatry 77(11), 1093-1094. https://doi.org/10.1001/jamaps chiatr .2020.1060.

[23] Roy, C.M., Bollman, E.B., Carson, L.M., Northrop, A.J., Jackson, E.F., Moresky, R.T., 2021. Assessing the indirect effects of COVID-19 on healthcare delivery, utilization and health outcomes: a scoping review. European Journal of Public Health 31, 634–640. https://doi.org/10.1093/eurpub/ckab047.

[24] Sanmarchi, F., Golinelli, D., Lenzi, J., Esposito, F., Capodici, A., Reno, C., Gibertoni, D., 2021. Exploring the Gap Between Excess Mortality and COVID-19 Deaths in 67 Countries. JAMA Network Open 4, https://doi.org/10.1001/jamanetworkopen.2021.17359.

[25] Soltesz, K., Gustafsson, F., Timpka, T., Jalden, J., Jidling, C., Heimerson, A., Schon, T.B., Spreco, A., Ekberg, J., Dahlstrom, O., Carlson, F.B., Joud, A., Bernhardsson, B., 2020. The

effect of interventions on COVID-19. Nature 588, E26–E28. https://doi.org/10.1038/s41586-020-3025- .

[26] Tanaka, H., Hirayama, A., Nagai, H., Shirai, C., Takahashi, Y., Shinomiya, H., Taniguchi, C., Ogata, T., 2021. Increased Transmissibility of the SARS-CoV-2 Alpha Variant in a Japanese Population. International Journal of Environmental Research and Public Health 18. https://doi.org/10.3390/ijerph18157752.

Table 1: COVID-19 の感染流行の波。原因は NIID [14] を参照した。夏と冬の季節的な要因とは、夏休みやお盆又は正月の帰省による接触機会の増加、外気温に対する冷暖房の使用による換気回数の減少を指す。免疫の減衰とは、ワクチン接種又は感染により獲得した免疫の減衰を指す。

	期間	一日の新規陽性者数の最大値	原因
1	Mar. 2020 - Jun. 2020	644	欧米もしくはその他の国からの旅行者や帰国者によるウイルス流入
2	Jul. 2020 - Sep. 2020	1597	行動抑制（緊急事態宣言）の緩和
3	Oct. 2020 - Feb. 2021	8045	季節的な要因
4	Mar. 2021 - Jun. 2021	7244	夜間滞留人口の増加（首都圏）、 株
5	Jul. 2021 - Sep. 2021	25975	季節的な要因、 株
6	Jan. 2022 - Jun. 2022		季節的な要因、 株、 株 BA.1 及び BA.2 系統
7	Jul. 2022 - Sep. 2022		免疫の減衰、季節的な要因、 株 BA.5 系統
8	Oct. 2022 -		

Table 2: 新型コロナウイルス対策予算と社会保障関係費（臨時・特別措置分を含む） [13]

年度	A. (当初) 新型コロナウイルス対策予算（億円）	B. (補正) 新型コロナウイルス対策予算（億円）	のうち医療体制の整備、拡充（億円）括弧内の数字は割合	cf. 社会保障関係費（億円）
2019	0	0	0	341306
2020	0	734173	206570 ( )	356914
2021	50000	203746	189293 ( )	358343

Table 3: 日本の超過死亡数と COVID-19 感染死者数 [11, 15]

年	実際の全死亡者数（A）	例年の死亡者数をもとに推定される死亡数（B）	超過死亡数（ ）	人口百万人当たりの超過死亡数	COVID-19 感染死者数
2020					3459
2021					14926

Table 4: 2015 年から 2019 年まで 5 年間（過去 5 年間）平均と 2020 年及び 2021 年の死因別死亡者数の比較 [12]

死因分類コード	死因	過去 5 年間の平均死亡数（人）	2020 年の増加率	2021 年の増加率
02108	膵の悪性新生物＜腫瘍＞	34245	1.10	1.13
02118	悪性リンパ腫	12580	1.11	1.11
05000	精神及び行動の障害	18972	1.22	1.32
05100	血管性及び詳細不明の認知症	16887	1.23	1.32
06000	神経系の疾患	41724	1.23	1.33
06400	アルツハイマー病	15913	1.31	1.44
06500	その他の神経系の疾患	13624	1.20	1.27
14202	慢性腎臓病	17611	1.13	1.20
18000	症状，徴候及び異常臨床所見・異常検査所見で他に分類されないもの	125222	1.27	1.44
18100	老衰	102164	1.30	1.49
18300	その他の症状，徴候及び異常臨床所見・ 異常検査所見で他に分類されないもの	22974	1.17	1.24

Table 5: 2015 年から 2019 年まで 5 年間（過去 5 年間）平均と 2020 年及び 2021 年の死因別死亡者数の比較 [12]

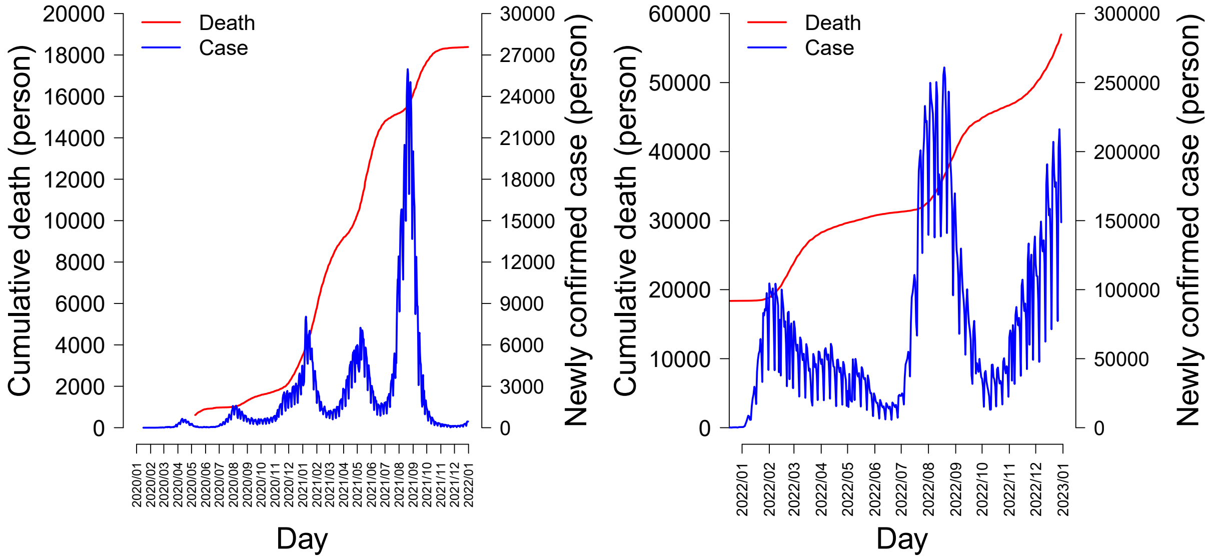
死因分類コード	死因	過去 5 年間の平均死亡数（人）	2020 年の減少率	2021 年の減少率
09202	急性心筋梗塞	34654	0.881	0.882
10000	呼吸器系の疾患	198158	0.872	0.886
10200	肺炎	105422	0.744	0.694

Table 6: 2015 年から 2019 年まで 5 年間（過去 5 年間）平均と 2020 年及び 2021 年の死亡者数と変化率 [12]

死因分類コード	死因	2020 年の変化率 (%)	過去 5 年間の変化率の平均値 (%)	過去 5 年間の死亡者数の平均値	2020 年の死亡者数	2021 年の死亡者数
02118	悪性リンパ腫	5.47	2.80	12580	13998	13997
09102	その他の高血圧性疾患	12.7	2.12	3781	4525	4631
11200	ヘルニア及び腸閉塞	4.62	0.735	7042	7443	7840
20200	自殺	4.09	-4.73	20803	20243	20282

Table 7: 2015 年から 2019 年まで 5 年間（過去 5 年間）平均と 2020 年及び 2021 年の死亡者数と変化率 [12]

死因分類コード	死因	2020 年の変化率 (%)	過去 5 年間の変化率の平均値 (%)	過去 5 年間の死亡者数の平均値	2020 年の死亡者数	2021 年の死亡者数
01000	感染症及び寄生虫症	-6.33	-1.68	24505	22129	22152
02102	食道の悪性新生物＜腫瘍＞	-5.79	0.0543	11549	10981	10958
02109	喉頭の悪性新生物＜腫瘍＞	-10.6	-2.57	899	781	795
02112	乳房の悪性新生物＜腫瘍＞	-1.05	2.25	14380	14779	14908
10000	呼吸器系の疾患	-11.8	-1.06	198158	172727	175483
10100	インフルエンザ	-274	13.6	2637	956	22
10300	急性気管支炎	-55.2	-6.49	415	239	210
10500	喘息	-27.8	-1.54	1570	1158	1037
11100	胃潰瘍及び十二指腸潰瘍	-10.0	-2.37	2563	2265	2326
15000	妊娠，分娩及び産じょく	-39.1	-1.96	35	23	28
17000	先天奇形，変形及び染色体異常	-11.1	0.247	2044	1866	1961
17200	循環器系の先天奇形	-9.35	-2.94	876	749	806
17400	その他の先天奇形及び変形	-14.1	0.369	572	524	570
20101	交通事故	-15.5	-5.90	4927	3718	3535



(a) 2020-2021 年　　(b) 2022 年

Figure 1: 日本国の COVID-19 の新規陽性者数と累積感染死者数 [11]

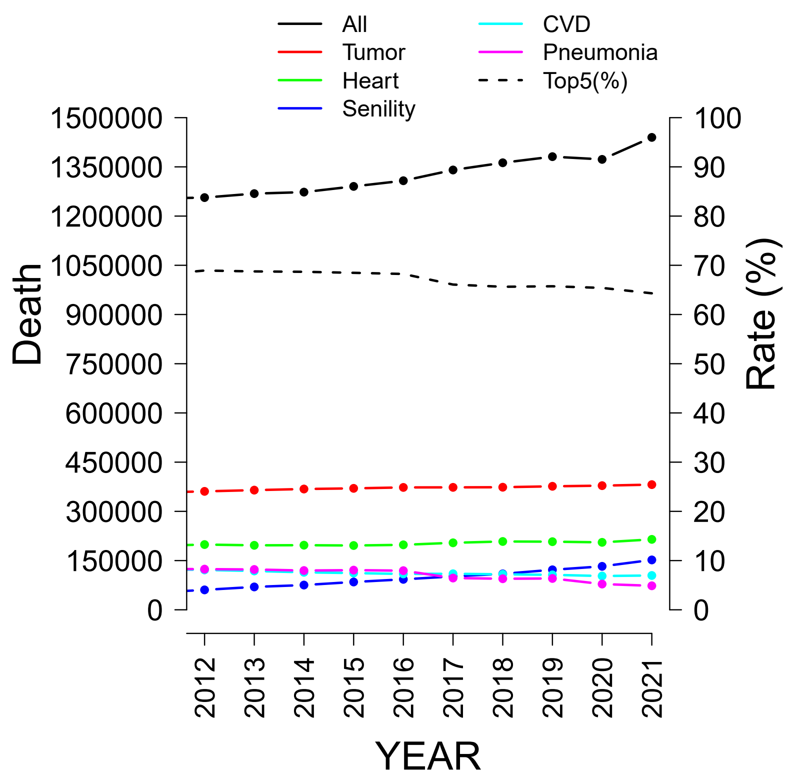
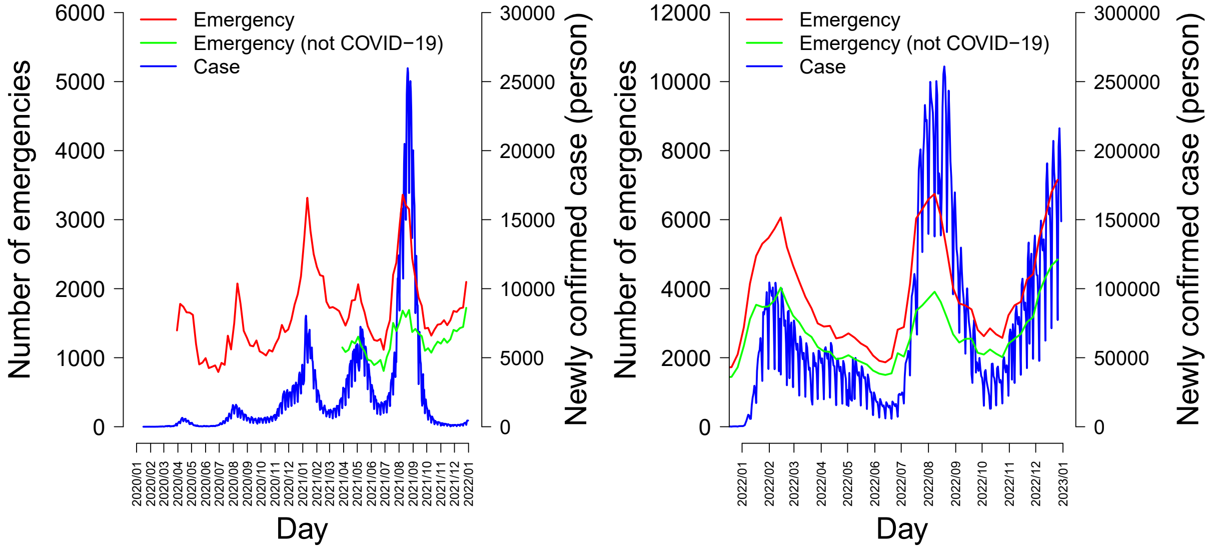


Figure 2: 日本人の全死亡数と 2020 年における死因上位５つの死亡数とその全死亡数に占める割合の移り変わり。ただし、Tumor 悪性新生物＜腫瘍＞、Heart 高血圧性を除く心疾患、Senility 老衰、CVD 脳血管疾患、Pneumonia 肺炎。



(a) 2020-2021 年　　(b) 2022 年

Figure 3: 日本国の救急搬送困難事案数と全事案数のうち非コロナ疑いの件数、及び COVID-19 の新規陽性者数 [5]

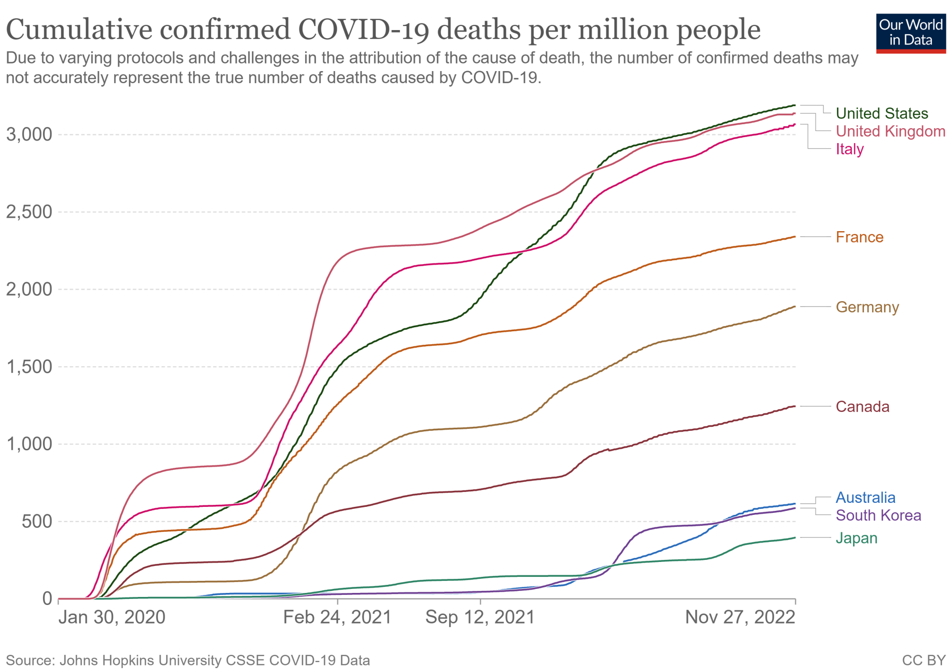


Figure 4: G7 諸国とオーストラリアと韓国の 100 万人当たりの COVID-19 感染死者数 [20]

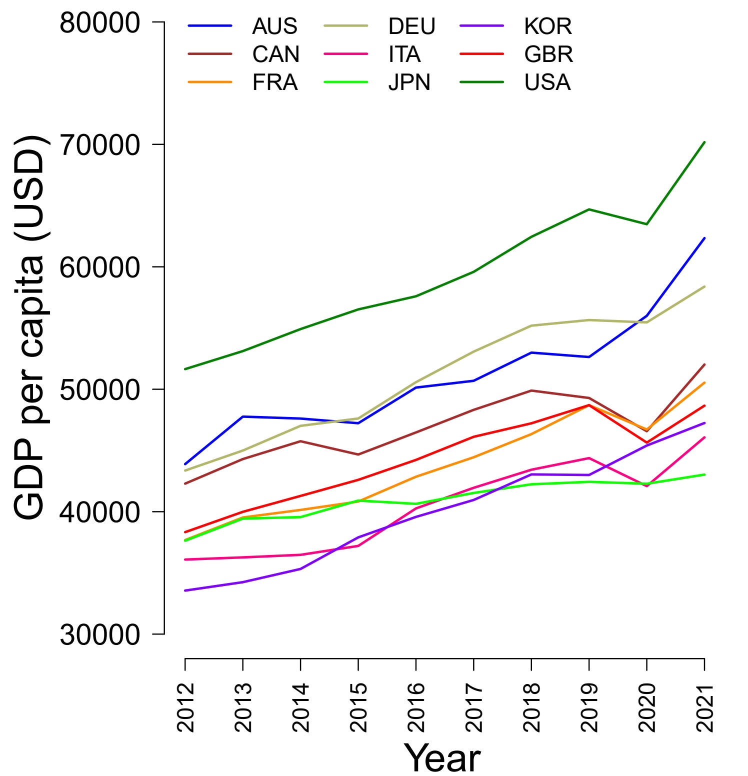
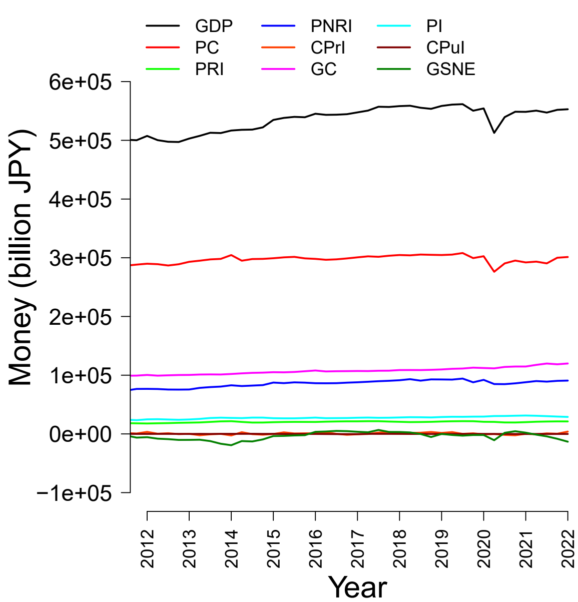
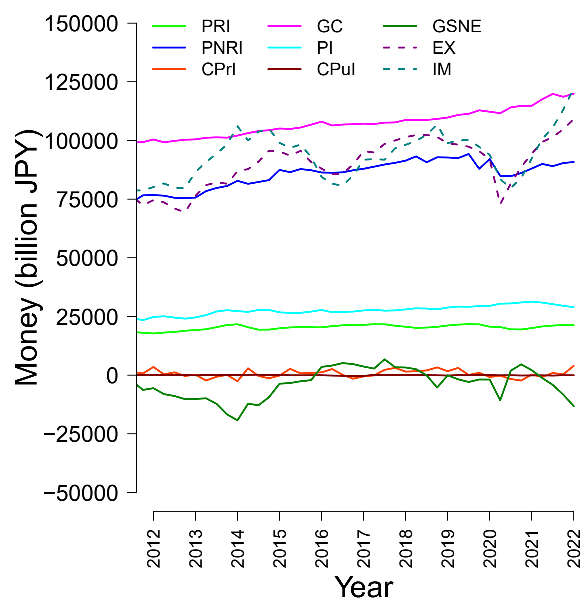


