An Economic Perspective on National Standard 1

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U.S. Department of Commerce
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ABSTRACT

This paper provides an economic perspective on the Magnuson-Stevens Fishery Conservation and Management Act (MSA) National Standard 1 (NS1) requirement to prevent overfishing while achieving the optimum yield (OY) from each fishery. Section 1 introduces NS1, key elements of the NS1 Guidelines, and some relevant economic concepts. Section 2 relates these economic concepts to the goals of preventing overfishing and achieving OY. In that Section, OY is defined as a stable long-term average amount of desired sustainable yield, and a simple deterministic long-term sustainable economic yield model is used to determine OY. Section 3 extends the discussion to address important issues not captured in the simpler setting in Section 2, namely dynamics, uncertainty, and stock interactions. Several appendices further develop these ideas and their application to NS1. The core message of the paper is that NS1 requires considering costs and benefits, uncertainty, fishery dynamics, stock interactions, and the structure of the fishery management regime. The intent is to frame economic considerations in interpreting and implementing NS1 for agency staff, regional Fishery Management Council members and staff, and others in the broader US marine fishery management community.

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EXECUTIVE SUMMARY

The Magnuson-Stevens Fishery Conservation and Management Act (MSA) includes ten national standards to be met by all fishery management plans and associated regulations. National Standard 1 (NS1) requires that management "prevent overfishing while achieving, on a continuing basis, the optimum yield from each fishery for the United States fishing industry." This paper demonstrates the relevance of economic concepts and analyses to NS1. The paper is intended primarily to be of use to agency staff, regional Fishery Management Council members and staff, and others in the broader US marine fishery management community who are involved in interpreting and implementing NS1.

Section 1 introduces NS1, key elements of the NS1 Guidelines, and key relevant economic concepts (see Box 1). Section 2 then explains how these economic concepts inform the goals of **preventing overfishing** and **achieving optimum yield** (OY). The main point regarding prevention of overfishing is that it generally entails a foregone value, or opportunity cost. The main point regarding OY is that maximum sustainable yield (MSY) is in general not a compelling proxy for OY because MSY provides only a crude and incomplete measure of the overall benefit to the Nation. Introducing economic value in the context of current NS1 Guidelines, which describe OY as a long-term average amount of desired sustainable yield, leads to an OY proxy we call optimum sustainable yield (OSY). OSY is normally a more conservative reference point than MSY—that is, it requires higher biomass and lower catch and effort—while resulting in greater overall net benefit to the Nation. In other words, more conservative management often promotes both of the NS1's goals.

The goals of preventing overfishing and achieving optimum yield are linked in other ways. First, the opportunity cost of preventing overfishing affects net benefits and should therefore figure into OY discussions. Second, any yield that does not prevent overfishing is inconsistent with the MSA definition of OY. Third, preventing overfishing does not guarantee that OY is achieved, because low yields may prevent overfishing while failing to achieve OY. Taken together, these ideas suggest that joint treatment of preventing overfishing and achieving OY is likely to lead to better management.

Section 3 takes up three important factors not treated in the simple setting of Section 2: dynamics (i.e., changes in the fishery system over time), uncertainty, and stock interactions. Most, if not all, fisheries change over time and seldom if ever attain an idealized long-term biological or economic optimum such as MSY or OSY. As a result, yield targets are generally best thought of as trajectories rather than single values, an idea formalized as optimum yield trajectory (OYT) in Section 3.1. Section 3.2 treats the subject of uncertainty in fisheries management. The main points here are that preventing overfishing is best thought of in probabilistic terms (similar to insurance) and that a fully formulated notion of OSY or OYT explicitly captures decision makers' attitude toward uncertainty in both scientific information and the application of management measures. Section 3.3 addresses the topic of ecological and economic interactions among stocks. Selecting yield targets given these interactions entails managing trade-offs that reflect a key tenet of ecosystem-based fisheries management (EBFM): MSY cannot be achieved simultaneously for all harvested stocks in an ecosystem. Froese et al. (2015) note that this is one of the few currently uncontested tenets of EBFM. Economics can contribute to a framework for assessing such trade-offs, consistent with NS1 and statements in the Ecosystem-Based Fisheries Management Policy of the National Marine Fisheries Service (National Marine Fisheries Service 2016).

Section 4 summarizes the connections made between economics and NS1 and offers recommendations for future work.

The most important points we make in this paper are as follows:

1. Economic concepts and analyses can contribute to understanding of the trade-offs inherent in fisheries management decisions that aim to prevent overfishing while achieving OY. For example, understanding how fishermen and others involved in the fisheries are likely to respond to alternative management actions is critical to determining or modifying those trade-offs.

2. Because uncertainty is inherent in fisheries, preventing overfishing is meaningful only in probabilistic terms. A greater probability of preventing overfishing generally comes at greater cost, in terms of forgone yield. In other words, reducing yield is a form of payment to insure against overfishing.

3. Optimum yield is defined by the MSA in terms of benefits to the Nation. Including economic benefits generally leads to harvest policies that imply higher levels of biomass and overall net benefit and lower levels of effort and catch. For example, OSY is normally a more conservative reference point than MSY and it results in greater overall net benefit to the Nation.

4. Measures to achieve the joint goals of preventing overfishing and attaining OY are more likely to succeed if they account for system dynamics, uncertainty, stock interactions, and the effects of alternative management regimes.

Economics is well-suited to exploring trade-offs inherent in fisheries management decisions that aim to prevent overfishing while achieving OY for each stock, as well as trade-offs between what is best for each stock and what is best for the fishery as a whole given stock interactions or other ecosystem factors. We therefore believe economics has an important role to play in both meeting NS1 and implementing EBFM.