Figure 5: G7 諸国とオーストラリアと韓国の一人当たりの名目 GDP[17]



(a) GDP とその内訳



(b) 民間最終消費支出を除く GDP の内訳

Figure 6: 日本国の名目 GDP（名目季節調整系列）[3]。PC 民間最終消費支出、PRI 民間住宅、PNRI 民間企業設備、CPrI 民間在庫変動、GC 政府最終消費支出、PI 公的固定資本形成、CPuI 公的在庫変動、GSNE 純輸出、EX 輸出、IM 輸入。

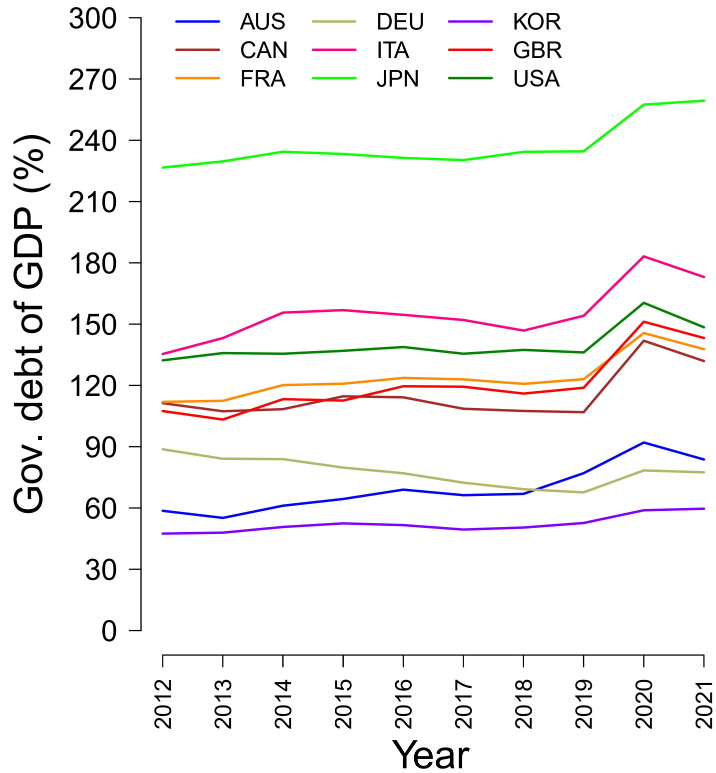


Figure 7: G7 諸国とオーストラリアと韓国の対 GDP 比国債発行残高 [18]

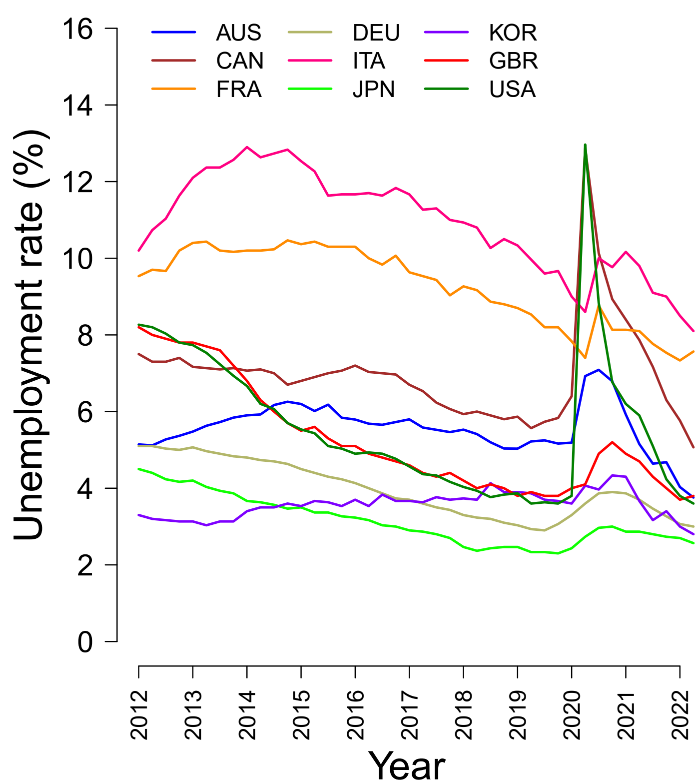


Figure 8: G7 諸国とオーストラリアと韓国の四半期ごとの失業率 [19]

Chapter V

日本国の水産業及び水産資源管理の評価と展望

1　Introduction

この章ではこれまでの日本国の水産業の評価と近年の先行研究から見出されるこれからの水産資源管理についての展望を述べる。

第 2 節では公開データを用いて日本国の水産業を見直す。日本国の水産関連予算は毎年国会の議決を経て決定され、水産庁（以下 JFA) のウェブサイトで公開されている [45]。さらに五年に一度水産基本計画が発表されており [46]、加えて毎年の行政側の発行物として水産白書がある [47]。また、農林水産省（以下 MAFF）が水産業にまつわる各種のデータを公開しており、五年に一度水産業を営んでいるすべての世帯や法人を対象に全国一斉の調査（漁業センサス）が実施される [61, 62]。研究機関の発行物として、は水産研究教育機構（以下 FRA）の資源評価がある [17, 18]。これらの中から水産基本計画、水産関係予算を見直し、更に経済活動としての水産業の動向について検証する。

次に第 3 節では、現在までと将来の水産資源管理にとって重大な概念と現象として、最大持続生産量（Maximum Sustainable Yield, MSY）、Ecosystem Based Fishery Management (EBFM) 、気候及び環境変動を挙げ、先行研究をまとめる。MSY は目指すべき資源水準の参考値として重要な概念であり、利用の賛否について長い論争があった [55, 60]。EBFM は単独の魚種ではなく生態系全体を管理する概念であり、近年多くの研究がなされている [13, 39, 74]。気候及び環境変動は現在世界中で課題となっており、水産資源管理の面でその関わりを見直す。

第 4 節で上記の知見から考えられる将来の水産資源管理の展望と取るべき政策を提言する。

貿易統計データや資源評価での魚種名の表記について、ひらがな表記の場合とカタカナ表記の場合があるが、以下ではカタカナ表記に統一する。イワシ、サバ、ブリは、総称する場合と個々の種を言及する場合を考慮して、適宜イワシ類、サバ類、ブリ類に表記を置き換えた。また、「スケトウダラ」と「スケソウダラ」は、「スケトウダラ」（*Theragra chalcogramma*）に表記を統一している。

2　Review of the Japanese fisheries policy

2.1　水産基本計画

水産基本計画は、水産基本法第 11 条に基づき水産に関する施策の総合的かつ計画的な推進を図るために政府が策定するものとされており、2002 年から五年に一度の頻度で改定が行われている [46]。水産基本計画では、水産業における労働力確保や漁港や漁村の利用などの経済政策、

及び資源管理や自給率目標などの資源の利用政策の方針が論じられている。2022 年の水産基本計画から、これまでの目標に加えて新たに重要業績評価指標 (Key Performance Indicator, KPI) として、養殖業で一部魚種の人口種苗比率と生産量目標、また輸出額目標や漁船の電化、燃料電池化等に関する技術確立が加えられた。

水産基本計画が初めて発表された 2002 年から、十年後の数値目標として魚介類全体、食用魚介類、海藻類それぞれに国内生産量目標、国内消費量目標、そこから導き出される自給率目標を設けている。ここでの国内生産量とは日本国における漁獲量と養殖収獲量を合計した値とする。2002 年、2007 年の計画当初の数値目標と十年後の実際の数値を比べた時、魚介類全体、食用魚介類、海藻類の生産量と消費量の目標は全て未達成のままになっている（Figure 1）。例えば、2002 年の水産基本計画で 2012 年の魚介類全体の生産量目標を 682 万トンと定めていたのに対し、実際の生産量は 433 万トンにとどまっている。水産基本計画が改定されるたびに各指標の目標値は下方修正されていくが、実際の値がその目標値を下回る事態が続いている。さらに、前の版の水産基本計画の中で設定し達成されなかった目標に対し、後年の水産基本計画での原因究明などの記述も見当たらない。

Figure 2 は、2011 年から 2020 年までの十年間の国内生産量の平均値が上位十種（ホタテガイ、サバ類、マイワシ、ブリ類、カツオ、カタクチイワシ、スケトウダラ、カキ類、マアジ、サンマ）の魚種の生産量の移り変わりを示す。ホタテガイ、サバ類、マイワシ、ブリ類、カツオを上位五種とし、上位十種と上位五種の国内生産量全体に占める割合も示している。それらの割合は共に 2002 年から増加傾向にあり、2020 年には上位十種で国内生産量の　　　、上位五種で　　　を占めていることが特徴である。2002 年の国内生産量と比べ、マイワシが増加傾向、サバ類が増減はあるものの増加傾向、ブリ類は微増であったの対し、ホタテガイ、カツオ、カタクチイワシ、スケトウダラ、カキ類、マアジ、サンマは減少傾向であった。

2.2　水産関係予算

日本政府の水産関係予算の当初予算は、2012 年度から 2022 年度は年間 2000 億円前後で推移している [45]。予算の内訳については、予算の項目の名前や区分けが年を経て変更されるものや単年度のみ別称が用いられたものがあるため、資源調査及び評価、外国漁船対策等、養殖業関連、内水面及びさけます等資源対策、捕鯨対策、水産多面的機能の発揮等、漁業経営安定対策事業、水産基盤整備事業、その他と分類した。水産関係予算は、公共と非公共の部門に区分けされており、公共部門では水産基盤整理や災害復旧、非公共部門では資源調査及び評価、外国漁船対策等、養殖業関連、内水面及びさけます等資源対策、捕鯨対策、水産多面的機能の発揮等、漁業

経営安定対策事業が計上される（Figure 3）。公共部門は 2009 年以前は年間 1300 億円以上を計上し、2010 年以降は 2019 年（1007 億円）を除いて 900 億円を下回っている。その内訳はどの年も 8 割以上が水産基盤整備に充てられている。非公共部門は、年間 900 億円から 1100 億円の間を推移しており、約 2 割が漁業収入安定対策等に充てられている。

水産資源の資源調査及び評価への予算は 2018 年まで年間 30 億から 50 億円程度だったのに対し、2019 年から増加し、2020 年以降は年間 90 億円以上が投じられている。2018 年成立の改正漁業法で資源評価対象魚種の拡大が掲げられ、2023 年度には 200 種程度を評価対象とするロードマップの存在が背景にある [48]。

養殖漁業に関しては、2020 年度から予算が大幅に増加し、2020 年は 330 億円、2022 年は 230 億円が投じられている（Figure 3）。また、Figure 4 によると、生産量と産出額は海面養殖が内水面養殖を大きく上回っている。生産量は、海面養殖で 1994 年の 1344 キロトンを最大に減少傾向が続き、内水面でも減少傾向である。産出額では、海面養殖で 1991 年の 6058 億円から減少傾向が続いていたが、2010 年代初めに底を打ち、2019 年には 4802 億円までに回復した。内水面での産出額も 2002 年から増加傾向に転じており、2019 年に 205 億円となっている。

内水面及びさけます等資源対策は、内水面漁業の持続的な管理の在り方の検討、ウナギ等の内水面資源の回復と適切な管理体制の構築、サケの回帰率の向上に必要な放流体制への転換、資源造成・回復効果の高い種苗生産・放流等の手法、対象種の重点化等を支援に充てられる。2013 年までは年間 7 億円弱程度の予算規模であったが、以降は年間 10 億円強程度の規模まで引き上げられている（Figure 3）。

捕鯨対策費用は 2015 年以前は年間 20 億円にも満たなかったが、2016 年度以降は年間 50 億円以上で推移している。捕鯨に関しては、日本は国際捕鯨取締条約から脱退し、2019 年 7 月から商業捕鯨を再開することを宣言した [75]。2019 年から捕鯨業による捕獲実頭数と産出額は急増し、2019 年に 309 頭及び　　億円、2020 年に 327 頭及び　　億円となっている（Figure 5）。

2.3　水産経済

2.3.1　生産性

MAFF の漁業経営統計調査のデータ [65] を用いて、Figure 6 に養殖業を営む個人経営体の漁労支出の内訳と漁労収入の移り変わりを示す。数値は主要な生産地別のデータを加重平均した値であるが、マダイ、カキ類、ノリ類で 2016 年から調査地域の数が変更され、必ずしも 2015 年以前と連続するものではない。ホタテガイ、カキ類、ノリ類の漁労所得（漁労収入から漁労支出を

引いたもの）が黒字を計上しており、ブリ類とマダイは年によって変動がある。ブリ類とマダイではえさ代と種苗代が漁労支出の大部分を占めており、漁労支出と漁労収入の値も他の魚種より大きかった。マダイのえさ代は 2011 年から上昇傾向にあり、2020 年と 2016 年の漁労収入は同程度（7111 万円と 7061 万円）だったにもかかわらず、2020 年はえさ代の高騰で漁労所得が赤字を計上している。2016 年のブリ類の漁労収入の下落は、九州の八代海で発生した赤潮の影響が考えられる [70]。他の魚種の漁労支出の内訳については、カキ類は雇用労賃、ノリ類は油費の割合が比較的多かった。

漁労所得を最盛期の漁業従業者数と延べ出漁日数で除したものを利益効率の指標として Figure 7 に示す。ノリ類の利益効率は 2006 年から 2020 年までやや増加したが、ホタテガイとカキ類はほぼ横ばいか微増にとどまっている。ブリ類の利益効率はカキ類のそれを下回っており、マダイの利益効率は年によって変動が大きい。

2.3.2　輸出入

MAFF の農林水産物輸出入情報・概況のデータ [66] を用いて、輸出入された水産物の金額を Figure 8 と Figure 10 に示す。これによると、輸入金額は 2020 年に落ち込みが見られるが、2019 年まではやや増加傾向にあった。また、その内訳を生きている魚、水産物（生鮮・冷蔵・冷凍）、塩乾水産物、水産調製品、魚油海獣油、その他に分類すると、金額は水産物（生鮮・冷蔵・冷凍）がその大部分を占めている。水産物（生鮮・冷蔵・冷凍）の輸入金額や輸入重量の上位種として、サケマス類、カツオマグロ類、エビ、タラ、イカ、カニの輸入重量と 1kg あたりの単価をそれぞれ Figure 9 (a) と (b) に示す。エビについては、シュリンプ、プローン及びイセエビ、ロブスターを合わせた値を示しているが、輸入重量と輸入金額ともにほとんどがシュリンプ、プローンで占められている。いずれの魚種も輸入重量は 2012 年と比べ横ばいかやや減少の傾向が見られるが、輸入単価はやや増加もしくは増加傾向であった。(Figure 9)。特にカニは 2012 年の 985 円/kg から 2021 年の 3063 円/kg まで 3 倍以上の上昇があった。

Figure 10 によると、水産物の輸出金額は、2020 年を除き増加傾向が続いている。その内訳を生きている魚、水産物（生鮮・冷蔵・冷凍・塩蔵・乾燥）、水産調製品、魚油海獣油、真珠、その他に分類すると、特に水産物（生鮮・冷蔵・冷凍・塩蔵・乾燥）の輸出金額が 2021 年に 2012 年の 2 倍以上になっている（2012 年 914 億円、2021 年 1923 億円）。水産物（生鮮・冷蔵・冷凍・塩蔵・乾燥）の輸出金額や輸出重量の上位種として、 サケマス類、カツオマグロ類、サバ類、ブリ類、スケトウダラ、ホタテガイ、イワシ類の輸出重量と 1kg あたりの単価をそれぞれ Figure 11 (a) と (b) に示す。輸出重量に着目すると、サバ類、イワシ類、ホタテガイが多く輸出されていること

が分かる。また、スケトウダラとサケマス類は 2012 年から 2021 年まで大きく減少した。2019 年からはブリ類の輸出重量が増えたが、輸出金額単価は大幅に低下した。サケマス類とカツオマグロ類はやや増加傾向が見られ、スケトウダラ、サバ類、イワシ類は低単価で横ばいであった。

2.4　日本の主要魚種

魚介類全体の生産量を大きく変動させるのは、マイワシ、サバ類、サンマ、マアジ、ニシンのような小型浮魚類であり、日本ではマイワシとサバ類の生産量が全体の一割をそれぞれ占めている（Figure 2）。生態系の観点からも小型浮魚類は、飼料魚（forage fish）としてプランクトンから上位捕食者までエネルギーを伝達する役割を負う重要な魚種である [15]。その特徴として環境変動や人間の漁獲活動に影響を受けて個体数が大きく変動することが一般的に言われている [14, 42]。現在 TAC 対象魚種に指定されているのはマイワシ、マサバ、ゴマサバ、サンマ、マアジである。マサバとゴマサバは別の種であるが、漁獲統計では多くの場合両方を合わせたサバ類として集計されており、抽出標本から混獲率を推定し、それぞれの漁獲量を推定している [25]。サンマは国際漁業資源であり、北太平洋の資源は日本以外にもロシア、台湾、韓国、中国、バヌアツによって漁獲される [26]。2019 年から 2021 年の資源水準は MSY 水準の 43%であるのに関わらず、2020 年と 2021 年の北太平洋公海での総漁獲可能量は　　万トンに設定されている。これは、2020 年の合計漁獲量が約 14 万トンだったことを踏まえると、現実に想定される漁獲量よりも TAC が大きく設定されてしまっている。日本国でもサンマの TAC が現実に漁獲される量よりも大きな値に設定される傾向が続いており、TAC 管理が機能していない恐れがある。マアジは特に太平洋系群において漁獲圧が望ましい水準より高く、かつ資源量が望ましい水準より低い状態が続いていると推定されている [27]。

水産物流通調査のデータ [49] を用いて 2006 年から 2020 年の小型浮魚類の漁獲量と単価の関係を Figure 12 に示すと、いずれの種も負の相関があることが分かる。マイワシは四種の中で最も単価が低く、2020 年は漁獲量が 70 万トンに対し単価は 1kg あたり 42 円であった。これに対しサンマは漁獲量に対する単価の変動が最も大きく、単価と漁獲量を単回帰分析すると、漁獲量が 1 千トン減少すると単価が約　　円上昇する関係が見られた。ただし 2019 年から 2020 年はサンマの漁獲量減少に対する価格上昇がより顕著になり、2020 年は漁獲量が約 3 万トンに対し単価は 1kg あたり 483 円であった。Figure 10 でも見られるように、サバ類やイワシ類のような小型浮魚類は単価が低いものの輸出重量は多いため、高い水準で安定した漁獲量を得ることのできる漁獲管理の必要性が示唆される。Yatsu[99] は小型浮魚類の漁獲管理について以下の四つ政策を推奨した。