Box 1. Key Economic Concepts

Value matters more than quantity. The value or net benefit of a fishery is a more appropriate guide to fishery conservation and management than is the quantity harvested alone. This is true because OY is defined in terms of the yield from a fishery that provides the greatest overall benefit to the Nation. Quantity harvested (i.e., weight or number of fish) is typically a limited measure of overall net benefit from a fishery. For example, catch weight is a poor measure of the benefits fishermen, consumers, and others receive from a fishery and it accounts for few of the costs associated with providing those benefits.

Every choice has an opportunity cost. The opportunity cost of using resources, including living marine resources, in a particular way is the forgone value of the best alternative use of those resources, which is determined by estimating the values of likely alternative uses.

Timing matters. Timing is important because most people prefer current benefits (e.g., income or consumption) to the same level of benefits in the future. A discount rate that reflects society's time preference is required to make useful comparisons among benefits and costs that occur in different periods.

Risk is unavoidable and there are trade-offs among risks. Because of inherent variability and the difficulty of fully understanding and observing fisheries systems, fisheries management decisions inevitably involve various risks, such as the risk of overfishing, the risk of underfishing (i.e., catching less than OY), the risk of unexpected system effects (e.g., through food-web effects), and the risk of economic and/or social welfare loss. Such risks often compete, meaning that there are trade-offs among them; often, one risk can be reduced only through actions that require taking on more of a different risk.

ACRONYMS, ABBREVIATIONS, AND VARIABLES

ABC	Acceptable biological catch
ACL	Annual catch limit
ACT	Annual catch target
AM	Accountability measures
B_{MEY}	Biomass at maximum economic yield (MEY)
B_{MSRev1}	Independently determined maximum sustainable revenue (MSRev) level of biomass for stock 1
$B_{MSRevF1}$	Biomass for stock 1 at MSRev for the fishery as a whole
B_{MSY}	Biomass at maximum sustainable yield (MSY)
B_{MSY1}	Independently determined MSY level of biomass for stock 1
B_{MSYF1}	Biomass for stock 1 at MSY for the fishery as a whole
B_{OSY}	Biomass at OSY
CGE model	Computable general equilibrium model
CPUE	Catch per unit of effort
EBFM	Ecosystem-based fisheries management
E_{MSRev1}	Effort at MSRev for stock 1
E_{MSRevF}	Effort at MSRev for the fishery as a whole
E_{MSY}	Effort at MSY
E_{MSY1}	Independently determined MSY level of fishing effort for stock 1
E_{MSYF}	Effort at MSY for the fishery as a whole
EO 12866	Executive Order 12866
E_{OSY}	Effort at optimum sustainable yield (OSY)
E_{OSYF}	Effort at OSY for the fishery as a whole
F_{MSY}	Fishing mortality at MSY
F_{OSY}	Fishing mortality at OSY
$F_{rebuild}$	Fishing mortality associated with achieving T_{target}
IFQ	Individual fishing quota
IVQ	Individual vessel quota
LME	Large marine ecosystem
MDP	Markov decision process
MEY	Maximum economic yield
MFMT	Maximum Fishing Mortality Threshold
MSA or MSFCMA	Magnuson-Stevens Fishery Conservation and Management Act
MSRev	Maximum sustainable revenue
MSRevF	Maximum sustainable revenue for the fishery as a whole
MSST	Minimum stock size threshold
MSY	Maximum sustainable yield
MSY1	Independently determined MSY for stock 1
MSYF	MSY for the fishery as a whole

MSYF1	MSY for stock 1 at MSY for the fishery as a whole
NMFS	National Marine Fisheries Service
NOAA	National Oceanic and Atmospheric Administration
NS1	National Standard 1
OECD	Organisation for Economic Co-operation and Development
OFL	Overfishing limit
OSY	Optimum sustainable yield
OSYF	OSY for the fishery as a whole
OSYF1	OSY for stock 1 at OSY for the fishery as a whole
OY	Optimum yield
OYT	Optimum yield trajectory
POMDP	Partially observable Markov decision process
SDC	Status determination criteria
SSC	Scientific and Statistical Committee
TAC	Total allowable catch
T_{max}	The maximum allowable rebuilding time prescribed in the NS1 Guidelines
T_{min}	The amount of time the stock or stock complex is expected to take to rebuild to its MSY biomass level in the absence of any fishing mortality
T_{target}	Target rebuilding period

1. Introduction

The Magnuson-Stevens Fishery Conservation and Management Act (MSA)[1] requires that fishery management plans and regulations implemented under its authority be consistent with ten National Standards. National Standard 1 (NS1) states that "conservation and management measures shall prevent overfishing while achieving, on a continuing basis, the optimum yield from each fishery for the United States fishing industry" (Sec. 301(a)(1)).

Economics is relevant to NS1 for two related reasons. First, optimum yield (OY) includes in principle considerations of employment, nonmarket and recreational values, the profitability of fishing and processing firms, and benefits to seafood consumers. Second, from an economic perspective, ending overfishing or rebuilding a fishery is an investment undertaken with the expectation that benefits to society will exceed costs over time; and economic analysis can aid in evaluating those benefits and costs. Therefore, the NS1 Guidelines[2] suggest that the specifications of acceptable biological catches (ABCs), annual catch limits (ACLs), and accountability measures (AMs), which may include annual catch targets (ACTs), can be refined through the use of economic analysis of costs, benefits, distributional impacts, and risks. In fact, the MSA and other applicable laws (e.g., the National Environmental Policy Act, the Regulatory Flexibility Act, and Executive Order 12866 [EO 12866]) require economic analysis of those specifications and all other management actions.