1. 管理戦略評価 (Management Strategy Evaluation, MSE) やオペレーティングモデルを用い、漁業と独立した監視を含む漁獲管理規則（Harvest Control Rule, HCR）と資源評価方法を改善する。

2. より現実的なオペレーティングモデルを作成のために、系群及び種間の個体群動態の機構や生態系の変化を比較研究する。

3. 小型浮魚類が気候変動の潜在的な影響に順応できるように海洋生物多様性を保全する。

4. 日本海、東シナ海、黄海における系群の資源評価管理のための国際的な枠組みを確立する。

前節での輸出入量や金額から判断すると、日本への輸入からは、特にサケマス類、カツオマグロ類、エビ類が日本人にとって重要魚種であることを推察することができる（Figure 9）。水産基本計画で目標にも掲げられている自給率の上昇の観点で見ると、これらの種の自国生産供給量を高めることが一つの案となる。

エビについては、養殖と漁獲を合わせたエビ類の国内生産量は減少傾向である。東南アジア諸国を中心に世界的にバナメイエビ *Litopenaeus vannamei* の養殖が商業的に行われており、日本でもその陸上養殖の効率的な収穫時期管理が企業との共同研究で調べられた例がある [80]。今後日本国内での養殖は、生産規模や効率で他国に対する優位性を持つことができるかが課題になる。

カツオマグロ類の管理に関しては、複数の地域漁業管理機関が設置されそれぞれ複数の国が加盟している [23]。カツオ、メバチ、キハダ、ビンナガ、クロマグロ（及びミナミマグロ）にそれぞれ管理基準値が設けられており、管理戦略評価（Management Strategy Evaluation）が実施されているのが特徴的である [24]。

前述の内水面及びさけます等資源対策の中で、サケマス類の種苗生産や放流の改善のために予算が割り当てられている。現在の FRA の資源評価ではサケマス類の魚種としてカラフトマス、シロザケ、サクラマスが管理対象となっている [17]。ただしそれらの資源評価の方法は、いずれも漁獲数や捕獲数の水準と動向（カラフトマスはこれらに加えて再生産モデルによる解析も含む）のみで、資源尾数及び資源量の推定は明記されていない [19, 20, 21]。3 種とも管理措置は稚魚放流と区域的な禁漁を主としており、シロザケには持続的漁獲量として 2004 万尾（6.4 万トン）という値が算出されているが、3 種ともに TAC 対象種ではない。Morita [69] はサケ類の資源変動の原因について漁獲、気候変動、放流を挙げ、このうち漁獲の影響についてあまり着目されることがないことを指摘した。そして孵化放流を通じて起こる遺伝的な変質（domestication）のリスクを低減させるために自然産卵を活用した資源管理を提案し、そのために河川に遡上し

たサケの捕獲数の上限設定や野生魚の漁獲率の低下、放流魚の漁獲率の上昇を提言した。養殖業においても、サケマス類の生産販売利益に関するデータがブリ類やマダイのように整備されておらず、早急な情報公開が求められる。

日本からの輸出では、輸出重量及び単価を鑑みてホタテガイが重要な商材であることが分かる（Figure 11）。現在ホタテガイの生産は養殖と漁獲が両方行われているが、FRA の資源評価には情報が示されておらず、生産量と養殖量のデータが MAFF [63] に公開されているのみである。さらに近年ブリ類が商材としての価値を高めてきており、多くの輸出先は米国である [66]。ブリの国内生産に関しては、天然のブリの幼魚（モジャコ）が持続的に採取できることが不可欠である。しかしながら、FRA [22] によると、2021 年のモジャコ採捕尾数は前年の 2020 年から大きく減少して過去最低の 880 万尾であったこと、モジャコの採捕重量に相当する統計データが 2019 年以降公開されていないことが指摘されている。また、日本国周辺の中緯度域の海面水温が上下することで地域別のブリの漁獲量が変動することが報告されているため、このような知見を活かした適切な資源管理の開発運用が求められる [81]。

3 Review of scientific literature

3.1 Maximum Sustainable Yield

Maximum Sustainable Yield (MSY) 最大持続生産量は、持続して利用可能な水産資源の収獲量として定義づけられ、系の平衡状態や空間構造の均一性など多くの仮定を前提にして導かれる量であった。これに対しては Larkin [55] の批判が有名である。Mace [60] では MSY への認識の変化について言及されている。MSY を達成するような漁獲係数（漁獲圧）　は国連食糧農業機関（FAO）が発行する協定やガイドラインに登場し、アメリカのマグナソン・スティーブンス法（Magnuson-Stevens Fishery Conservation and Management Act）にも組み込まれ、一つの目安、参照点として活用されている。日本国の漁業法第 2 節第十二条でも MSY が目指すべき資源量の水準の一つとされている。 MSY を政策として実行するためには (i) 科学者が主要な経済漁業の既存の資源レベルをある程度正確に推定することができること、(ii) 科学者が資源が持続可能な最大レベルに達したときを正確に認識できること、(iii) これらのレベルに達したときに政府が漁業を削減するために迅速に行動すること、(iv) 科学者が漁業の再開を可能にするのに十分な回復レベルを正確に特定できること、という四つの仮定に基づく必要がある [16]。

Walters et al. [94] は、単魚種への MSY 政策の広範な適用は、一般に生態系構造の深刻な悪化、特に頂点捕食者種の喪失を引き起こすことを示した。また、複数の魚種を収獲する場合に

Lotka Volterra 方程式を用いて MSY を達成しようとすると、捕食者被捕食者系と競争系のいずれにおいても一部の種が絶滅する可能性があることが指摘されている [34, 57, 58]。Legovic [58] は Lotka Volterra 捕食者被捕食者系方程式での MSY について調べ、生態系構造を考えたとき MSY を目指して収獲をすることは、収獲対象となる生物種の栄養段階より上位の捕食者たちの絶滅を招く可能性があることを示した。よって MSY の概念を生態系管理に持ち込むべきではないと結論付けている。Takashina and Mougi [87] は、収獲項付き logistic model (Schafer model) にパッチ構造を組み込むことで収獲対象種の生息地の空間不均一性を考慮し、従来の MSY は過大評価であることを示した。

近年では、MSY に代わる指標も提案されている。例えば、Hilborn [38] は Pretty Good Yield（"sustainable yield at least 80 percent of the maximum sustainable yield" と定義）という指標を導入し、尖度（steepness）という量を導入して感度分析を行った。結果として、尖度が大きい魚種ほど収穫量も大きいことや、尖度が枯渇率が大きくしながらもより大きな収穫量をあげることを示した。また、Pretty Good Yield は複数魚種の管理に応用することも可能である [40, 78, 88]。Hilborn et al. [40] は食料安全保障と利益と生物多様性の保護との間にはトレードオフがあると主張し、どの系群も乱獲しないために漁獲割合は最大漁獲の　、最大利益の　　パーセントになるまで低くすることが必要と結論付けた。さらに資源量の多い状態で系群を維持することは気候変動や海洋酸性化、外来種の流入などの環境変動の影響を和らげ、かつ海鳥や海洋哺乳類にとっても良いと言及した。Kempf et al. [52] は、マダラと saithe を頂点捕食者としてモデル化した北海の生態系に対し複数魚種の漁獲管理戦略を比較し、結論として Pretty Good Yield（この論文では漁獲量を MSY の　　にすると定義）が良いのではないかと提案している。

3.2 Ecosystem Based Fishery Management

資源管理において単一魚種を漁獲することはほとんどなく、多くの漁業は複数の魚種を同時に漁獲していることに注意を払う必要がある [41]。ある魚種の系群を単体で管理するモデルから複数魚種及び生態系全体を捉えたモデルがあり、 Ecosystem Based Fishery Management (EBFM) の研究が近年注目されている。Pikitch et al. [74] によると、EBFM の全体的な目的は、健全な海洋生態系やそれが支える漁業を維持することである。特に EBFM には、環境の質や生態系の状態を指標で測り生態系の悪化を避けること、自然生態系の不可逆的な変化のリスクを最小化すること、生態系を損なうことなく長期的な社会経済的利益を獲得し維持すること、人間活動の結果を理解するため生態系の過程の知見を創出することが求められる。また、単一種ごとの管理がうまくいっていたとしてもそれは漁獲対象種にならない種に対する考慮が含まれていない

ため、EBFM の導入が推奨されるという意見もある [39]。生態系管理に加えて経済的な漁獲管理を入れた EBFM の評価も試みられている [12, 13]。このうち Doyen et al. [13] は複数のシミュレーションから資源量の管理を重視したシナリオが生態学的、経済学的リスクを大きく減らし EBFM を促進すると言及した。EBFM のように包括的なシステムを採用する際の障壁としては、EBFM のまず概念が知られていないこと、伝統的な慣習が続いていること、新しい方法への猜疑心があること、生態系が複雑なために何の試みもしなくなることが指摘されている [59]。

EBFM への一つの手段として、単一の種の管理ではなく、生態系の栄養段階の上位から下位までを取り扱う包括的な End to end (E2E) モデル がある。Fulton [30] は、それを戦術的な道具ではなく、what if の仮想的な世界をシミュレーションで調査する戦略的な手段として効果があると言及した。E2E モデルについては、生態系を網羅的に扱う Atlantis [1, 31, 51, 83] や OSMOSE [28, 29, 35, 36, 79]、 Ecopath with Ecosim (EwE) [6, 7, 33] のようなモデルがある。とりわけ EwE については、日本でも瀬戸内海周防灘 [95]、三陸沖 [100] への適用例がある。E2E モデルは気候の影響まで拡張した非生物的環境に沿って生態系全体を表現しようと試みる [30] が、系が複雑になるにつれて必要なデータ数が多くなることが課題であり [84]、データ不足でそれほど性能が改善されないこともあるという指摘がある [6]。これらに加え、生態系管理を考慮しつつ関心のある問題にモデル構築の焦点を当てた MICE (Model of Intermediate Complexity for Ecosystem Assessments) モデルなどがある [73, 77, 91]。

3.3 気候及び環境変動

Williams and Brown [97] はレビュー論文の中で気候変動、広範囲の地理的条件の変化、生物多様性の喪失の加速、そして文化的な価値の変化が資源管理の文脈の中で拡大し、順応的管理の適用に新たな課題を与えていると言及した。長期的な気候変動としての地球温暖化と中期的な生産性変化としてのレジームシフトが環境変動の例として挙げられる。

過去の事象からは予測できない長期的な環境変動を考慮した研究が進められている。例えば、Tucker and Runge [90] は収獲項付きロジスティックモデルから環境収容力もしくは内的成長力が長期的に減っていくときに最適と思われる収獲行動をとった時の資源状態の差異について言及した。Bryndum-Buchholz et al. [4] は気候変動に対する世界各国の漁獲管理について調べ、日本の水産業はより持続的な漁獲活動や変動する気候に順応する規制作りに向かう必要性が生じることを予見した。

Lee et al. [56] によると、レジームシフトについてはっきりとした定義はないが、海洋の気候条件と海洋生物群集の不連続な変化を指す。北大西洋では 1960 年代初めと 1980 年代終わりに、太

平洋では1925、1945、1977、1989、1998年にレジームシフトが起こったとされる。Yasunaka and Hanawa [98] はレジームシフトを “the ’significant’ and ’systematic’ changes between the two quasi steady states, continuing more than 5 years” と定義し、1910年代から1990年代までのレジームシフトを1925/26、1945/46、1957/58、1970/71、1976/77、1988/89の六回と判定した。レジームシフトの検出には様々な方法が試みられてきており [54, 68, 71]、判定に使う指標は、北大西洋でNorth Atlantic Oscillation Index (NAOI) と Gulf Stream Index (GSI)、太平洋でALPI (Aleutian Low Pressure Index) と PDO (Pacific Decadal Oscillation) が挙げられる。また、DeYoung et al. [10] は、海洋レジームシフトの三つの主要な要因は、非生物的プロセス、生物的プロセス、および構造的生息地の変化であるとした。これら三つの要因には、相乗的に作用し、その影響を分離することが困難な自然および人為的成分が含まれ得る。地球温暖化や大気や海洋における大規模な振動などの非生物的要因は、一般的に最も容易に特定される。生物的要因には、乱獲に起因する食物網の再構築や、湧昇系におけるマイワシとカタクチイワシの個体群の魚種交代のような主要種の内部個体群動態が含まれる。構造的生息地の破壊は、ハリケーンなどの自然の非生物的事象、またはサンゴ礁での dynamite fishing やマングローブ林の伐採と破壊、その後のサンゴ礁魚の苗床エリアの喪失、外来種の導入などの人為的影響の結果である可能性がある。

Essington et al. [15] は資源崩壊は自然要因の生産力の低下に対し、漁業割合が高い割合を保ったままにした事で起こることを言及し、生産力の低下に対する漁業活動の行動変化の遅れが資源崩壊を招くことを言及した。長期的な気候変動やレジームシフトによる生産性の変化、もしくは一時的な環境変化を漁獲管理に組み込むかはこれまで多く議論され、先行研究のレビューがされてきた [53, 76]。例えば、Ianelli et al. [43] は東ベーリング海のスケトウダラについて、気候変動に関する政府間パネル (IPCC) の気候モデルを用いて気候変動がない場合とある場合に基づく漁獲管理戦略の比較し、現状維持の管理戦略では平均漁獲量が下がることを示した。Chavez et al. [5] は1970年代半ばに暖かい anchovy regime から sardine regime への変化があり、その逆が1990年代半ばから後半にあったと言及し、これらの大規模な自然変動は人為的な気候変動や海洋生物資源の管理の際考慮に入れなければならないと主張した。ただし、King et al. [53] は、表面海水温のような環境指標を漁獲管理ルールに組み込む試みはされてきたが、海洋の複雑性で指標間の相関関係の有意性が時間に連れて失われることもあるため、実用例は多くないと指摘した。Punt et al. [76] は、環境要因を含むように管理戦略を変更しても管理目標を達成する能力をそれほど向上させないと結論付けた。

4 Discussion

4.1 日本国の水産業と水産資源管理

水産基本計画及び水産関係予算について考察し、水産業の経済的な動向について検証を行った。過去の生産量、消費量、自給率の目標値はいずれも達成されておらず、目標設定から基準年までに行われた政策、あるいは指標そのものの適切さの見直しが必要である。国内の生産量については、Ichinokawa et al. [44] は日本で漁獲される魚種のうち 37 系群の資源評価を行った結果、37 種のうち約半分が漁獲圧が大きすぎる状態で、半分が資源量が望ましい水準を下回っていると主張した。しかし、漁獲可能量（Total allowable catch, TAC）を設定した資源管理の有効性も示し、日本の漁業は適切な漁獲係数で操業すれば資源回復したり漁獲量を増やしたりできると結論付けた。この主張が妥当ならば、2017 年の水産基本計画から掲げられた漁業の成長産業化のための資源は確保できるはずである。Figure 3 が示すように、2018 年の漁業法改正以降水産資源評価への予算は増加が見られた。このことは、資源評価対象魚種及び TAC 対象魚種の拡大を根拠とするなら妥当ではある。

TAC のような出口管理導入の際の課題として、科学的根拠のある適切な値を設定しないと資源量と漁獲量は減ること [93] や、漁業者による獲った魚の海上投棄 [2] が挙げられる。また、TAC で定めた量の取り残しを次の年の TAC や個別割り当てに持ち越すことは、漁獲量を増やすことにつなげることができるが、乱獲、資源量の低下、漁獲量の低下、漁獲量の年変動のリスクを高めてしまうこと [96] が指摘されている。Fulton et al. [32] も TAC のような出口管理は報告されない漁獲を誘因してしまい、資源評価の不確実性が高まる欠点があると言及した。Tokunaga et al. [89] は、出口管理に必要な資金をつくるために、乱獲を促進する政府の歳出 (漁船の建造や燃料への補助金など) を、漁業資源の再建に沿ったもの (船舶の買い戻し、研究、監視、執行など) に移行していくことを提言した。

Sumaila et al. [86] は入手可能な 2013 年から 2019 年までの各国の漁業補助金のデータを集め、 使途を有益（beneficial）、漁獲能力の増大（capacity-enhancing）、曖昧（ambiguous）に三分類した。その結果アジア地域の国々で世界全体の補助金金額の 55%を拠出していたことと、北米とオセアニア地域を除く全ての地域で漁獲能力の増大のための補助金が最も割合が大きかったことを指摘した。Clark et al. [8] は、政府による漁業者への補助金や船舶の買い戻し（buyback）が、過剰な漁獲能力を残してしまうことで資源の保全や経済的な効率性に負の影響を与えてしまうことを欠点として挙げている。また、Makino and Matsuda [67] は日本国の水産資源管理の歴史をまとめ、日本の沿岸漁業の特徴である共同資源管理の成り立ちについて探求した。さら

に水産資源管理の費用区分を information costs (TC-1)、The Collective Fisheries Decision-Making Costs (TC-2)、 The Collective Operational Costs (TC-3) に分類して神奈川県を例に挙げ、県の費用を分類し、結論として、監視、執行、コンプライアンスの費用が著しく低いことを指摘した。費用対効果が高く実効性のある監視体制の開発と運用が望まれる。

内水面及びさけます等資源対策の一つの事業として、ウナギ資源の回復のために予算が投じられている。しかし Kaifu [50] は報告されたウナギ稚魚の漁獲量と国内養殖池のウナギ稚魚の現存量からウナギ稚魚の輸入量を引いた差から得られる漁獲量が大きく異なっていることを指摘し、適切なデータ収集システムを早急に開発する必要があると主張した。

捕鯨業に関しては、2019 年から捕鯨業による捕獲実頭数と産出額は急増したものの、捕鯨対策予算と比べた場合はまだその規模には及ばない。これからの状況や取り組みを定期的に評価検証することが必要である。

2022 年の水産基本計画からは養殖業の成長産業化が明記され、マーケットイン型養殖業の推進、ICT 等を活用した生産性の向上、経営体の強化、輸出の拡大等を方針とし、2020 年からは養殖業への予算が大幅に増加している。ただし養殖業全体の収獲量は横ばいか微減傾向であり、ブリ類とマダイでは一人一日当たりの漁労所得は不安定である。漁船（漁獲）漁業については、漁業現場に合わせたスマート水産技術の開発と現場実装、資源変動等の変化に適応可能な経営体の育成や漁船の脱炭素化、不足する漁業人材の確保が目標に挙げられている。また、2020 年の輸出入金額の突発的な下落は、2019 年末からの SARS-CoV-2 による COVID-19 の流行によるところが大きい。COVID-19 の流行は水産業経営、特に養殖業の経営に悪影響を及ぼしたとする報告もある [85]。

4.2　展望

Hilborn et al. [41] は、水産業にとっての持続可能性（Sustainability） の定義は人によって異なり、決定者が何を重視するかで定義が変わると言及した。個体群は MSY を達成したり MSY に到達する漁獲圧を超えると乱獲になるが、そのような乱獲が社会的な理由で望ましい事もあるからである。水産業の生態学的、経済的、社会的、制度的側面の統合は、持続可能な開発にとって重要であるが、複雑である [3]。水産政策に関する意思決定の場において、漁業者、管理者、科学者など利害関係者で知識や認識の乖離があることが言及されている [37]。日本国の水産分野の研究機関である FRA は、資源調査及び評価を主たる業務としており、水産業の経済面での分析は必ずしもその役割ではない。また、戦後水産業は日本国民への蛋白質源の供給という役割を帯びて長らくその認識が色濃く残っていたからか、水産業の成長産業化のような経済活動として目

標が明示的に打ち出されたのも近年になってからである。これからの日本国の水産業の発展のためには、経済的な面を考慮した bioeconomic モデルや最大経済生産量の知見が求められる [11]。

これまでの日本国の水産資源管理の評価と近年の先行研究から考えうる政策の方向性を提言し、結論とする。

- 過去に発表した水産基本計画の評価検証を定期的に行う。
- TAC のような出口管理の適切な運用のために、予算から漁獲活動の監視費用の割り当てを増やす。また、効果的な監視体制を整備する。
- 日本人の消費及び日本の貿易上重要と思われる魚種の資源管理を見直し、必要があれば改善する。例えば放流だけでなく漁獲管理規則も考慮したサケマス類の資源管理を開発する。
- 一人一日当たりの漁労所得（利益）のような経済指標も導入し、必要があれば水産基本計画に数値目標として設定する。

また、必要なことは、供給できる水産物が潜在的に確保されていること、供給が実行可能であること、漁業従事者に利益がもたらされることである。設定された目標について検証する独立した主体が存在することが望ましい。

References

[1] Audzijonyte, A., Pethybridge, H., Porobic, J., Gorton, R., Kaplan, I., Fulton, E.A., 2019. Atlantis: A spatially explicit end-to-end marine ecosystem model with dynamically integrated physics, ecology and socio-economic modules. Methods in Ecology and Evolution 10, 1814-1819. https://doi.org/10.1111/2041-210X.13272.