1.1 Purpose and Organization of the Paper

The purpose of this paper is to demonstrate the relevance of economic concepts and analyses to NS1. The paper is intended primarily to be of use to agency staff, regional Fishery Management Council members and staff, and others in the broader US marine fishery management community who are involved in interpreting and implementing NS1 and exploring the trade-offs inherent in meeting NS1. Economic information is particularly useful since these trade-offs cannot be addressed adequately in terms of differences in levels of sustainable yield and biomass. For example, economic analyses are valuable when assessing trade-offs that require understanding how fishermen and others involved in fisheries are likely to respond to alternative management actions. More generally, economic analysis can support more informed decision-making as fishery managers face the joint problem of preventing overfishing and achieving OY.

The remainder of Section 1 describes NS1, key elements of the NS1 Guidelines, and some relevant economic concepts. Section 2 relates these economic concepts to the goals of **preventing overfishing** and **achieving optimum yield**. After discussing the economics of preventing overfishing, we examine economics' relevance to achieving optimum yield by: 1) introducing the concept of optimum sustainable yield (OSY); 2) comparing OSY to maximum sustainable yield (MSY); and 3) exploring the use of OSY as an OY-related reference point. Section 3 then explores the important complications of dynamics (i.e., changes in the fishery system over time and the timing of those changes), uncertainty, and stock interactions.

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[1] https://www.fisheries.noaa.gov/resource/document/magnuson-stevens-fishery-conservation-and-management-act

[2] The NS1 Guidelines are in the Federal Register at: https://www.gpo.gov/fdsys/pkg/FR-2016-10-18/pdf/2016-24500.pdf).

NOTE: This paper demonstrates how economics is relevant to understanding and implementing NS1; it is not intended to serve as a guide for the practice of economic analysis in support of NS1.

1.2 National Standard 1 and Key Elements of the NS1 Guidelines

Several changes to the MSA enacted in January 2007 were designed to prevent overfishing. Those changes included the addition of requirements for ACLs and AMs, where the ACLs established by a Council for its fisheries may not exceed the ABC recommendations of its Scientific and Statistical Committee (SSC) or a comparable MSA-approved peer review process. NOAA's National Marine Fisheries Service (NMFS) revised the NS1 Guidelines in 2009 to provide guidance for implementing the requirements in MSA for ACLs and AMs to end and prevent overfishing (74 FR 3178; 1/16/2009). NMFS revised the NS1 guidelines again in 2016 to improve and clarify the guidance and address experiences gained during the implementation of ACLs and AMs (81 FR 71858; 10/18/2016). The NS1 Guidelines define and provide guidance on the terms ACL, AM, and ABC (used but not defined in the MSA), and provide separate definitions of "overfished"[3] and "overfishing."[4] The NS1 Guidelines also explain the relationships between ACTs, ACLs, ABCs, and OFLs (overfishing limits) and how those reference points and the use of AMs play key roles in addressing scientific and management uncertainty.

The MSA provides the following definitions of the terms "optimum yield," "overfishing," and "overfished" (Sec. 3(33 and 34)). These definitions establish the importance of the concept of MSY for NS1 and the MSA as a whole. Specifically, they prohibit OY from exceeding MSY, define overfishing and overfished in terms of MSY, and require overfished fisheries to be rebuilt to a level consistent with producing MSY.

> The term **optimum**, with respect to the yield from a fishery, means the amount of fish that:
>
> - Will provide the greatest overall benefit to the Nation, particularly regarding food production and recreational opportunities and taking into account the protection of marine ecosystems.
> - Is prescribed as such on the basis of the MSY from the fishery, as reduced by any relevant economic, social, or ecological factor.
> - In the case of an overfished fishery, provides rebuilding to a level consistent with producing the MSY in such a fishery.
>
> The terms **overfishing** and **overfished** mean a rate or level of fishing mortality that jeopardizes the capacity of a fishery to produce the MSY on a continuing basis.

NMFS and the Councils typically implement the concept of MSY using single-species biological models. MSY-based stock size limits and targets, and fishing mortality or catch limits, are fundamental features of the NS1 Guidelines. The NS1 Guidelines require each Council to establish a minimum stock size threshold (MSST) and other status determination criteria (SDC) based on MSY or MSY proxies for each stock or stock complex[5] in need of conservation and management unless data are not available to

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[3] A stock or stock complex is considered ''overfished'' when its biomass has declined below the minimum stock size threshold (MSST), where MSST is the level of biomass below which the capacity of the stock or stock complex to produce MSY on a continuing basis has been jeopardized.

[4] Overfishing occurs whenever a stock or stock complex is subjected to a level of fishing mortality or total catch that jeopardizes its capacity to produce MSY on a continuing basis.

[5] The NS1 Guidelines define "stock complex" as a tool to manage a group of stocks within a FMP.

specify MSY-based SDC. In that case, alternative types of SDC can be used. The NS1 Guidelines do not address the use of alternative types of SDC when the rationale for using MSY-based SDC is in doubt. However, the NS1 Guidelines recognize that MSY can be estimated for an aggregate group of stocks (including stock complexes and the fishery as a whole). If an aggregate MSY is used, it is conceivable that the SDC should be based on the aggregate MSY and the corresponding MSYs for individual stocks as opposed to the independently estimated MSYs for the individual stocks. NMFS has advised that the use of aggregate MSY estimates does not negate the need to use individual stock SDC (based on the best scientific information available), ACLs, and related reference points to ensure that individual stocks do not become overfished or experience overfishing. NMFS needs to determine whether the best scientific information available actually supports the use of SDC for the individual stocks that are based on independently determined MSYs, which ignore stock interactions and which cannot be achieved simultaneously for all harvested stocks in an ecosystem according to EBFM (e.g., Froese et al. 2015). The use of SDC based on aggregate MSYs and the associated MSYs for individual stocks that do account for those interactions is discussed further in Section 3.3.4.

The NS1 Guidelines define an overfished stock or stock complex as one that is below its MSST, which should be between ½ B_{msy} and B_{msy}. Although the NS1 Guidelines allow MSSTs to be set for stocks or stock complexes, they recommend that where practicable, stock complexes should include one or more indicator stocks (each of which has SDC and ACLs). The NS1 Guidelines also stipulate that the rebuilding stock size target for an overfished stock is $B_{MSY,}$ and that the target rebuilding period (T_{target}) must not exceed T_{max}[6] and shall be as short as possible, taking into account: the status and biology of any overfished stock, the needs of fishing communities, recommendations by international organizations in which the U.S. participates, and interaction of the stock within the marine ecosystem. The fishing mortality associated with achieving T_{target} is referred to as $F_{rebuild}$.

Fishing mortality limits and catch limits are intended to prevent or end overfishing and to ensure that overfished stocks are rebuilt to B_{MSY} as quickly as required by the NS1 Guidelines. The NS1 Guidelines require each Council to evaluate and describe MSY-based[7] OFLs, ABCs, ACLs, and OYs, as well as AMs, for all the stocks and stock complexes in need of conservation and management that are not subject to at least one of two exceptions.[8] The NS1 Guidelines require Councils to take an approach that considers uncertainty in scientific information and management control of the fishery.[9]

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[6] If T_{min} for the stock or stock complex is 10 years or less, then T_{max} is 10 years, where T_{min} is the amount of time the stock or stock complex is expected to take to rebuild to its MSY biomass level in the absence of any fishing mortality. If T_{min} for the stock or stock complex exceeds 10 years, then one of the following methods can be used to determine T_{max}: T_{min} plus the length of time associated with one generation time for that stock or stock complex; the amount of time the stock or stock complex is expected to take to rebuild to B_{msy} if fished at 75 percent of maximum fishing mortality threshold (MFMT); or T_{min} multiplied by two.

[7] As noted above, alternative types of SDC can be used when data are not available to specify SDC based on MSY or MSY proxies but not when the rationale for using MSY-based SDC is in doubt.

[8] The exceptions are for species with a life cycle of approximately 1 year, unless subject to overfishing, and for stocks managed under an international agreement to which the U.S. is party.

[9] The term "fishery" is defined in the MSA as one or more stocks of fish that can be treated as a unit for purposes of conservation and management and that are identified on the basis of geographical, scientific, technical, recreational, and economic characteristics; and any fishing for such stocks. Therefore, "fishery" refers to commercial, recreational, and subsistence fishing.

Five key elements of the ACL-setting process described in the NS1 Guidelines are as follows:

1. ACL may not exceed ABC.
2. For overfished stocks and stock complexes, a rebuilding ABC must be set to reflect the annual catch that is consistent with the schedule of fishing mortality rates (i.e., $F_{rebuild}$) in the rebuilding plan.
3. ABC may not exceed OFL.
4. The difference between OFL and ABC depends on how scientific uncertainty and the Council's risk policy are accounted for in the ABC control rule.
5. The MSA requires that ABC be provided by the Council's SSC or a comparable peer review process.

The NS1 Guidelines also suggest that Councils adopt an explicit risk policy as part of their ABC control rules, and go on to define acceptable probabilities of overfishing:

> The Council's risk policy could be based on an acceptable probability (at least 50 percent) that catch equal to the stock's ABC will not result in overfishing, but other appropriate methods can be used. When determining the risk policy, Councils could consider the economic, social, and ecological trade-offs between being more or less risk adverse.

The NS1 Guidelines encourage Councils to address management uncertainty through a range of ACLs and AMs. Examples of management uncertainty include uncertainty in fishery managers' ability to constrain catch so that the ACL is not exceeded and uncertainty in quantifying true catch amounts (i.e., estimation errors). AMs are intended to prevent ACLs from being exceeded and to correct or mitigate overages if they occur. The NS1 Guidelines also recommend that management uncertainty be accounted for in the ACL if an ACT is not used.

For fisheries without in-season management control to prevent ACLs from being exceeded, the NS1 Guidelines note that AMs should include ACTs that are set below ACLs so that catches do not exceed the ACLs. If catches do exceed ACLs, AMs must be implemented as soon as possible to correct the operational issue that caused the ACL overage, as well as to mitigate the biological consequences to the stock, if any.

Although the goals of NS1 are to prevent overfishing while achieving OY, which includes rebuilding overfished fisheries, the NS1 Guidelines and the 2007 changes to the MSA discussed previously focus on preventing overfishing and rebuilding overfished stocks. Unfortunately, preventing overfishing and rebuilding overfished stocks do not ensure that OY will be attained. Indeed, with the exception of rebuilding overfished stocks, the guidance on developing and applying OY has been minimal, and practices have varied widely. In the remainder of this paper, we explore how economics can contribute to achieving both NS1 goals, in part by giving more attention to OY and the trade-offs faced when addressing overfishing and optimum yield simultaneously.

1.3 Key Economic Ideas Relevant to NS1

As suggested above, preventing overfishing while achieving OY is in part an economic problem. Here, we introduce some key ideas from economics that we will use in later sections to examine the economic content of NS1.

Value matters more than quantity. The value or net benefit of a fishery is a more appropriate guide to fishery conservation and management than is the quantity harvested alone. This is true because OY is defined in terms of the yield from a fishery that provides the greatest overall benefit to the Nation. Quantity harvested (i.e., weight or number of fish) is typically a limited measure of overall net benefit from a fishery. For example, catch weight is a poor measure of the benefits fishermen, consumers, and others receive from a fishery and it accounts for few of the costs associated with providing those benefits.