[2] Batsleer, J., Hamon, K.G., van Overzee, H.M.J., Rijnsdorp, A.D., Poos, J.J., 2015. High-grading and over-quota discarding in mixed fisheries. Reviews in Fish Biology and Fisheries 25, 715-736. https://doi.org/10.1007/s11160-015-9403-0.

[3] Benson, A.J., Stephenson, R.L., 2018. Options for integrating ecological, economic, and social objectives in evaluation and management of fisheries. Fish and Fisheries 19, 40-56. https://doi.org/10.1111/faf.12235.

[4] Bryndum-Buchholz, A., Tittensor, D.P., Lotze, H.K., 2021. The status of climate change adaptation in fisheries management: Policy, legislation and implementation. Fish and Fisheries 22, 1248-1273. https://doi.org/10.1111/faf.12586.

[5] Chavez, F.P., Ryan, J., Lluch-Cota, S.E., C., M.N., 2003. From anchovies to sardines and back: Multidecadal change in the pacific ocean. Science 299, 217-221. https://doi.org/10.1126/science.1075880.

[6] Christensen, V., Walters, C.J., 2004. Ecopath with Ecosim: methods, capabilities and limitations. Ecological Modelling 172, 109-139. https://doi.org/10.1016/j.ecolmodel.2003.09.003.

[7] Cisneros-Montemayor, A.M., Ishimura, G., Munro, G.R., Sumaila, U.R., 2020. Ecosystem-based management can contribute to cooperation in transboundary fisheries: The case of pacific sardine. Fisheries Research 221, 105401. https://doi.org/10.1016/j.fishres.2019.105401.

[8] Clark, C.W., Munro, G.R., Sumaila, U.R., 2005. Subsidies, buybacks, and sustainable fisheries. Journal of Environmental Economics and Management 50, 47-58. https://doi.org/10.1016/j.jeem.2004.11.002.

[9] Costello, C., Ovando, D., Clavelle, T., Strauss, C.K., Hilborn, R., Melnychuk, M.C., Branch, T.A., Gaines, S.D., Szuwalski, C.S., Cabral, R.B., Rader, D.N., Leland, A., 2016. Global fishery prospects under contrasting management regimes. Proceedings of the National Academy of Sciences 113, 5125-5129. https://doi.org/10.1073/pnas.1520420113.

[10] De Young, B., Barange, M., Beaugrand, G., Harris, R., Perry, R.I., Scheffer, M., Werner, F., 2008. Regime shifts in marine ecosystems: detection, prediction and management. Trends in Ecology & Evolution 23, 402-409. https://doi.org/10.1016/j.tree.2008.03.008.

[11] Dichmont, C.M., Pascoe, S., Kompas, T., Punt, A.E., Deng, R., 2010. On implementing maximum economic yield in commercial fisheries. PNAS 107, 16-21. https://doi.org/10.1073/pnas.0912091107.

[12] Doyen, L., Thébaud, O., Béné, C., Martinet, V., Gourguet, S., Bertignac, M., Fifas, S., Blanchard, F., 2012. A stochastic viability approach to ecosystem-based fisheries management. Ecological Economics 75, 32-42. https://doi.org/10.1016/j.ecolecon.2012.01.005.

[13] Doyen, L., Béné, C., Bertignac, M., Blanchard, F., Cissé, A.A., Dichmont, C., Gourguet, S., Guyader, O., Hardy, P.Y., Jennings, S., Little, L.R., Macher, C., Mills, D.J., Noussair, A., Pascoe, S., Pereau, J.C., Sanz, N., Schwarz, A.M., Smith, T., Thébaud, O., 2017. Ecoviability for ecosystem-based fisheries management. Fish and Fisheries 18, 1056-1072. https://doi.org/10.1111/faf.12224.

[14] Engelhard, G.H., Peck, M.A., Rindorf, A., C. Smout, S., van Deurs, M., Raab, K., Andersen, K.H., Garthe, S., Lauerburg, R.A., Scott, F., Brunel, T., Aarts, G., van Kooten, T., Dickey-Collas, M., 2013. Forage fish, their fisheries, and their predators: who drives whom? ICES Journal of Marine Science 71, 90-104. https://doi.org/10.1093/icesjms/fst087.

[15] Essington, T.E., Moriarty, P.E., Froehlich, H.E., Hodgson, E.E., Koehn, L.E., Oken, K.L., Siple, M.C., Stawitz, C.C., 2015. Fishing amplifies forage fish population collapses. Proceedings of the National Academy of Sciences 112, 6648-6652. https://doi.org/10.1073/pnas.1422020112.

[16] Finley, C., Oreskes, N., 2013. Maximum sustained yield: a policy disguised as science. ICES Journal of Marine Science 70, 245-250. https://doi.org/10.1093/icesjms/fss192.

[17] 水産研究教育機構（FRA）, 2022a. 資源評価.
http://abchan.fra.go.jp/index1.html (Accessed on 8 January 2023)

[18] 水産研究教育機構（FRA）, 2022b. 国際漁業資源の現況.
https://kokushi.fra.go.jp/index-2.html (Accessed on 8 January 2023)

[19] 水産研究教育機構（FRA）, 2022b. 国際漁業資源の現況（カラフトマス　日本系）.
https://kokushi.fra.go.jp/R03/R03_60_PIN.pdf (Accessed on 8 January 2023)

[20] 水産研究教育機構（FRA）, 2022d. 国際漁業資源の現況（サケ（シロザケ）　日本系）
https://kokushi.fra.go.jp/R03/R03_61_CHU.pdf (Accessed on 8 January 2023)

[21] 水産研究教育機構（FRA）, 2022e. 国際漁業資源の現況（サクラマス　日本系）.
https://kokushi.fra.go.jp/R03/R03_62_CHE.pdf (Accessed on 8 January 2023)

[22] 水産研究教育機構（FRA）, 2022f. 我が国周辺水域の漁業資源評価　令和 3(2021) 年度ブリの資源評価.
http://www.abchan.fra.go.jp/digests2021/details/202145.pdf (Accessed on 8 January 2023)

[23] 水産研究教育機構（FRA）, 2022g. 国際管理漁業機関の概要
https://kokushi.fra.go.jp/index-1c.html (Accessed on 8 January 2023)

[24] 水産研究教育機構（FRA）, 2022h. マグロ類 RFMO における管理方策（総説）
https://kokushi.fra.go.jp/R03/R03_04_RFMO-R.pdf (Accessed on 8 January 2023)

[25] 水産研究教育機構（FRA）, 2022i. 我が国周辺水域の漁業資源評価　令和 3(2021) 年度マサバ太平洋系群の資源評価.
http://www.abchan.fra.go.jp/digests2021/details/202105.pdf (Accessed on 8 January 2023)

[26] 水産研究教育機構（FRA）, 2022j. 国際漁業資源の現況（サンマ　北太平洋）
https://kokushi.fra.go.jp/R03/R03_81_SAP.pdf (Accessed on 8 January 2023)

[27] 水産研究教育機構（FRA）, 2022k. 我が国周辺水域の漁業資源評価　令和 3(2021) 年度マアジ太平洋系群の資源評価.

http://www.abchan.fra.go.jp/digests2021/details/202103.pdf (Accessed on 8 January 2023)

[28] Fu, C., Perry, R.I., Shin, Y.J., Schweigert, J., Liu, H., 2013. An ecosystem modelling framework for incorporating climate regime shifts into fisheries management. Progress in Oceanography 115, 53-64. https://doi.org/10.1016/j.pocean.2013.03.003. (Accessed on 8 January 2023)

[29] Fu, C., Olsen, N., Taylor, N., Gruss, A., Batten, S., Liu, H., Verley, P., Shin, Y.J., 2017. Spatial and temporal dynamics of predator-prey species interactions off western Canada. ICES Journal of Marine Science 74, 2107-2119. https://doi.org/10.1093/icesjms/fsx056.

[30] Fulton, E.A., 2010. Approaches to end-to-end ecosystem models. Journal of Marine Systems 81, 171-183. https://doi.org/10.1016/j.jmarsys.2009.12.012.

[31] Fulton, E.A., Link, J.S., Kaplan, I.C., Savina-Rolland, M., Johnson, P., Ainsworth, C., Horne, P., Gorton, R., Gamble, R.J., Smith, A.D.M., Smith, D.C., 2011a. Lessons in modelling and management of marine ecosystems: the Atlantis experience. Fish and Fisheries 12, 171-188. https://doi.org/10.1111/j.1467-2979.2011.00412.x.

[32] Fulton, E.A., Smith, A.D.M., Smith, D.C., van Putten, I.E., 2011b. Human behaviour: the key source of uncertainty in fisheries management. Fish and Fisheries 12, 2-17. https://doi.org/10.1111/j.1467-2979.2010.00371.x.

[33] Gaichas, S.K., Odell, G., Aydin, K.Y., Francis, R.C., 2012. Beyond the defaults: functional response parameter space and ecosystem level fishing thresholds in dynamic food web model simulations. Canadian Journal of Fisheries and Aquatic Sciences 69, 2077-2094. https://doi.org/10.1139/f2012-099.

[34] Gecek, S., Legovic, T., 2012. Impact of maximum sustainable yield on competitive community. Journal of Theoretical Biology 307, 96-103. https://doi.org/10.1016/j.jtbi.2012.04.027.

[35] Gruss, A., Harford, W.J., Schirripa, M.J., Velez, L., Sagarese, S.R., Shin, Y.J., Verley, P., 2016. Management strategy evaluation using the individual-based, multispecies modeling approach

osmose. Ecological Modelling 340, 86-105. https://doi.org/10.1016/j.ecolmodel.2016.09.011.

[36] Guo, C., Fu, C., Forrest, R.E., Olsen, N., Liu, H., Verley, P., Shin, Y.J., 2019. Ecosystem-based reference points under varying plankton productivity states and fisheries management strategies. ICES Journal of Marine Science 76, 2045-2059. https://doi.org/10.1093/icesjms/fsz120.

[37] Hanzawa, W., Yamakawa, T., Watari, S., 2021. Potential for and challenges facing stakeholder involvement in participatory modeling for fisheries resource management in Japan. Nippon Suisan Gakkaishi 87, 225-242. https://doi.org/10.2331/suisan.20-00042.

[38] Hilborn, R., 2010. Pretty Good Yield and exploited fishes. Marine Policy 34, 193-196. https://doi.org/10.1016/j.marpol.2009.04.013.

[39] Hilborn, R., 2011. Future directions in ecosystem based fisheries management: A personal perspective. Fisheries Research 108, 235-239. https://doi.org/10.1016/j.fishres.2010.12.030.

[40] Hilborn, R., Stewart, I.J., Branch, T.A., Jensen, O.P., 2012. Defining trade-offs among conservation, profitability, and food security in the california current bottom-trawl fishery. Conservation Biology 26, 257-268. https://doi.org/10.1111/j.1523-1739.2011.01800.x.

[41] Hilborn, R., Fulton, E.A., Green, B.S., Hartmann, K., Tracey, S.R., Watson, R.A., 2015. When is a fishery sustainable? Canadian Journal of Fisheries and Aquatic Sciences 72, 1433-1441. https://doi.org/10.1139/cjfas-2015-0062.

[42] Hilborn, R., Amoroso, R.O., Bogazzi, E., Jensen, O.P., Parma, A.M., Szuwalski, C., Walters, C.J., 2017. When does fishing forage species affect their predators? Fisheries Research 191, 211-221. https://doi.org/10.1016/j.fishres.2017.01.008.

[43] Ianelli, J.N., Hollowed, A.B., Haynie, A.C., Mueter, F.J., Bond, N.A., 2011. Evaluating management strategies for eastern Bering Sea walleye pollock (*Theragra chalcogramma*) in a changing environment. ICES Journal of Marine Science 68, 1297-1304. https://doi.org/10.1093/icesjms/fsr010.

[44] Ichinokawa, M., Okamura, H., Kurota, H., 2017. The status of Japanese fisheries relative to fisheries around the world. ICES Journal of Marine Science 74, 1277-1287. https://doi.org/10.1093/icesjms/fsx002.

[45] 水産庁 (JFA), 2022a. 水産予算・決算の概要
https://www.jfa.maff.go.jp/j/budget/ (Accessed on 8 January 2023)

[46] 水産庁（JFA）, 2022b. 水産基本計画
https://www.jfa.maff.go.jp/j/policy/kihon_keikaku/ (Accessed on 8 January 2023)

[47] 水産庁 (JFA), 2022c. 水産白書
https://www.jfa.maff.go.jp/j/kikaku/wpaper/index.html (Accessed on 8 January 2023)

[48] 水産庁 (JFA), 2022d. 新たな資源管理の推進に向けたロードマップ.
https://www.jfa.maff.go.jp/j/press/kanri/200930.html (Accessed on 8 January 2023)

[49] 水産庁 (JFA), 2022e. 水産物流通調査
https://www.market.jafic.or.jp/index.html. (Accessed on 8 January 2023)

[50] Kaifu, K., 2019. Challenges in assessments of Japanese eel stock. Marine Policy 102, 1-4. https://doi.org/10.1016/j.marpol.2019.02.005.

[51] Kaplan, I.C., Horne, P.J., Levin, P.S., 2012. Screening California current fishery management scenarios using the Atlantis end-to-end ecosystem model. Progress in Oceanography 102, 5-18. https://doi.org/10.1016/j.pocean.2012.03.009.

[52] Kempf, A., Mumford, J., Levontin, P., Leach, A., Hoff, A., Hamon, K.G., Bartelings, H., Vinther, M., St bler, M., Poos, J.J., Smout, S., Frost, H., van den Burg, S., Ulrich, C., Rindorf, A., 2016. The MSY concept in a multi-objective fisheries environment - Lessons from the North Sea. Marine Policy 69, 146-158. https://doi.org/10.1016/j.marpol.2016.04.012.

[53] King, J.R., McFarlane, G.A., Punt, A.E., 2015. Shifts in fisheries management: adapting to regime shifts. Philosophical Transactions of the Royal Society B: Biological Sciences 370, 20130277. https://doi.org/10.1098/rstb.2013.0277.

[54] Klaer, N.L., O'Boyle, R.N., Deroba, J.J., Wayte, S.E., Little, L.R., Alade, L.A., Rago, P.J., 2015. How much evidence is required for acceptance of productivity regime shifts in fish stock assessments: Are we letting managers off the hook? Fisheries Research 168, 49-55. https://doi.org/10.1016/j.fishres.2015.03.021.

[55] Larkin, P.A., 1977. An epitaph for the concept of maximum sustained yield. Transactions of the American Fisheries Society 106, 1-11.

[56] Lees, K., Pitois, S., Scott, C., Frid, C., Mackinson, S., 2006. Characterizing regime shifts in the marine environment. Fish and Fisheries 7, 104-127. https://doi.org/10.1111/j.1467-2979.2006.00215.x.

[57] Legovic, T., Gecek, S., 2010a. Impact of maximum sustainable yield on independent populations. Ecological Modelling 221, 2108-2111. https://doi.org/10.1016/j.ecolmodel.2010.05.015.

[58] Legovic, T., Klanjscek, J., Gecek, S., 2010b. Maximum sustainable yield and species extinction in ecosystems. Ecological Modelling 221, 1569-1574. https://doi.org/10.1016/j.ecolmodel.2010.03.024.

[59] Link, J.S., 2018. System-level optimal yield: increased value, less risk, improved stability, and better fisheries. Canadian Journal of Fisheries and Aquatic Sciences 75, 1-16. https://doi.org/10.1139/cjfas-2017-0250.

[60] Mace, P.M., 2001. A new role for MSY in single-species and ecosystem approaches to fisheries stock assessment and management. Fish and Fisheries 2, 2-32.

[61] 農林水産省（MAFF）, 2022a. 統計情報（分野別分類/水産業）. https://www.maff.go.jp/j/tokei/kouhyou/kensaku/bunya6.html (Accessed on 8 January 2023)

[62] 農林水産省 (MAFF), 2022b. 漁業センサス. https://www.maff.go.jp/j/tokei/census/fc/ (Accessed on 8 January 2023)

[63] 農林水産省（MAFF）, 2022c. 漁業・養殖業生産統計 https://www.maff.go.jp/j/tokei/kouhyou/kaimen_gyosei/index.html (Accessed on 8 January 2023)

[64] 農林水産省（MAFF）, 2022d. 漁業産出額 https://www.maff.go.jp/j/tokei/kouhyou/gyogyou_seigaku/index.html (Accessed on 8 January 2023)

[65] 農林水産省（MAFF）, 2022e. 漁業経営統計調査 https://www.maff.go.jp/j/tokei/kouhyou/gyokei/index.html (Accessed on 8 January 2023)

[66] 農林水産省（MAFF）, 2022f. 農林水産物輸出入情報・概況 https://www.maff.go.jp/j/tokei/kouhyou/kokusai/index.html (Accessed on 8 January 2023)

[67] Makino, M., Matsuda, H., 2005. Co-management in Japanese coastal fisheries: institutional features and transaction costs. Marine Policy 29, 441-450. https://doi.org/10.1016/j.marpol.2004.07.005.