Every choice has an opportunity cost. The opportunity cost of using resources in a particular way is the forgone value of the best alternative use of those resources, which is determined by estimating the values of likely alternative uses. Consider the following examples:

- Preventing a decline in future harvests or allowing an increase in future harvests may require a reduction in current harvest.
- An increase in recreational harvest may require a reduction in commercial harvest, or vice versa.
- Because of the complex interactions among the stocks in a fishery, higher levels of sustainable yield for some stocks may require lower levels for other stocks.
- A reduction in fishing activity and catch may be required to provide additional protection for an endangered species and its habitat.

Timing matters. Timing is important because most people prefer current benefits (e.g., income or consumption) to the same level of benefits in the future. A discount rate that reflects society's time preference is required to make useful comparisons among benefits and costs that occur in different periods.

Risk is unavoidable and there are trade-offs among risks. Because of inherent variability and the difficulty of fully understanding and observing fisheries systems, fisheries management decisions inevitably involve various risks, such as the risk of overfishing, the risk of underfishing (i.e., catching less than OY), the risk of unexpected system effects (e.g., through food-web effects), and the risk of economic and/or social welfare loss. Such risks often compete, meaning that there are trade-offs among them; often, one risk can be reduced only through actions that require taking on more of a different risk.

In the following sections, we will first explore the implications of these ideas in a very simple setting, and then consider more complicated and realistic settings.

2. Applying Economic Principles to NS1 in a Simple Setting

In this section, we first briefly consider the economic aspects of the requirement to prevent overfishing. Then, we use a single-species, long-term sustainable economic yield model of OSY to explore the application of economics to OY in a simple setting. Including economic measures of benefits and costs leads to a measure of greatest overall net benefit to the Nation, which we call OSY. OSY is a well-defined and useful—if, in practice, necessarily an incomplete—benchmark of management performance.

OSY is relevant to NS1 because it provides a measure of a well-managed fishery's potential net benefit, as well as a reference point for estimating the forgone net benefit of pursuing particular harvest policies. OSY is derived from a more meaningful measure of net benefits to society than is MSY and can be kept consistent with the MSA's conservation goals by defining it such that it satisfies all appropriate biological constraints, including MSY itself.

2.1 Economics and Preventing Overfishing

The NS1 requirement to prevent overfishing, a fundamentally biological constraint, has important economic implications. First, the most obvious implication is that the yield forgone to account for uncertainty and decrease the probability of overfishing represents an opportunity cost that should be compared to the benefit of decreasing the probability of overfishing.

Second, because uncertainty is inherent in fisheries, preventing overfishing is meaningful only in probabilistic terms, and a greater probability of preventing overfishing generally comes at greater cost in terms of forgone short-term yield and long-term average sustainable yield. In other words, reducing yield is a form of insurance against overfishing.

Third, preventing overfishing is required to achieve OY but does not ensure that OY will be achieved. That is, preventing overfishing is necessary but not sufficient to achieve OY.

Fourth, management actions intended to prevent overfishing will have economic implications because:

- Economic incentives resulting from those management actions may encourage or discourage accurate and timely reporting and compliance with fishery regulations;
- Accurate and timely reporting and compliance may affect managers' ability to move toward optimum yield while preventing overfishing; and
- The monitoring, reporting, and enforcement components affect fishery management costs.

Fifth, preventing overfishing should involve institutional design that promotes efficiency in a fishery. National Standards 5 and 7 include requirements to consider efficiency.[10] Overfishing may be prevented in various ways, and the identification of the costs and benefits of alternative measures to prevent overfishing requires economic information.

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[10] National Standards 5 and 7 are as follows:

> (5) Conservation and management measures shall, where practicable, consider efficiency in the utilization of fishery resources; except that no such measure shall have economic allocation as its sole purpose.
>
> (7) Conservation and management measures shall, where practicable, minimize costs and avoid unnecessary duplication.

Finally, efforts to prevent overfishing may have differential impacts among individuals, communities, fleets, and sectors. These impacts often involve market and nonmarket effects that make economics relevant to discussions of equity in relation to preventing overfishing.

2.2 The Economics of OY: Why MSY Is Not OY

In this section, we apply economic principles to show that MSY is in general not a compelling proxy for OY. Specifically, we use a simple deterministic long-term sustainable economic yield model to develop the concept of OSY, compare OSY to MSY, and explore the use of OSY as an OY-related reference point. Appendix 1 describes extensions to our simple model that more effectively capture the full range of net benefits from alternative levels of sustainable catch, biomass, and effort.

Because the MSA does not define MSY, the NS1 Guidelines provide the following definition:

> MSY is the largest long-term average catch or yield that can be taken from a stock or stock complex under prevailing ecological, environmental conditions and fishery technological characteristics (e.g., gear selectivity), and the distribution of catch among fleets.[11]

The prevailing ecological and environmental conditions and fishery technological characteristics, and the distribution of catch among fleets are, in part, determined by regulatory and market conditions. Therefore, each MSY is defined for a specific set of regulatory and market conditions, and as those conditions change, the MSY can change. For example, a change in the fishery management regime, the price of fuel, gear selectivity, or the distribution of catch among fleets can affect MSY. This characteristic of MSY is discussed more fully in Section 2.2.3.

MSY for a stock of fish is usually determined using a biological model in which sustainable levels of yield (catch) and biomass, as well as the associated sustainable age, size, or stage structure (when an age-, size-, or stage-structured model is used[12]), are functions of the level of fishing effort. Typically, relationships among sustainable levels of effort, yield, and biomass are depicted by a sustainable yield curve, such as that in Figure 1. As effort increases, the sustainable level of biomass decreases, and sustainable yield increases, reaches a maximum at MSY, and then decreases as the actual level of effort exceeds the MSY level of effort (E_{MSY}) by a larger amount, and actual biomass decreases farther below the MSY biomass level (B_{MSY}).

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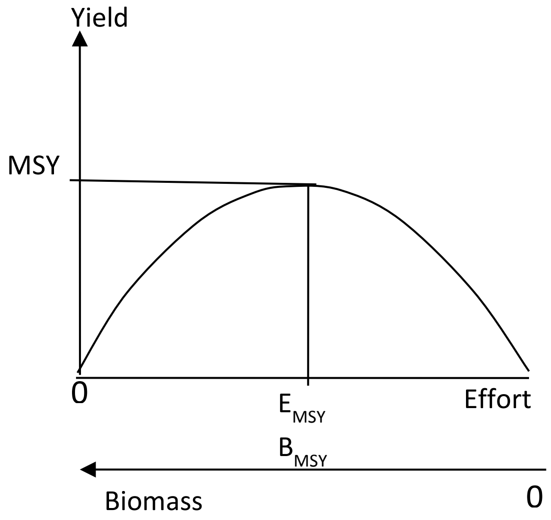
[11] The term "user groups" may be more appropriate than “fleets” in this context to clarify that this definition includes the distribution of catch among user groups in or among commercial, recreational, and subsistence fisheries.

[12] When such a model is used, the reference to the associated sustainable age, size, or stage structure is implied but not made explicit in the rest of this paper.

Figure 1. MSY on a sustainable yield curve, where levels of sustainable yield and biomass are functions of the level of fishing effort.



MSY (measured as numbers or weight of fish) is not a sound proxy for OY because it is a poor measure of the benefits of catching and consuming fish and because it doesn't account for most of the associated costs. There are many trade-offs when selecting among the sustainable sets of effort, biomass, and yield, and those trade-offs cannot be adequately addressed in terms of differences in levels of sustainable yield and biomass. Therefore, a reference point based on a more inclusive measure of overall net benefit would be useful for implementing NS1; OSY is such a reference point.

2.2.1 Defining OSY and Net Benefit to the Nation

Neither the MSA nor the NS1 Guidelines refer to OSY. The definition of OSY, which we derived from that of MSY on the previous page, is as follows:

> OSY is the catch associated with the largest long-term average overall net benefit to the Nation that can be provided by a stock or stock complex under prevailing ecological, environmental, and economic conditions; fishery technological characteristics (e.g., gear selectivity); and the distribution of catch among user groups (e.g., fleets), where the sustainable levels of effort and biomass associated with each sustainable level of catch are among the determinants of the overall net benefit of that sustainable level of catch.[13]

To avoid the implication that we are referring to a narrowly defined set of net benefits, we use the term "OSY" instead of the more common term "MEY" (maximum economic yield). We define OSY in a way that, in principle, accounts for all the determinants of overall net benefit to the Nation for each sustainable level of yield and associated sustainable levels of biomass and effort. However, we recognize that data and model limitations will determine the extent to which OSY is, in practice, a more inclusive concept than MEY has often been.

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[13] In the definitions of MSY and OSY and throughout this paper, the terms "yield" and "catch" are used interchangeably.

As with MSY, OSY is, in part, determined by regulatory and market conditions. Therefore, each OSY is defined for a specific set of regulatory and market conditions, and OSY will change as those conditions change. This characteristic of OSY is discussed more fully in Section 2.2.3 and Appendix 2.

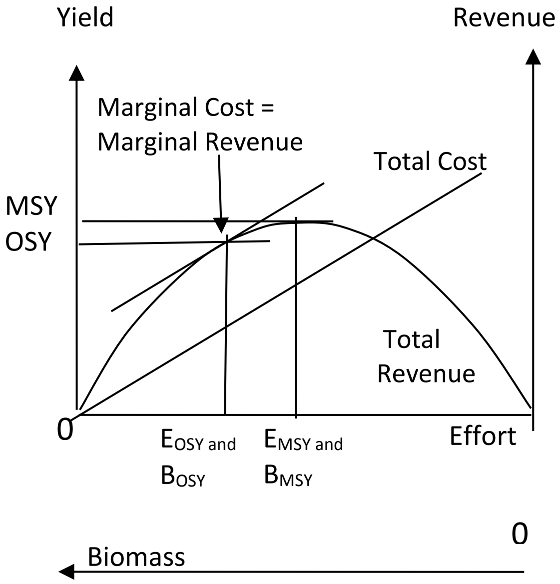
There are various ways to define overall net benefit to the Nation. Executive Order 12866 provides a broad definition in its guidance concerning the requirement that NMFS and other federal agencies assess the costs and benefits of proposed regulations and alternative regulations. Specifically, it indicates that net benefit includes "potential economic, environmental, public health and safety, and other advantages; distributive impacts; and equity" (see Federal Register, 58(190), October 4, 1993 at http://cdn.loc.gov/service/ll/fedreg/fr058/fr058190/fr058190.pdf).

2.2.2 Using a Simple Model to Depict OSY and Compare It to MSY

Figure 2 depicts a simple model of OSY in which: 1) Net benefit is measured narrowly as the difference between total revenue and total cost; 2) Total revenue is the product of sustainable catch and a constant ex-vessel price; 3) Total cost, which includes only the cost of labor, capital, and other inputs fishermen pay for, is the product of the level of effort and a fixed cost per unit of effort; 4) The stock of fish is caught exclusively in one commercial fishery and not in any recreational or subsistence fisheries; and 5) There are no ecological or economic interactions between this stock and any other living marine resources. With these simplifications, OSY and MEY are equivalent. A more comprehensive model of OSY, which eliminates this equivalency by including a much broader range of benefits and costs and by addressing recreational and subsistence fisheries, is discussed in Appendix 1. Appendix 2 shows how a change in the fishery management regime will affect OSY through its effects on the ex-vessel price and the marginal cost of effort. Section 3.3 discusses extension of the concepts of MSY, OSY and optimum yield trajectory (OYT) to a fishery with significant ecological or economic stock interactions. That discussion is based in part on the numerical examples in Appendix 5 for a two-stock fishery in which the economic interactions is that both stocks are caught together.