[68] Mantua, N., 2004. Methods for detecting regime shifts in large marine ecosystems: a review with approaches applied to North Pacific data. Progress in Oceanography 60, 165-182. https://doi.org/10.1016/j.pocean.2004.02.016.

[69] Morita, K., 2020. Toward sustainable salmon fisheries under environmental stewardship. Nippon Suisan Gakkaishi 86(3), 180-183. https://doi.org/10.2331/suisan.WA2730.

[70] Nakashima, H., Murata, K., Yano, K., Nishi, H., Yoshimura, N., Kuroki, Y., Kawasaki, S., Furukawa, S., Ura, K., Matsuo, H., Kitatsuji, S., Shikata, T., Abe, K., Tokunaga, T., Okamura, K., Aoki, K., Onitsuka, G., 2019. A *Chattonella* bloom in the Yatsushiro Sea, Japan in summer 2016: environmental characteristics during the bloom and mortality of cultured yellowtail *Seriola quinqueradiata*. Nippon Suisan Gakkaishi 85(2), 162-172. https://doi.org/10.2331/suisan.18-00006.

[71] Per 1 , T., Kuparinen, A., 2015. Detecting regime shifts in fish stock dynamics. Canadian Journal of Fisheries and Aquatic Sciences 72, 1619-1628. https://doi.org/10.1139/cjfas-2014-0406.

[72] Pikitch, E.K., Santora, C., Babcock, E.A., Bakun, A., Bonfil, R., Conover, D.O., Dayton, P., Doukakis, P., Fluharty, D., Heneman, B., Houde, E.D., Link, J., Livingston, P.A., Mangel,

M., McAllister, M.K., Pope, J., Sainsbury, K.J., 2004. Ecosystem-Based Fishery Management. Science 305, 346-347. https://doi.org/10.1126/science.1098222.

[73] Plagányi, E.E., Punt, A.E., Hillary, R., Morello, E.B., Thebaud, O., Hutton, T., Pillans, R.D., Thorson, J.T., Fulton, E.A., Smith, A.D.M., Smith, F., Bayliss, P., Haywood, M., Lyne, V., Rothlisberg, P.C., 2014. Multispecies fisheries management and conservation: tactical applications using models of intermediate complexity. Fish and Fisheries 15, 1-22. https://doi.org/10.1111/j.1467-2979.2012.00488.x.

[74] Pikitch, E.K., Santora, C., Babcock, E.A., Bakun, A., Bonfil, R., Conover, D.O., Dayton, P., Doukakis, P., Fluharty, D., Heneman, B., Houde, E.D., Link, J., Livingston, P.A., Mangel, M., McAllister, M.K., Pope, J., Sainsbury, K.J., 2004. Ecosystem-based fishery management. Science 305, 346-347. https://doi.org/10.1126/science.1098222.

[75] 首相官邸（PMOJ）, 内閣官房長官談話 2018, https://www.kantei.go.jp/jp/tyokan/98_abe/20181226danwa.html (Accessed on 8 January 2023)

[76] Punt, A.E., A'mar, T., Bond, N.A., Butterworth, D.S., de Moor, C.L., De Oliveira, J.A.A., Haltuch, M.A., Hollowed, A.B., Szuwalski, C., 2013. Fisheries management under climate and environmental uncertainty: control rules and performance simulation. ICES Journal of Marine Science 71, 2208-2220. https://doi.org/10.1093/icesjms/fst057.

[77] Punt, A.E., MacCall, A.D., Essington, T.E., Francis, T.B., Hurtado-Ferro, F., Johnson, K.F., Kaplan, I.C., Koehn, L.E., Levin, P.S., Sydeman, W.J., 2016. Exploring the implications of the harvest control rule for Pacific sardine, accounting for predator dynamics: A MICE model. Ecological Modelling 337, 79-95. https://doi.org/10.1016/j.ecolmodel.2016.06.004.

[78] Rindorf, A., Dichmont, C.M., Levin, P.S., Mace, P., Pascoe, S., Prellezo, R., Punt, A.E., Reid, D.G., Stephenson, R., Ulrich, C., Vinther, M., Clausen, L.W., 2016. Food for thought: pretty good multispecies yield. ICES Journal of Marine Science 74, 475-486. https://doi.org/10.1093/icesjms/fsw071.

[79] Shin, Y.J., Cury, P., 2004. Using an individual-based model of fish assemblages to study the response of size spectra to changes in fishing. Canadian Journal of Fisheries and Aquatic Sciences 61, 414-431. https://doi.org/10.1139/f03-154.

[80] Shinji, J., Nohara, S., Yagi, N., Wilder, M., 2019. Bio-economic analysis of super-intensive closed shrimp farming and improvement of management plans: a case study in Japan. Fisheries Science 85, 1055-1065. https://doi.org/10.1007/s12562-019-01357-5.

[81] Shishidou, H., Sakaji, H., Tian, Y., 2016. Catch fluctuation of yellowtail species in relation to fluctuations in the geographical catch center. Bulletin of the Japanese Society of Fisheries Oceanography 80, 27-34. https://doi.org/10.34423/jsfo.80.1_27.

[82] Silvar-Viladomiu, P., Minto, C., Halouani, G., Batts, L., Brophy, D., Lordan, C., Reid, D.G., 2021. Moving reference point goalposts and implications for fisheries sustainability. Fish and Fisheries https://doi.org/10.1111/faf.12591.

[83] Smith, M.D., Fulton, E.A., Day, R.W., 2014. An investigation into fisheries interaction effects using Atlantis. ICES Journal of Marine Science 72, 275-283. https://doi.org/10.1093/icesjms/fsu114.

[84] Steele, J.H., Aydin, K., Gifford, D.J., Hofmann, E.E., 2013. Construction kits or virtual worlds; Management applications of E2E models. Journal of Marine Systems 109-110, 103-108. https://doi.org/10.1016/j.jmarsys.2011.10.016.

[85] Sugimoto, A., Roman, R., Hori, J., Tamura, N., Watari, S., Makino, M., 2022. How has the 'customary nature' of Japanese fisheries reacted to Covid-19? An interdisciplinary study examining the impacts of the pandemic in 2020. Marine Policy 138, 105005. https://doi.org/10.1016/j.marpol.2022.105005.

[86] Sumaila, U.R., Ebrahim, N., Schuhbauer, A., Skerritt, D., Li, Y., Kim, H.S., Mallory, T.G., Lam, V.W., Pauly, D., 2019. Updated estimates and analysis of global fisheries subsidies. Marine Policy 109, https://doi.org/10.1016/j.marpol.2019.103695.

[87] Takashina, N., Mougi, A., 2015. Maximum sustainable yields from a spatially-explicit harvest model. Journal of Theoretical Biology 383, 87-92. https://doi.org/10.1016/j.jtbi.2015.07.028.

[88] Thorpe, R.B., Jennings, S., Dolder, P.J., 2017. Risks and benefits of catching pretty good yield in multispecies mixed fisheries. ICES Journal of Marine Science 74, 2097-2106. https://doi.org/10.1093/icesjms/fsx062.

[89] Tokunaga, K., Ishimura, G., Iwata, S., Abe, K., Otsuka, K., Kleisner, K., Fujita, R., 2019. Alternative outcomes under different fisheries management policies: A bioeconomic analysis of Japanese fisheries. Marine Policy 108, 103646. https://doi.org/10.1016/j.marpol.2019.103646.

[90] Tucker, A.M., Runge, M.C., 2021. Optimal strategies for managing wildlife harvest under system change. The Journal of Wildlife Management 85, 847-854. https://doi.org/10.1002/jwmg.22047.

[91] Tulloch, V.J.D., Plágányi, E.E., Matear, R., Brown, C.J., Richardson, A.J., 2018. Ecosystem modelling to quantify the impact of historical whaling on Southern Hemisphere baleen whales. Fish and Fisheries 19, 117-137. https://doi.org/10.1111/faf.12241.

[92] Ulrich, C., Vermard, Y., Dolder, P.J., Brunel, T., Jardim, E., Holmes, S.J., Kempf, A., Mortensen, L.O., Poos, J.J., Rindorf, A., 2016. Achieving maximum sustainable yield in mixed fisheries: a management approach for the North Sea demersal fisheries. ICES Journal of Marine Science 74, 566-575. https://doi.org/10.1093/icesjms/fsw126.

[93] Villasante, S., do Carme Garcia-Negro, M., Gonzalez-Laxe, F., Rodriguez, G.R., 2011. Overfishing and the Common Fisheries Policy: (un)successful results from TAC regulation? Fish and Fisheries 12, 34-50. https://doi.org/10.1111/j.1467-2979.2010.00373.x.

[94] Walters, C.J., Christensen, V., Martell, S.J., Kitchell, J.F., 2005. Possible ecosystem impacts of applying MSY policies from single-species assessment. ICES Journal of Marine Science 62, 558-568. https://doi.org/10.1016/j.icesjms.2004.12.005.

[95] Watari, S., 2015. Fish stock assessment targeting on multi-species and multifisheries based on Ecopath with Ecosim approach in Suo-nada, Seto Inland Sea, Japan. Bulletin of the Japanese Society of Fisheries Oceanography 79(4), 255-265.

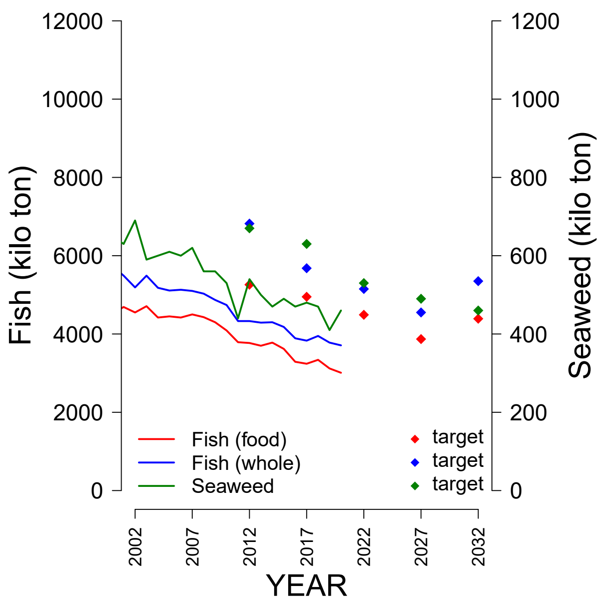
[96] Wiedenmann, J.R., Holland, D.S., 2020. Trade-offs in fishery management objectives when allowing catch limit carry-over between years. ICES Journal of Marine Science 77, 2825-2839. https://doi.org/10.1093/icesjms/fsaa154.

[97] Williams, B.K., Brown, E.D., 2016. Technical challenges in the application of adaptive management. Biological Conservation 195, 255-263. https://doi.org/10.1016/j.biocon.2016.01.012.

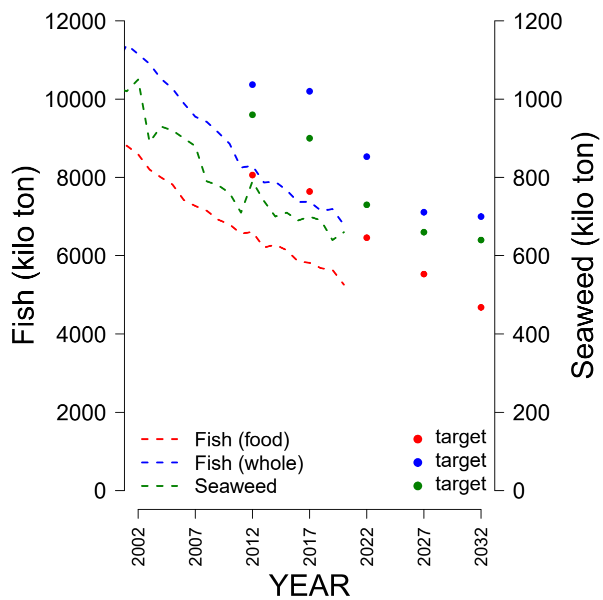
[98] Yasunaka, S., Hanawa, K., 2002. Regime shifts found in the northern hemisphere SST field. Journal of the Meteorological Society of Japan 80, 119-135. https://doi.org/10.2151/jmsj.80.119.

[99] Yatsu, A., 2019. Review of population dynamics and management of small pelagic fishes around the Japanese Archipelago. Fishery Science 85, 611-639. https://doi.org/10.1007/s12562-019-01305-3.

[100] Yonezaki, S., Kiyota, M., Narimatsu, Y., Hattori, T., Ito, M., 2016. Quantification of the demersal marine ecosystem structure in the northern district of the Tohoku sea area, northeastern Japan based on Ecopath approach. Bulletin of the Japanese Society of Fisheries Oceanography 80(1), 1-19. https://doi.org/10.34423/jsfo.80.1_1.



(a) 生産量目標



(b) 消費量目標

Figure 1: 水産基本計画 [46]: 実線と破線は実際のデータで、食用魚介類 Fish (food)、魚介類全体 Fish (whole)、海藻類 Seaweed を示し、点は 10 年前の水産基本計画で設けられた目標値を表す。

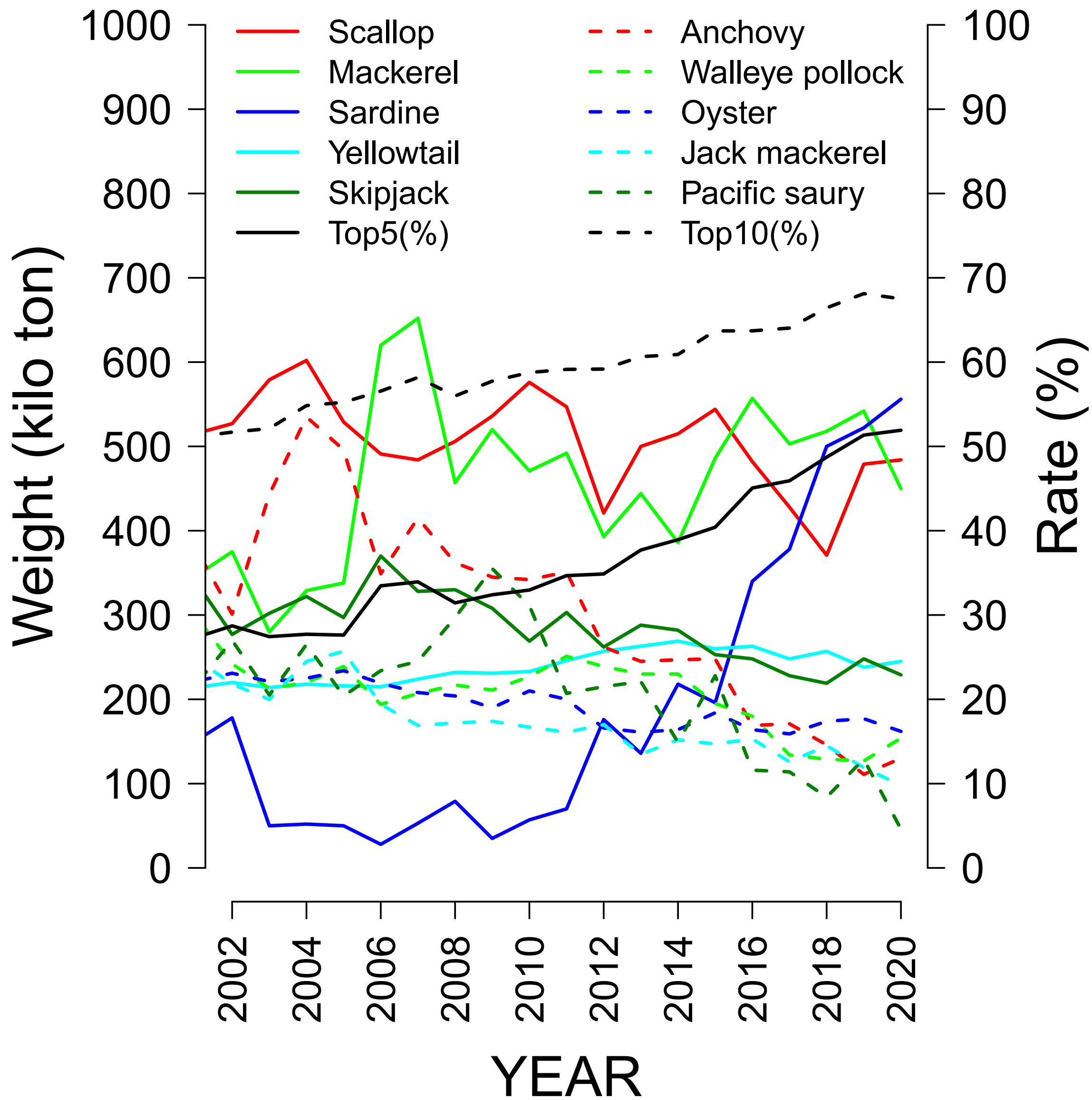
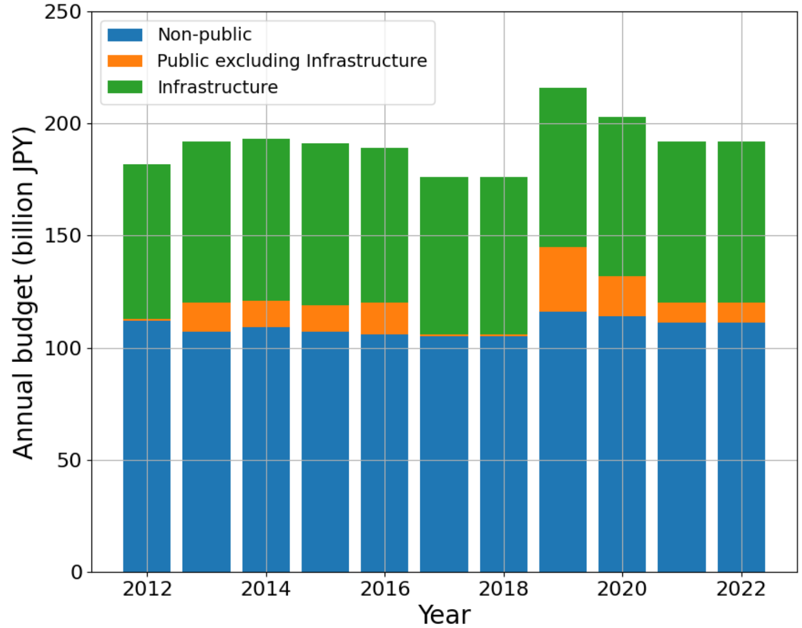
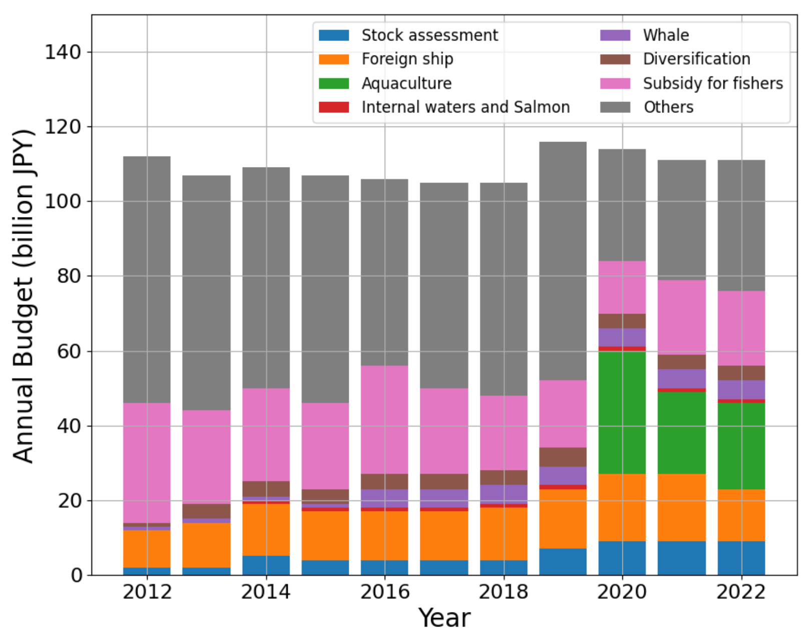


Figure 2: 日本国の魚種のうち、2011 年から 2020 年までの国内生産量の平均が上位の魚種: ホタテガイ Scallop、サバ類 Mackerel、マイワシ Sardine、ブリ類 Yellowtail、カツオ Skipjack、カタクチイワシ Anchovy、スケトウダラ Walleye pollock、カキ類 Oyster、マアジ Jack mackerel、サンマ Pacific saury [63]。上位五種と上位十種の国内生産量全体に占める割合（Top5 と Top10）



(a) 公共部門と非公共部門



(b) 非公共部門の内訳

Figure 3: 日本国の水産関係当初予算 [45]: 資源調査及び評価 stock assessment、外国漁船対策等 foreign ship、養殖業関連 Aquaculture、内水面及びさけます等資源対策 Internal waters and Salmon、捕鯨対策 Whale、水産多面的機能の発揮等 Diversification、漁業経営安定対策事業 Subsidy for fishers、水産基盤整備事業 Infrastructure、その他 others

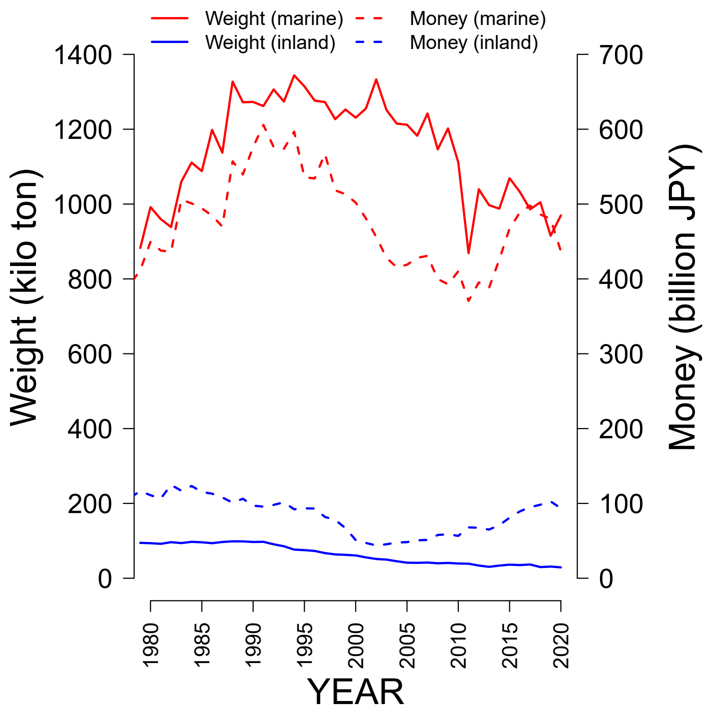


Figure 4: 日本国の海面養殖と内水面養殖の生産量と産出額 [63, 64]

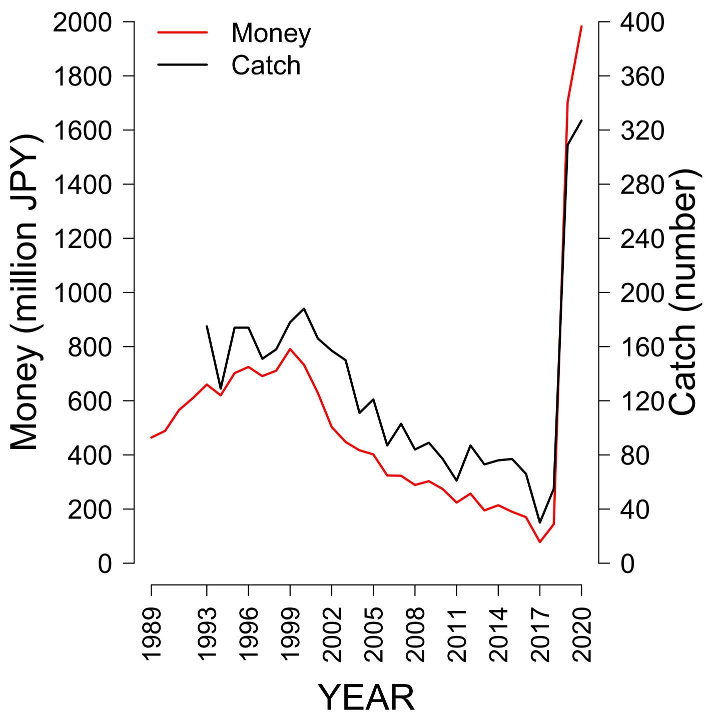
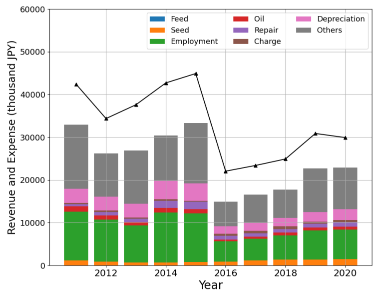
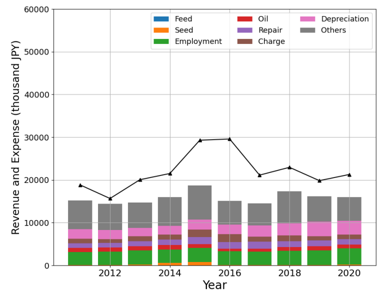


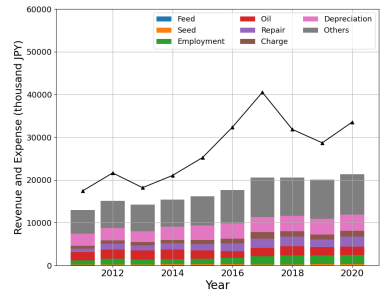
Figure 5: 日本国の捕鯨業による産出額と捕獲実頭数 [63, 64]



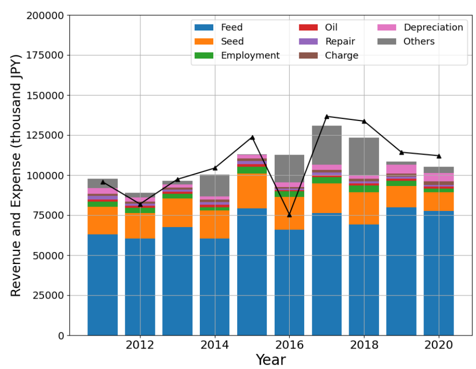
(a) カキ類



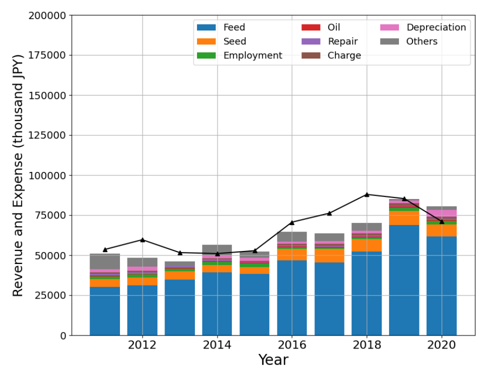
(b) ホタテガイ



(c) ノリ類



(d) ブリ類



(e) マダイ

Figure 6: 日本国の養殖業の個人経営体の支出と収入：えさ代 Feed、種苗代 Seed、雇用労賃 Employment、油費 Oil、修繕費 Repair、販売手数料 Charge、減価償却費 Depreciation、その他 Others。

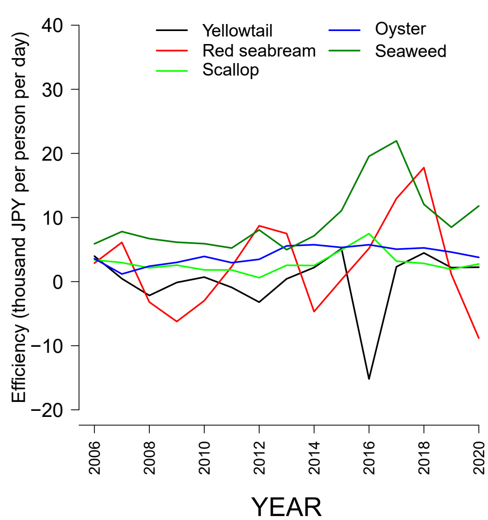


Figure 7: 日本国の養殖業の個人経営体の利益効率（一人一日当たりの漁労所得）。ブリ類 Yellowtail、マダイ Red seabream、ホタテガイ Scallop、カキ類 Oyster、ノリ類 Seaweed。

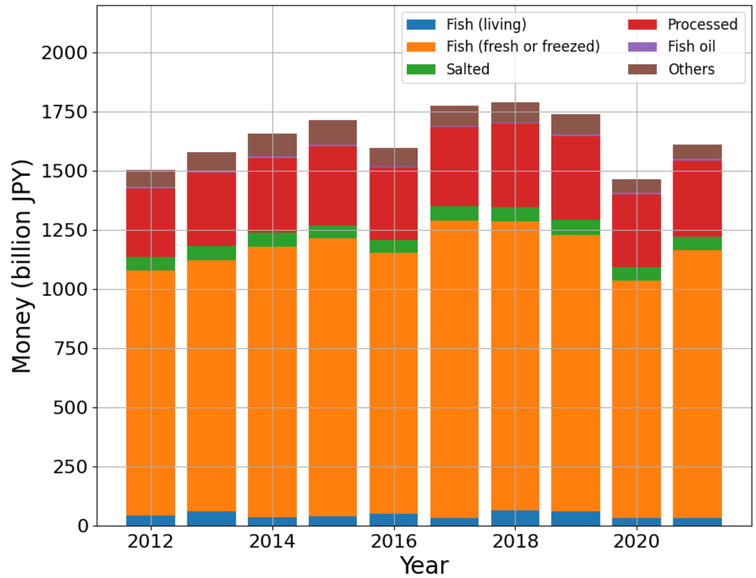
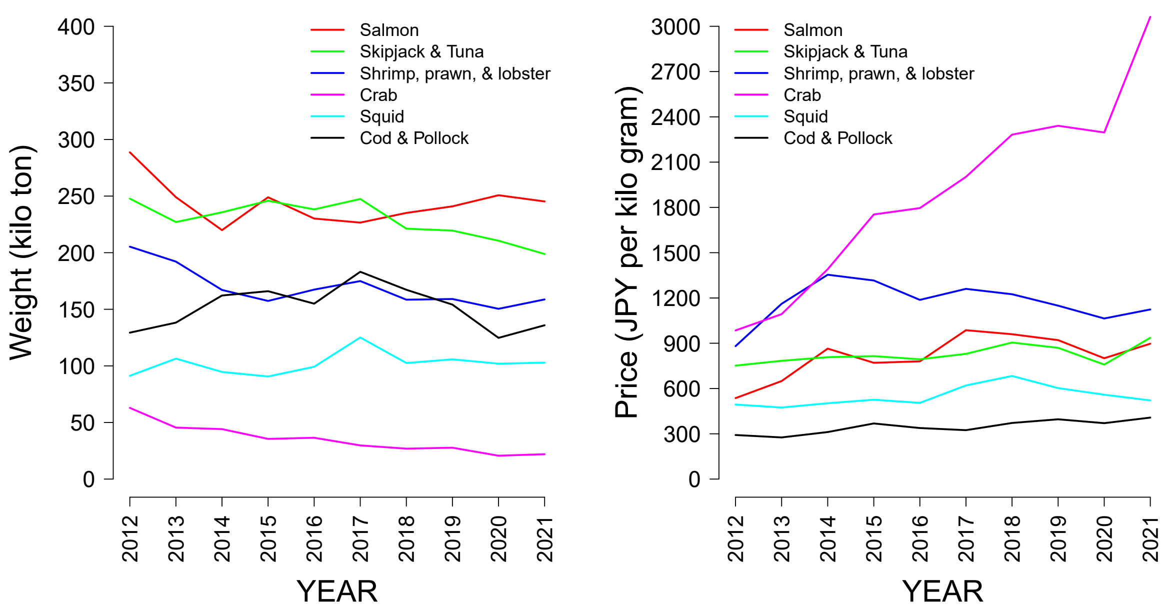


Figure 8: 日本国への水産物輸入金額: 生きている魚 Fish (living)、水産物（生鮮・冷蔵・冷凍）Fish (fresh or freezed)、塩乾水産物 Salted、水産調製品 Processed、魚油海獣油 Fish oil、その他 Others [64]



(a) 輸入重量

(b) 1kg あたりの輸入単価

Figure 9: 日本国への輸入水産物（生鮮・冷蔵・冷凍）: サケマス類 Salmon、カツオマグロ類 Skipjack and Tuna、エビ Shrimp, Prawn and Lobster、カニ Crab、イカ Squid、タラ Cod [64]

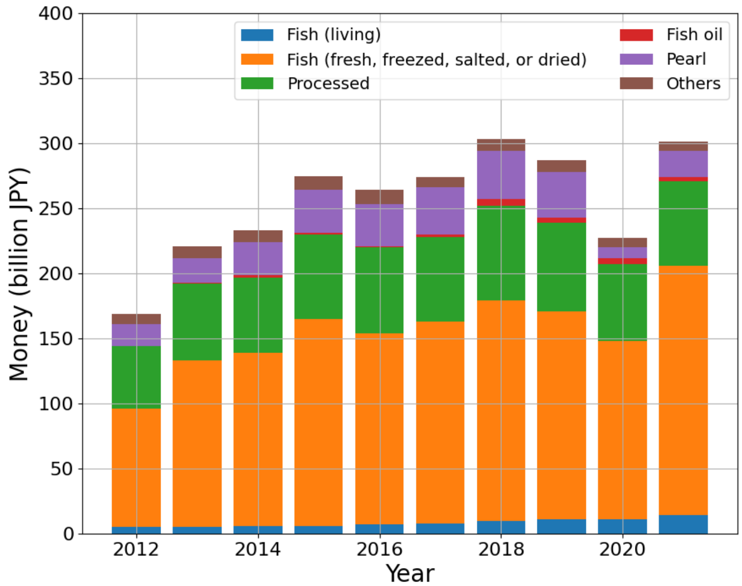
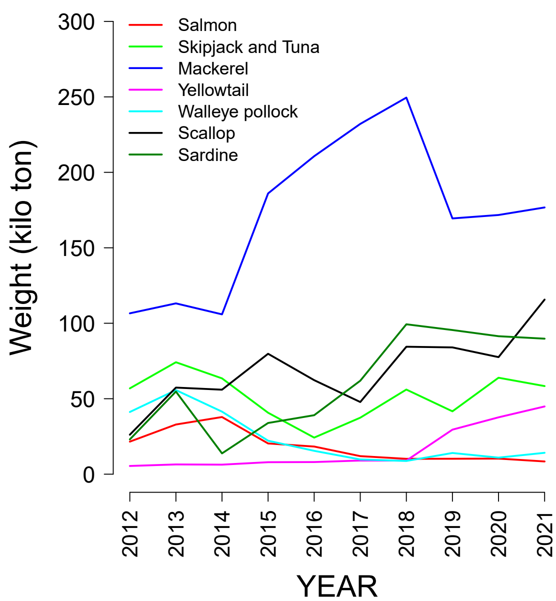
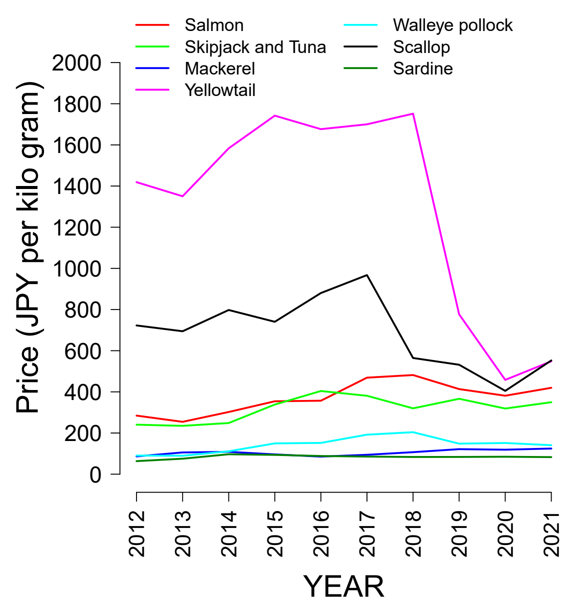


Figure 10: 日本国からの水産物輸出金額: 生きている魚 Fish (living)、水産物（生鮮・冷蔵・冷凍・塩蔵・乾燥） Fish (fresh, freezed, salted, or dried)、水産調製品 Processed、魚油海獣油 Fish oil、真珠 Pearl、その他 Others [64]



(a) 輸出重量



(b) 1kg あたりの輸出単価

Figure 11: 日本国からの輸出水産物（生鮮・冷蔵・冷凍）: サケマス類 Salmon、カツオマグロ類 Skipjack and Tuna、サバ類 Mackerel、ブリ類 Yellowtail、スケトウダラ Walleye pollock、ホタテガイ Scallop、イワシ類 Sardine [64]

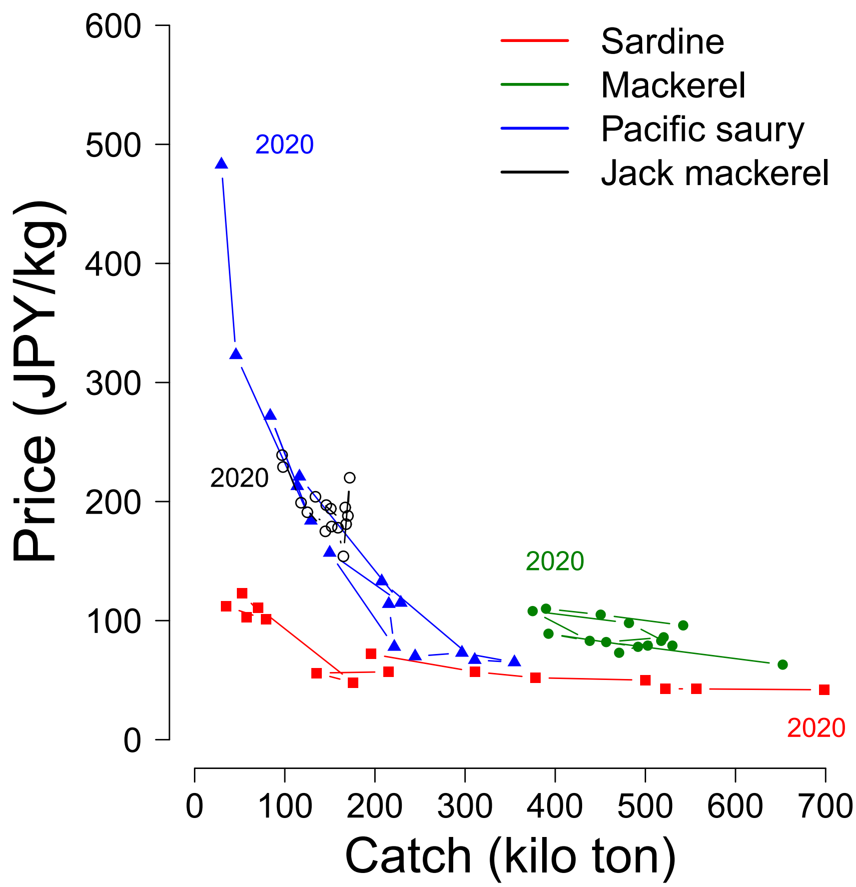


Figure 12: 小型浮魚類の漁獲量と単価。マイワシ Sardine、サバ類 Mackerel、サンマ Pacific saury、マアジ Jack mackerel [49]。