Figure 2 is based on the Gordon-Schaefer model (Gordon, 1954). This figure includes a standard sustainable yield curve for a surplus production model. The curve doubles as a sustainable revenue curve with the addition of a vertical axis with a scale that reflects a constant ex-vessel price (e.g., dollars per ton). In addition, the figure includes a linear cost curve. In Figure 2, the difference between the revenue curve and the linear total cost curve is maximized when the slope of the cost curve (the marginal cost of effort) is equal to the slope of the revenue curve (marginal revenue, or the additional revenue resulting from an additional unit of effort). Clark (1990) calls this outcome "maximization of sustainable economic rent."

Figure 2. A simple model of OSY and comparison of MSY and OSY levels of sustainable yield, biomass, and effort, where the simple model includes a narrowly defined measure of overall net benefit, a linear cost curve, a constant ex-vessel price, and logistic growth.



With this simple model, sustainable levels of yield, biomass, and revenue, as well as cost, and the narrowly defined measure of overall net benefit, are functions of the level of fishing effort. The following occur as effort increases:

- The sustainable level of biomass decreases.
- The sustainable levels of yield and revenue increase, reach a maximum at MSY, and then decrease because effort exceeds E_{MSY} by a larger amount, and biomass falls farther below B_{MSY}.
- Cost increases continuously.
- The sustainable level of net benefit increases, reaches a maximum at OSY, and then decreases because cost is increasing more rapidly than revenue (i.e., marginal cost becomes greater than marginal revenue); the OSY level of effort (E_{OSY}) is exceeded by larger amounts; and biomass falls farther below the level that supports OSY (B_{OSY}).

In this simple model, OSY is a more conservative reference point than MSY and provides greater overall net benefit to the Nation. It is more conservative because it is associated with a higher sustainable level of biomass ($B_{OSY} > B_{MSY}$) and lower sustainable levels of effort ($E_{OSY} < E_{MSY}$) and catch (OSY < MSY). Therefore, use of OSY as a reference point for OY is consistent with the MSA requirement that OY is to be less than MSY based on “any relevant economic, social, or ecological factor.” Although achieving a stock size of B_{osy} (which is higher than B_{msy}) would be a higher standard than in the NS1 Guidelines, the following description of OY in the NS1 Guidelines indicates that a higher standard can be used:

> In NS1, the phrase “achieving, on a continuing basis, the OY from each fishery” means: producing, from each stock, stock complex, or fishery, an amount of catch that is, on average, equal to the Council’s specified OY; prevents overfishing; maintains the long-term average biomass near or above B_{msy}; and rebuilds overfished stocks and stock complexes consistent with timing and other requirements of section 304(e)(4)(j) of the MSA and paragraph 50 CFR 600.310(j) of the National Standard 1 Guidelines.

2.2.3 Using OSY as an Additional Management Reference Point

As defined previously, MSY and OSY are complementary, stable long-term management reference points that are similar in the following ways:

- They are based on biological models that estimate long-term sustainable levels of catch and associated sustainable levels of biomass and effort for a stock of fish.

- Because MSY is constrained by “prevailing ecological, environmental conditions and fishery technological characteristics (e.g., gear selectivity), and the distribution of catch among fleets,” and because OSY is additionally constrained by prevailing economic conditions, the numeric values of MSY and OSY depend on variables that can fluctuate frequently and significantly. Examples of such variables include: 1) the conditions of other stocks in a fishery or large marine ecosystem that have ecological interactions (predation and competition) with the stock for which MSY or OSY is being assessed; 2) fleet-specific costs and ex-vessel prices and fishery regulations that change over time and affect gear selectivity and the distribution of catch among fleets, which in turn affect MSY and OSY through their effects on catch size composition; 3) variables that define the climate or environmental regime and affect recruitment, growth rates, and natural mortality; and 4) variables that affect time-varying catchability, gear selectivity, areas and depths fished, and even choice of gear and equipment.

- Changes in fishery management measures can change these constraints, which in turn lead to changes in MSY and OSY for a stock. For example, a fishery management action that changes the distribution of catch among fleets or the spatial or temporal distribution of catch could change the size composition of catch in a way that increases MSY and OSY. Similarly, a management action that decreases the marginal cost of effort would increase OSY. For example, by eliminating the race for fish, a well-designed catch share program can decrease fishing costs by decreasing fishing capacity, allocating catch to the most efficient fishing operations, and allowing each remaining fishing operation to fish more efficiently (e.g., reduce the amount of fuel and labor, bycatch, and fishing accidents for a given amount of catch). In addition, a well-designed catch share program can increase ex-vessel revenue by increasing ex-vessel prices and catch utilization rates.

- The actual biomass of a stock of fish is often not equal to B_{MSY} or B_{OSY}.

However, because OSY maximizes sustainable overall net benefit rather than sustainable catch for a given set of ecological, environmental, regulatory, and market conditions, these two complementary reference points (i.e., OSY and MSY) have the following important differences:

- OSY is or should be derived subject to various biological, ecological, oceanographic, climatic, economic, and social constraints or conditions that often interact with each other. Thus, OSY is fundamentally based on human values, consistent with the MSA requirement to manage fisheries to achieve the “greatest overall benefit to the Nation.”