Chapter VI

新興感染症における意思決定のための戦略作成方法の提案

1 Introduction

新興感染症が発生したときの課題の一つは、感染症の性質やパラメータの不確実性である [22, 38]。新たなる新興感染症に向けて Kubo [22] はリスク学の観点からの評価と管理として、国民に対し今後の感染症の拡大において起こりうる具体的な実像をイメージさせ、それに対応した施策メニュー群を提示し心構えをしてもらうことが重要であると言及している。水産資源管理の分野で、不確実性のある問題への取り扱い手法として Management Strategy Evaluation（管理戦略評価、MSE）がある [14, 33, 40, 42]。これは元々捕鯨への漁獲管理で作り上げられた概念である [3] が、手順は以下のとおりである [42]。

1. Identify management objectives　管理目的を明らかにする
2. Identify critical sources of uncertainty　不確実性の重要な発生源を特定する
3. Construct operating model(s)　オペレーティングモデルを構築する
4. Select operating model parameters　パラメータを選択する
5. Identify management strategies to implement　実行すべき管理戦略を明らかにする
6. Simulate application of management strategies　管理戦略を適用する
7. Summarize and interpret outcomes, refining process　結果を要約し解釈する、そして過程を改善する

MSE は不確実性に対して頑健な管理戦略を作ることを目的するのであり、不確実性が解決されるという仮定の下で最良の戦略を見つけることではないことが特徴である [33]。

本章では、感染症対策を一つの個体群の管理と捉え、意思決定のための戦略作りの枠組みとして感染症制御への MSE の応用を提示する。以下では、感染期間を感染初期、流行期、転換期に分ける。感染初期はウイルスの性質の特定、感染経路の追跡が行われる。流行期は感染者が増加し、感染経路の追跡が困難になり、かつワクチン及び治療薬などの医学的介入手段が無い状態の時期とする。転換期はワクチン及び治療薬などの医学的介入手段が実行可能で、ウイルスの新たな変異株が発生する時期とする。各時期の管理目的として、感染初期は感染経路の追跡による感染者の検出隔離、流行期は社会経済費用を抑えつつ感染者数または感染死者数の増加を抑制すること、転換期は医学的介入を導入して流行期と同じ目的を果たすことを挙げる。以下の節では、2019 年 12 月から感染事例が発生し、2023 年 1 月現在も感染流行が続く SARS-CoV-2 による COVID-19 への流行期の対策を MSE の手順に沿って行う。

2 MSE approach

2.1 Identify management objectives

管理目的として、感染死者数の抑制、医療資源の確保、経済活動の維持を挙げる。よって戦略の評価指標として感染死者数、自宅等隔離者数、入院者数、検査数、社会経済費用を用いる。対象とする人口は日本国の東京都の人口約 1400 万人を想定する [45]。2020 年 3 月 27 日から欧州の大部分の国から入国が禁止されたこと、同年 4 月 3 日にイギリス、アメリカ、中華人民共和国全域からの入国が禁止されたこと、及び同年 4 月 1 日時点の東京都の新規陽性者数（67 人、7 日間移動平均は　　人 [46]）を勘案して、以下の流行期のシミュレーションの想定期間は 2020 年 4 月 1 日から 2021 年 3 月 31 日までの 365 日間とする。

2.2 Identify critical sources of uncertainty

不確実性の発生源としては、真の感染者数、感染しても発症せずに回復する無症候性感染者の割合、検査による感染者の検出率、緊急事態宣言のような行動抑制の実効性が挙げられる。

2.3 Construct operating model(s)

オペレーティングモデルとパラメータに関しては各期間ごとに検討や見直し、改良を加えることが望ましい。シミュレーションのためのモデルの構築に際して Currie et al. [9] は大きく四つの分類をしている。一つ目は連続型及び離散型の微分方程式で量の時間変化を捉えた System dynamics、二つ目は集団の中の個人の振る舞いや相互作用に着目した Agent Based modelling、三つ目はある事象の発生する時間間隔やある活動にかかる時間の変動を考慮した Discrete event simulation、四つ目はそれらを混合したモデルである。流行期の数理モデルの一例として Watanabe and Matsuda [47] で用いられた次の連続型微分方程式モデルを採用する。

(1)

ここで、　はウイルスに感受性を持つ人の数、　はウイルスに曝露した人の数、　は隔離されていない無症候性感染者の数、　は隔離されておらず、症状がまだ出ていない（将来発症する）感染者の数、　は隔離されていない症状ありの感染者の数、　は隔離されている無症候性感染者の数、　は隔離されている症状がまだ出ていない（将来発症する）感染者の数、　隔離されている症状ありの感染者の数、　は回復して免疫を獲得した人の数を表す（Table 1）。また、各パラメータは Table 2 に示す。

前の節で挙げた評価指標を感染死者数　、自宅等隔離者数　、入院者数　、検査数　、社会経済費用　とすると、以下のように算出できる。ただし　は 2020 年 4 月 1 日、　は 2021

年 3 月 31 日を表す。 は 時刻 から の間に感染し、それが原因で死亡した人の数を表す。

$$\times \tag{2}$$

は自宅や宿泊施設に隔離された感染者の累積数である。. は時刻 における東京都の確保病床数を表す。

$$\{ \quad - \quad \} \tag{3}$$

は入院した発症感染者の累積数である。

$$\{ \quad \} \tag{4}$$

管理期間に検査を受けた人の累積人数である。

$$- \tag{5}$$

は社会経済費用を表す。社会経済費用はここでは緊急事態宣言が発令された日数とする。

2.4 Select operating model parameters

断りがない限りパラメータは Watanabe and Matsuda [47] と同様のものを用いる（Table 2）。ただし、以下のシミュレーションでは管理対象期間内は としている。初期値となる 2020 年 4 月 1 日時点の真の感染者数は、Eq.1 の第 6 式と第 7 式より以下の式を満たすように 、 、 に非負の乱数を割り当てる。

$$\tag{6}$$

無症候性感染者の割合 – は から までの一様乱数とし、時間変化する。検査による感染者の検出率 は から までの一様乱数とし、時間変化する。平時は 、緊急事態宣言が発令されている期間は が満たされているとする [32] 。

2.5 Identify management strategies to implement

管理戦略としては検査隔離及び行動抑制を行う。医学的介入ができるようになるまで持続的もしくは断続的な物理的距離（physical distancing）が必要 [18] という前提から以下の戦略案を作成した。病床使用率は で表される。

1. 病床使用率が 10%を超え、且つ増加傾向のとき緊急事態宣言発令 。病床使用率が 10%を下回り、且つ減少傾向のとき解除。
2. 病床使用率が 60%を超え、且つ増加傾向のとき緊急事態宣言発令 。病床使用率が 10%を下回り、且つ減少傾向のとき解除。
3. 直近 7 日間の新規感染者数が 100 人を超えたら緊急事態宣言発令 。直近 7 日間の新規感染者数が 50 人を下回ると解除。
4. 直近 7 日間の新規感染者数が 350 人を超えたら緊急事態宣言発令 。直近 7 日間の新規感染者数が 100 人を下回ると解除。
5. 病床使用率と直近 7 日間の新規感染者数の両方を参照点とする。「病床使用率が 30%を超え、且つ増加傾向」又は「直近 7 日間の新規感染者数が 100 人を超えた」とき緊急事態宣言発令 。「病床使用率が 10%を下回り、且つ減少傾向」且つ「直近 7 日間の新規感染者数が 10 人を下回る」とき解除。

以下では n 番目の戦略を Sn と略す（例えば 1 番目の戦略は S1）。

2.6 Simulate application of management strategies

各管理戦略ごとに 1000 回ずつシミュレーションを行い、結果の平均値とばらつきを見る。ばらつきは信頼区間や標準偏差、分位点などいくつか候補はあるものの、ここでは標準偏差を用いた。

2.7 Summarize and interpret outcomes, refining process

計算結果を Table 3 に示す。提案された戦略の中では、S1 が と の平均値を最も小さくすることができ、 と の平均値は S5 が最小であった。また、5 つの指標のばらつきも S1 が最小であった。ただし の平均値は S1 と S5 がともに最大で、他の戦略を見た場合も と

その他の指標でトレードオフがあることが分かる。S4 は　の平均値を 22 日間に抑えることができたが、その他の指標の平均値は他の戦略の結果よりかなり大きくなってしまった。

戦略間の比較には計算した値をそのまま比較する他に、各指標を金銭に換算して比較する方法がある。例えば、感染死者数の被害金額換算には統計的生命価値（Value of Statistical Life, VSL）[1] を利用したり、行動抑制による社会経済費用には今回の新型コロナウイルスの流行下で実施された休業協力金その他の助成金が参考になる。ただし、単位金額の設定や比較の仕方は一意に決まるものではなく場合によることに注意する。

3　Discussion

感染症制御を個体群管理の問題と捉え、戦略作りの手法として MSE を適用した。MSE の利点は、単に将来予測をするだけでなく、不確実性がある中でいくつかの管理戦略の候補を用意し、管理目的を定量化した評価指標を比べることができる点である。評価指標は感染者数や死者数だけでなく社会経済的な費用も含むことができる。大事なことは、枠組みに則る意思決定をすることと実行しうる選択肢を見せることで当事者間（行政、研究者、国民全体）の信頼関係を築くことにある。

MSE では数理モデルの設定が一つの大きな課題となるが、モデルは系の詳細を反映するために充分複雑であるが、煩雑になりすぎないモデルを見つけることを心がけなければならない [21]。数理モデルに関しては、今回用いたもの以外にも年齢構造モデルや離散型力学系を使う手段もある [48]。また、変異株への置き換わりやワクチン及び治療薬の開発普及、獲得した免疫の喪失が起こる転換期には別のモデルがある [2, 10, 13, 24]。Shea et al. [41] は複数のモデル比較と活用のための意思決定の枠組みを提案した。MSE では複数のモデルを同時に活用することはそれほど明示されていないが、これも新しい感染症対策形成に資すると考えられる。計算結果やトレードオフの示し方も、表にしたりレーダーチャートを採用するなどサイエンスコミュニケーションを前提とした工夫が必要である [39]。

公衆衛生政策においては、科学者や経済学者がモデリングや分析に基づく費用と便益の推定を行い、政策決定者が目的の優先順位を特定し最終的な決定権と責任を持つ仕組みを構築することが重要である [15, 19, 27]。科学者が政策に近づきすぎると、客観性や政府の政策を批判する自由などを喪失してしまう懸念などがある [8, 39]。先行研究でも言及されるように、感染症対策には数学的知識と生物学的および社会的洞察を組み合わせ、医療経済学やコミュニケーションスキルを含む様々な学際的な専門知識が必要である [16, 21]。将来の新興感染症に向けて科学

者と政策立案者の間の緊密なコミュニケーションと共に学際的な協力体制が必要であるが、今回の新型コロナウイルス流行は、将来の対策のための過去の教訓になりうる [22]。ただし、それが技術の進歩で新しく生まれた選択肢を制限する経験や硬直した社会規範にはならぬよう注意が必要である。

新型コロナウイルス対策の意思決定の機構を見直すと、新型インフルエンザ等対策特別措置法第 15 条を根拠に新型コロナウイルス感染症対策本部（以下対策本部）が内閣官房（以下 CAS）に設置された [6]。2020 年の感染症流行初期には対策本部の下に新型コロナウイルス感染症対策専門家会議（以下専門家会議）が設置され、2020 年 2 月 16 日の初会合から計 17 回の会議が開かれた。専門家会議は 2020 年 7 月 3 日に廃止となり、同日新型コロナウイルス感染症対策分科会（以下分科会）に改組され、新型インフルエンザ等対策推進会議の下に位置づけされた。構成員も専門家会議では感染症を専門とする研究者が中心であったが、分科会の構成員は感染症の専門家に加え、医療系業界団体、経済団体、労働組合も含んでいる。この他 CAS や厚生労働省（以下 MHLW）の記録を見ると新型コロナウイルス流行に際し多くの会議や部会が開かれた [7, 31]。調べる限りある期間内に一時的に会合が行われたものや、設置目的や役割及び指揮系統の位置づけが他と重複しているかもしくは不明瞭と思われるものもある。例えば、MHLW に対し医療・公衆衛生分野の専門的・技術的な事項について助言するため新型コロナウイルス感染症対策アドバイザリーボード（初会合は 2020 年 2 月 7 日）が感染症流行初期から設置されていたが、これは専門家会議と役割が重複していたと考えられる。また、2022 年 10 月に発足した新型コロナ・インフル同時流行対策タスクフォースは 2022 年冬の新型コロナウイルスと新型インフルエンザの同時流行に備えたものであるが、分科会のように新型インフルエンザ等対策推進会議の中に位置づけられているかは 2022 年 12 月末の時点で確認できなかった。迅速で明確な政策決定のために権限と責任の所在を明らかにした意思決定構造を整えることが新興感染症発生時に必要となるだろう。

References

[1] Banzhaf, H.S., 2022. The Value of Statistical Life: A Meta-Analysis of Meta-Analyses. Journal of Benefit-Cost Analysis 13, 182-197. https://doi.org/10.1017/bca.2022.9.

[2] Bartsch, S.M., O'Shea, K.J., Wedlock, P.T., Strych, U., Ferguson, M.C., Bottazzi, M.E., Randall, S.L., Siegmund, S.S., Cox, S.N., Hotez, P.J., Lee, B.Y., 2021. The Benefits of Vaccinating With the First Available COVID-19 Coronavirus Vaccine. American Journal of Preventive Medicine 60, 605-613. https://doi.org/10.1016/j.amepre.2021.01.001.

[3] Butterworth, D.S., Bentley, N., De Oliveira, J.A.A., Donovan, G.P., Kell, L.T., Parma, A.M., Punt, A.E., Sainsbury, K.J., Smith, A.D.M., Stokes, T.K., 2010. Purported flaws in management strategy evaluation: basic problems or misinterpretations? ICES Journal of Marine Science 67, 567-574. https://doi.org/10.1093/icesjms/fsq009.

[4] Byrne, A.W., McEvoy, D., Collins, A.B., Hunt, K., Casey, M., Barber, A., Butler, F., Griffin, J., Lane, E.A., McAloon, C., O'Brien, K., Wall, P., Walsh, K.A., More, S.J., 2020. Inferred duration of infectious period of SARS-CoV-2: rapid scoping review and analysis of available evidence for asymptomatic and symptomatic COVID-19 cases. BMJ Open 10. https://doi.org/10.1136/bmjopen-2020-039856.

[5] Byambasuren O., Cardona M., Bell K., Clark J., McLaws M., Glasziou P., 2020. Estimating the extent of asymptomatic COVID-19 and its potential for community transmission: systematic review and meta-analysis. Official Journal of the Association of Medical Microbiology and Infectious Disease Canada. https://doi.org/10.3138/jammi-2020-00305.

[6] 内閣官房（CAS）, 2022. 新型コロナウイルス感染症対策本部 https://www.kantei.go.jp/jp/singi/novel_coronavirus/taisaku_honbu.html (Accessed on 8 January 2023)

[7] 内閣官房（CAS）, 2022. 各種本部・会議等の活動情報 https://www.cas.go.jp/jp/seisakukaigi/index.html (Accessed on 8 January 2023)

[8] Choi, B.C.K., Pang, T., Lin, V., Puska, P., Sherman, G., Goddard, M., Ackland, M.J., Sainsbury, P., Stachenko, S., Morrison, H., Clottey, C., 2005. Can scientists and policy makers work

together? Journal of Epidemiology & Community Health 59, 632-637. https://doi.org/10.1136/jech.2004.031765.

[9] Currie, C.S.M., Fowler, J.W., Kotiadis, K., Monks, T., Onggo, B.S., Robertson, D.A., Tako, A.A., 2020. How simulation modelling can help reduce the impact of COVID-19. Journal of Simulation 14. https://doi.org/10.1080/17477778.2020.1751570.

[10] Dutta, A., 2022. COVID-19 waves: variant dynamics and control. Scientific Reports 12. https://doi.org/10.1038/s41598-022-13371-2.

[11] Emanuel, E.J., Osterholm, M., Gounder, C.R., 2022. A National Strategy for the "New Normal" of Life With COVID. JAMA 327, 211-212. https://doi.org/10.1001/jama.2021.24282.

[12] Furuse, Y., Oshitani, H., 2020. Viruses That Can and Cannot Coexist With Humans and the Future of SARS-CoV-2. Frontiers in Microbiology 18. https://doi.org/10.3389/fmicb.2020.583252.

[13] Furuse, Y., 2021. Simulation of future COVID-19 epidemic by vaccination coverage scenarios in Japan. Journal of Global Health 11. https://doi.org/10.7189/jogh.11.05025.

[14] Goethel, D.R., Lucey, S.M., Berger, A.M., Gaichas, S.K., Karp, M.A., Lynch, P.D., Walter, J.F., Deroba, J.J., Miller, S., Wilberg, M.J., 2019. Closing the feedback loop: on stakeholder participation in management strategy evaluation. Canadian Journal of Fisheries and Aquatic Sciences , 1895-1913 https://doi.org/10.1139/cjfas-2018-0162.

[15] Grimm, V., Johnston, A.S.A., Thulke, H., Forbes, V.E., Thorbek, P., 2020. Three questions to ask before using model outputs for decision support. Nature Communications 11. https://doi.org/10.1038/s41467-020-17785-2.

[16] Hadley, L., Challenor, P., Dent, C., Isham, V., Mollison, D., Robertson, D.A., Swallow, B., Webb, C.R., 2021. Challenges on the interaction of models and policy for pandemic control. Epidemics 37, 100499. https://doi.org/10.1016/j.epidem.2021.100499.

[17] He, J., Guo, Y., Mao, R., Zhang, J., 2020. Proportion of asymptomatic coronavirus disease 2019 (COVID - 19): a systematic review and meta-analysis. Journal of Medical Virology https://doi.org/10.1002/jmv.26326.

[18] Kissler, S.M., Tedijanto, C., Goldstein, E., Grad, Y.H., Lipsitch, M., 2020. Projecting the transmission dynamics of SARS-CoV-2 through the post-pandemic period. Science 22, 860-868. https://doi.org/10.1126/science.abb.

[19] Knight, G.M., Dharan, N.J., Fox, G.J., Stennis, N., Zwerling, A., Khurana, R., Dowdy, D.W., 2016. Bridging the gap between evidence and policy for infectious diseases: How models can aid public health decision-making. International Journal of Infectious Diseases 42, 17-23. https://doi.org/10.1016/j.ijid.2015.10.024.

[20] Kofman, A., Kantor, R., Adashi, E.Y., 2021. Potential COVID-19 Endgame Scenarios: Eradication, Elimination, Cohabitation, or Conflagration? JAMA 326, 303-304. https://doi.org/10.1001/jama.2021.11042.

[21] Kretzschmar, M.E., Ashby, B., Fearon, E., Overton, C.E., Panovska-Griffiths, J., Pellis, L., Quaife, M., Rozhnova, G., Scarabel, F., Stage, H.B., Swallow, B., Thompson, R.N., Tildesley, M.J., Villela, D., 2022. Challenges for modelling interventions for future pandemics. Epidemics 38, 100546. https://doi.org/10.1016/j.epidem.2022.100546.

[22] Kubo, H., 2020. Risk Governance for Systemic Risks, Not Measures for Infectious Diseases. Japanese Journal of Risk Analysis 29, 233-236. https://doi.org/10.11447/sraj.29.233.

[23] Kuniya, T., 2020. Prediction of the epidemic peak of coronavirus disease in Japan. Journal of Clinical Medicine 9, 789. https://doi.org/10.3390/jcm9030789.

[24] LaJoie, Z., Usherwood, T., Sampath, S., Srivastava, V., 2022. A COVID-19 model incorporating variants, vaccination, waning immunity, and population behavior. Scientific Reports 12. https://doi.org/10.1038/s41598-022-24967-z.

[25] Lauer, S.A., Grantz, K.H., Bi, Q., Jones, F.K., Zheng, Q., Meredith, H.R., Azman, A.S., Reich, N.G., Lessler, J., 2020. The Incubation Period of Coronavirus Disease 2019 (COVID-19) From Publicly Reported Confirmed Cases: Estimation and Application. Annals of Internal Medicine https://doi.org/10.7326/M20-0504.

[26] Liu, X., Huang, J., Li, C., Zhao, Y., Wang, D., Huang, Z., Yang, K., 2021. The role of seasonality in the spread of COVID-19 pandemic. Environmental Research 195, 110874. https://doi.org/10.1016/j.envres.2021.110874.

[27] Metcalf, C., Edmunds, W., Lessler, J., 2015. Six challenges in modelling for public health policy. Epidemics 10, 93-96. https://doi.org/10.1016/j.epidem.2014.08.008.

[28] 厚生労働省（MHLW）, 2020.
https://www.mhlw.go.jp/content/000657892.pdf (Accessed on 5 August 2021)

[29] Ministry of Health, Labor, and Welfare, 2021. Open data
https://www.mhlw.go.jp/stf/covid-19/open-data_english.html (Accessed on 8 January 2023)

[30] 厚生労働省（MHLW）, 2022a. 療養状況等及び入院患者受入病床数等に関する調査について
https://www.mhlw.go.jp/stf/seisakunitsuite/newpage_00023.html (Accessed on 8 January 2023)

[31] 厚生労働省（MHLW）, 2022b. 政府の取組
https://www.mhlw.go.jp/stf/covid-19/seifunotorikumi.html (Accessed on 8 January 2023)

[32] Ministry of Land, Infrastructure, Transport and Tourism, 2020.
https://corona.go.jp/toppage/pdf/area-transition/20201030_station.pdf
(Accessed on 8 January 2023)

[33] Nakatsuka, S., 2017. Management strategy evaluation in regional fisheries management organizations - how to promote robust fisheries management in international settings. Fisheries Research 187, 127-138. https://doi.org/10.1016/j.fishres.2016.11.018.

[34] Nishiura, H., Kobayashi, T., Miyama, T., Suzuki, A., Jung, S., Hayashi, K., Kinoshita, R., Yang, Y., Yuan, B., Akhmetzhanov, A.R., Linton, N.M., 2020. Estimation of the asymptomatic ratio of novel coronavirus infections (COVID-19). International Journal of Infectious Diseases 94, 154-155. https://doi.org/10.1016/j.ijid.2020.03.020.

[35] Oran, D.P., Topol, E.J., 2020. Prevalence of Asymptomatic SARS-CoV-2 Infection: A Narrative Review. Annals of Internal Medicine https://doi.org/10.7326/M20-3012.

[36] Peirlinck, M., Linka, K., Costabal, F.S., Kuhl, E., 2020. Outbreak dynamics of COVID-19 in China and the United States. Biomechanics and Modeling in Mechanobiology 19, 2179-2193. https://doi.org/10.1007/s10237-020-01332-5.

[37] Petersen, E., Koopmans, M., Go, U., Hamer, D.H., Petrosillo, N., Castelli, F., Storgaard, M., Al Khalili, S., Simonsen, L., 2020. Comparing SARS-CoV-2 with SARS-CoV and influenza pandemics. The Lancet Infectious Diseases 20, e238-e244. https://doi.org/10.1016/S1473-3099(20)30484-9.

[38] Probert, W.J.M., Jewell, C.P., Werkman, M., Fonnesbeck, C.J., Goto, Y., Runge, M.C., Sekiguchi, S., Shea, K., Keeling, M.J., Ferrari, M.J., Tildesley, M.J., 2018. Real-time decision-making during emergency disease outbreaks. PLOS Computational Biology 14, 1-18. https://doi.org/10.1371/journal.pcbi.1006202.

[39] Punt, A.E., 2015. Strategic management decision-making in a complex world: quantifying, understanding, and using trade-offs. ICES Journal of Marine Science 74, 499–510. https://doi.org/10.1093/icesjms/fsv193.

[40] Punt, A.E., Butterworth, D.S., de Moor, C.L., De Oliveira, J.A.A., Haddon, M., 2016. Management strategy evaluation: best practices. Fish and Fisheries 17, 303-334. https://doi.org/10.1111/faf.12104.

[41] Shea, K., Runge, M.C., Pannell, D., Probert, W.J.M., Li, S.L., Tildesley, M., Ferrari, M., 2020. Harnessing multiple models for outbreak management. Science 368, 577-579. https://doi.org/10.1126/science.abb9934.

[42] Siple, M.C., Koehn, L.E., Johnson, K.F., Punt, A.E., Canales, T.M., Carpi, P., de Moor, C.L., De Oliveira, J.A.A., Gao, J., Jacobsen, N.S., Lam, M.E., Licandeo, R., Lindegren, M., Ma, S., Oskarsson, G.J., SanchezMarono, S., Smolinski, S., Surma, S., Tian, Y., Tommasi, D., Gutierrez T., M., Trenkel, V., Zador, S.G., Zimmermann, F., 2021. Considerations for management strategy evaluation for small pelagic fishes. Fish and Fisheries 22. https://doi.org/10.1111/faf.12579.

[43] Sugishita, Y., Kurita, J., Sugawara, T., Yasushi Ohkusa, Y., 2020. Preliminary evaluation of voluntary event cancellation as a countermeasure against the COVID-19 outbreak in Japan as of 11 March, 2020. medRxiv https://doi.org/10.1101/2020.03.12.20035220.

[44] Thompson, R.N., Hollingsworth, T.D., Isham, V., Arribas-Bel, D., Ashby, B., Britton, T., Challenor, P., Chappell, L.H.K., Clapham, H., Cunniffe, N.J., Dawid, A.P., Donnelly, C.A., Eggo, R.M., Funk, S., Gilbert, N., Glendinning, P., Gog, J.R., Hart, W.S., Heesterbeek, H., House, T., Keeling, M., Kiss, I.Z., Kretzschmar, M.E., Lloyd, A.L., McBryde, E.S., McCaw, J.M., McKinley, T.J., Miller, J.C., Morris, M., O'Neill, P.D., Parag, K.V., Pearson, C.A.B., Pellis, L., Pulliam, J.R.C., Ross, J.V., Tomba, G.S., Silverman, B.W., Struchiner, C.J., Tildesley, M.J., Trapman, P., Webb, C.R., Mollison, D., Restif, O., 2020. Key questions for modelling covid-19 exit strategies. Proceedings of the Royal Society B: Biological Sciences 287, 20201405. https://doi.org/10.1098/rspb.2020.1405.

[45] Statistics Division, Bureau of General Affairs, Tokyo Metropolitan Government 2020. https://www.toukei.metro.tokyo.lg.jp/tnenkan/2019/tn19q3e002.htm (Accessed on 2 January 2023)

[46] Tokyo Metropolitan Government, 2020.
https://stopcovid19.metro.tokyo.lg.jp/en/ (Accessed on 3 January 2023)

[47] Watanabe, A. and Matsuda, H., 2022. Effectiveness of feedback control and the trade-off between death by COVID-19 and costs of countermeasures. Health Care Management Science https://doi.org/10.1007/s10729-022-09617-0.

[48] Yang, H., Lombardi Junior, L., Castro, F., Yang, A., 2020. Mathematical model describing CoViD-19 in São Paulo, Brazil - evaluating isolation as control mechanism and forecasting epidemiological scenarios of release. Epidemiology and Infection 148, E155. https://doi.org/10.1017/S0950268820001600.

Table 1: 変数及び評価指標

Symbol	Definition
	時刻　におけるウイルスに感受性を持つ人の数
	時刻　におけるウイルスに曝露した人の数
	時刻　における隔離されていない無症候性感染者の数
	時刻　における隔離されておらず、症状がまだ出ていない（将来発症する）感染者の数
	時刻　における隔離されていない症状ありの感染者の数
	時刻　における回復して免疫を獲得した人の数
	時刻　における隔離されている無症候性感染者の数
	時刻　における隔離されている症状がまだ出ていない（将来発症する）感染者の数
	時刻　における隔離されている症状ありの感染者の数
	時刻　から　の間に感染し、それが原因で死亡した人の数
	時刻　における移動制限や営業時間短縮のような行動抑制の度合い
	行動抑制による社会経済費用
	自宅や宿泊施設に隔離された感染者の累積数
	入院した発症感染者の累積数
	管理期間に検査を受けた人の累積人数

Table 2: パラメータと値（Reference が空白のものは仮定の値である）

Symbol	Definition	Value	Reference
	2019 年 10 月 1 日時点の東京都の人口		[45]
	無症候性感染者の感染力		[47]
	症状あり感染者の感染力		[47]
	無症候性感染者の回復率	≈	
	発症してから回復するまでの平均日数		[4]
	平均隔離期間		[28]
	症状あり感染者の退院率		[29]
–	全感染者のうち無症候性感染者の割合		[5, 17, 34, 35]
	感染してから感染力を持つまでの期間の中央値 (latent period)		[36]
	潜伏期間（incubation period）と latent period の差	2.54	[25, 36]
	発症から入院までの時間	2	
	感染者の検出率		
$\Re$	基本再生産数		[23, 43]
	時刻　における東京都の確保病床数		[30]
	致命割合（Case fatality rate）	···	[29]
	RT-PCR 検査の陽性率		[46]
	シミュレーションの開始日 (yyyy/mm/dd)	2020/04/01	
	シミュレーションの終了日 (yyyy/mm/dd)	2021/03/31	

Table 3: 流行期の管理戦略シミュレーションにより得られた各指標の平均値。括弧内の数字は標準偏差を表す。小数は切り上げて表示している。単位は　　は日数であり、それ以外は人数である。

Strategy					
1	93 (4)	19599 (8969)	74424 (9572)	45303 (18233)	62 (11)
2	248 (32)	55183 (30721)	201182 (14869)	125375 (64492)	59 (13)
3	357 (76)	65325 (13323)	285424 (97774)	157997 (25423)	37 (12)
4	900 (225)	396805 (119185)	479521 (143639)	391929 (67561)	22 (13)
5	101 (35)	18806 (9400)	82877 (32669)	44957 (21013)	62 (15)

Chapter VI

総合的考察

順応的管理を枠組みと手順に沿って運用する際、具体的に必要になるのは効果的かつ実用的と思われる制御規則及び管理規則である。第 2 章と第 3 章では数理モデルを使用した感染症制御則と漁獲管理規則を提案し、検証した。どちらもフィードバックコントロールを組み込んであり、根底には本論文の主題である順応的管理がある。第 2 章の感染症制御則は病床の使用率を参照して行動抑制の度合いを調整し、第 3 章の漁獲管理規則は親魚資源量の 2 年後の予測値を参照して生物学的許容漁獲量を設定した。参照点を別の指標に変えたり（e.g.[3, 9]）、値を動的なもの（e.g.[2, 5]）にする考え方もあるが、本論文では筆者の調べる限り最善と思われるものを提示した。

不確実性の大きな問題に取り組む際も数理モデルは有用な道具になりうるが、それでも新型コロナウイルスのように事前予測が困難で事後になって初めて課題となる事象がある。そこで順応的学習が活用され、次に起こりうる問題への備えになる。第 4 章と第 5 章で現実に起きた事象を見直し、予測を目的として構築された数理モデルでは事前に捉えることが困難と思われる課題を探求した。いつ流行が起こるかが不確実な感染症については、その感染症そのものへの感染症制御則と将来より良い対策を取るための視点を評価指標として準備しておくことを提言した。2022 年現在も続く SARS-CoV-2 の流行に対し、国債発行残高の積み増しと引き換えた経済状態の現状維持だけでなく、出口戦略が求められる。さらに毎年利用する再生産性のある資源について、小型浮魚の代表種であるマイワシを例とした漁獲管理規則と中長期的な水産資源管理戦略の評価指標を提言した。今後引き続き水産業を持続さらに発展させるためには漁獲管理規則に加えて産業自体の構造的な見直しのための指標が必要である。

Allen and Gunderson [1] は順応的管理の課題について以下を取り上げた。

1. 科学者が様々な管理の可能性を理解していないこと、または意思決定者が直接使用できる情報を提供する必要性を認識していないこと
2. 意思決定者が順応的管理が必要な理由を理解していないこと
3. 重複する管理機関が順応的管理計画を実施する責任を明確に定義していないこと
4. 単一の最良の政策が信頼性を与えるという管理機関の信念
5. 順応的手法を実装する複雑なプロセスに対するリーダーシップの欠如
6. 研究利益のための管理目標の乗っ取り
7. 官僚的および政治的不作為を政策選択として使用すること

8. 多様な利害関係者の間で共有された理解と共有された意思決定を構築するために必要な過程を強調したり注意を向けることの欠如
9. 実験を通じて複雑な機能的関係を測定する能力を誇張する科学者の傾向
10. 学習よりも行動を重視すること
11. 学習を実践に翻訳することの難しさ
12. 情報の収集と学習に関連する費用と遅延
13. 順応的管理の手法が機能するかどうかの不確実性
14. 代替政策の結果を首尾よく比較するために必要な監視を強化するための資金が不十分であること

本論文では、公衆衛生における感染症対策と水産資源管理について取り扱ったが、外来種の排除のような問題にも順応的管理は基本的な考え方となる [4, 6]。これらの問題が発生する度ごとに、順応的管理の手順に基づき、個々の政策を作成運用していくことになるが、上記の課題を鑑みることは常に必要となるだろう。Williams et al. [7] は、すべての天然資源の問題に順応的管理が適しているわけではないと指摘し、例としてどんな管理行動が取られどんな結果が得られるかほぼ不確実性がない場合、効果的な監視計画が作ることができない場合、管理戦略への監視や調査のフィードバック機構がない場合を挙げた。また、Williams and Brown [8] は、気候変動、広範囲の地理的条件の変化、生物多様性の喪失の加速、そして文化的な価値観の変化が資源管理の文脈の中で拡大し、順応的管理の適用に新たな課題を与えていると述べている。

本論文で取り扱った個別の内容について、公衆衛生は政策決定への科学文献からの根拠を重んじる姿勢と科学的な知見を実践に移すための考察が多く見られ、水産資源管理は解決できない不確実性に対する有効な手段や戦略を探求する方針が色濃く見られた。個体群の管理という大きな枠組みで見たとき、互いの分野で参考になる部分があると思われる。二つの分野に共通して重要となる知見は、不確実性の高い問題に対しても数理モデルはある程度有力であること、新しい知見を得たときに順応できる意思決定の仕組みがあること、そしてウイルスの感染者数や水産資源量の動向を監視する体制が存在することである。本論文が、二つの分野、さらには他の分野との理論と実践の交流を促し、互いの長所を生かし、より有効な管理方策の発展に寄与することを期待する。

References

[1] Allen, C.R., Gunderson, L.H., 2011. Pathology and failure in the design and implementation of adaptive management. Journal of Environmental Management 92, 1379-1384. https://doi.org/10.1016/j.jenvman.2010.10.063.

[2] Bessell-Browne, P., Punt, A.E., Tuck, G.N., Day, J., Klaer, N., Penney, A., 2022. The effects of implementing a 'dynamic ' harvest control rule in Australia's Southern and Eastern Scalefish and Shark Fishery. Fisheries Research 252, 106306. https://doi.org/10.1016/j.fishres.2022.106306.

[3] Katsukawa, T., Matsuda, H., Matsumiya, Y., 2002. Population reproductive potential: Evaluation of long-term stock productivity. Fisheries Science 68, 1106–1112. https://doi.org/10.1046/j.1444-2906.2002.00539.x.

[4] Kotani, K., Kakinaka, M., Matsuda, H., 2010. Adaptive management for eradication of exotic species. Population Ecology 52, 349-358. https://doi.org/10.1007/s10144-010-0202-0.

[5] O'Leary, C.A., Thorson, J.T., Miller, T.J., Nye, J.A., 2019. Comparison of multiple approaches to calculate time-varying biological reference points in climate-linked population-dynamics models. ICES Journal of Marine Science 77, 930–941. https://doi.org/10.1093/icesjms/fsz215.

[6] Segura, J., Hilker, F.M., Franco, D., 2019. Enhancing population stability with combined adaptive limiter control and finding the optimal harvesting-restocking balance. Theoretical Population Biology 130, 1-12. https://doi.org/10.1016/j.tpb.2019.09.012.

[7] Williams, B.K., Eaton, M.J., Breininger, D.R., 2011. Adaptive resource management and the value of information. Ecological Modelling 222, 3429-3436. https://doi.org/10.1016/j.ecolmodel.2011.07.003.

[8] Williams, B.K., Brown, E.D., 2016. Technical challenges in the application of adaptive management. Biological Conservation 195, 255-263. https://doi.org/10.1016/j.biocon.2016.01.012.

[9] Yagi, T., Yamakawa, T., 2020. Optimal shape of the harvest control rule for different fishery management objectives. ICES Journal of Marine Science 77, 3083–3094. https://doi.org/10.1093/icesjms/fsaa210.

Acknowledgements

本博士論文を執筆するにあたり、責任指導教員の松田裕之教授に感謝の言葉を申し上げます。また、指導教員の小池文人教授、酒井暁子教授、そして 2021 年度まで指導教員を務めて下さった森章教授に感謝します。上記三名に加え博士論文の公聴会で審査員を務めて下さった佐々木雄大教授と中井里史教授に感謝します。横浜国立大学大学院環境情報学府松田研究室秘書の中田賢子氏、そして松田研究室所属のポストドクター及び学生の皆様に御礼の言葉を申し上げます。