- In order to estimate an OSY that accounts for all the determinants of the overall net benefit to the Nation of alternative levels of sustainable catch, we need economic, biological, and ecological data and models in addition to the biological data and models used to estimate MSY.

- The uncertainty concerning numerical value, and the frequency and magnitude of fluctuations in that value, may be greater for OSY than for MSY because more variables determine OSY. For example, changes in fuel costs and ex-vessel prices have more direct and often larger effects on OSY than on MSY. Their effects on MSY are less direct; they result from effects on gear selectivity and the distribution of catch among fleets, which are among the determinants of MSY as it is defined in the NS1 Guidelines.

- OSY is a more conservative reference point (i.e., OSY < MSY, $B_{OSY} > B_{MSY}$, and $E_{OSY} < E_{MSY}$). This is not necessarily (or exclusively) due to precautionary considerations. For example, though OSY is smaller than MSY in the model discussed earlier, it is not appropriate to think of OSY in terms of a precautionary buffer for MSY. Rather, the difference between MSY and OSY in the long-term sustainable yield models is the result of their different objectives (maximizing catch weight versus maximizing a measure of the net benefit of catch). However, the inequality may have implications for the cost of a precautionary buffer (e.g., the cost of a buffer below MSY may be negative). Although OSY cannot in practice capture the full range of factors that determine a fishery’s overall net benefit to the Nation, it can capture many factors that MSY and MSY-based measures are not designed to address.

- OSY has rarely been estimated for U.S. fisheries and even more rarely, if ever, estimated based on broadly defined overall net benefit to the Nation. Obstacles to OSY estimates include inadequate data and particular technical challenges. The information required for estimating magnitudes and distributions of all the benefits and costs of harvesting and consuming fish has rarely been available. The lack of information is due to various factors, including limited economic data collection programs for many fisheries. Other factors include the challenges of developing economic and ecosystem models that can provide useful estimates of the opportunity cost of using living marine resources and marine habitat to harvest fish. Accounting for that opportunity cost is an important but difficult step in moving toward ecosystem-based fisheries management (EBFM).

Although the concept of OSY and the typically more narrowly defined concept of MEY have had limited use in U.S. fishery management, the concept of MEY is used extensively in Australian Commonwealth fisheries (Grafton et al., 2010). Vieira and Pascoe (2013), in a very useful paper, review relevant literature to provide a detailed description of the challenges to operationalizing MEY and, where possible, identify potential approaches to resolving them. They outline key economic definitions and concepts; discuss general experiences operationalizing MEY in Australian Commonwealth fisheries; and address issues relevant to particular types of fisheries (e.g., international and mixed-stock fisheries and fisheries with market power or highly variable stocks). In addition, Christensen, 2010; Sumaila and Hannesson, 2010; Norman-López and Pascoe, 2011; Grafton et al., 2012; and Squires and Vestergaard, 2016 have expanded the concept of MEY to include a broader range of benefits and costs than were typically addressed.

Even though OSY is not among the reference points described in the NS1 Guidelines, it should be of great interest to policymakers. If, as in the NS1 Guidelines, OY is defined as a stable long-term average amount of desired sustainable yield, OSY can be a useful approximation of OY. Therefore, OSY provides a direct approach for assessing management performance in relation to the NS1 challenge of preventing overfishing while achieving OY.

We expect steady progress in overcoming the modeling challenges associated with estimating OSY; however, data requirements for developing useful models of OSY are formidable. Given the current paucity of economic data—and particularly cost data—in many federally managed fisheries, new data collection programs are at least as important as modeling innovations to defining and managing for OSY. The basic economic data and analyses that will result in more informed decisions concerning the implementation of NS1 and most other fishery management actions are similar. In general, they are the data and analyses that can be used to assess the expected effects of such actions on the overall net benefit a fishery or set of fisheries in a large marine ecosystem provides to the Nation. Ideally, such assessments would begin with a prediction of how fishermen and others involved in the fishery will respond to the management action; include predictions of resulting biological, ecological, and economic effects, including cumulative effects; and present the result of those effects on overall net benefit to the Nation.

Anderson and Seijo (2010) note that managing fisheries requires detailed knowledge of factors that influence fishing behavior, which can vary depending on fishermen’s cultural background and context, fishing technology used, and perceptions and strategic behavior affecting compliance with the regulatory scheme. Similarly, the National Research Council’s report (2013) on the effectiveness of stock rebuilding plans recognizes the importance of considering fishermen’s behavior. For example, it states that:

> Fulton et al. (2011) suggest that human behavior is perhaps the greatest source of uncertainty in fisheries management, but the least adequately accounted for (see also Wilen, 2006). For example, fishermen’s decisions on where, when, for what species, and how to allocate fishing effort may affect the dynamics of rebuilding; reallocation of fishing effort can either slow or speed recovery.

As one example of efforts to predict fishermen’s behavior, fisheries economists have since the 1980s modeled the factors that influence fishermen’s spatial and participation choices to understand the trade-offs of fishing in different locations. This knowledge can improve predictions of how fishermen will respond to the creation of marine reserves, changes in market conditions, or management actions such as the implementation of catch share programs or time and area closures. Similarly, predicting targeting-behavior changes is important in mixed-stock fisheries. Therefore, economic data and analysis are used both to predict the implications of the behavioral effects and how they will affect measures of expected overall net benefit to the Nation.

3. Applying Economic Principles to NS1 in a More Realistic Setting that Addresses the Complications of Dynamics, Uncertainty, and Stock Interactions

Economic principles apply to important aspects of fisheries management that are not captured in the simple setting described in Section 2. Three key aspects—fishery dynamics, uncertainty, and stock interactions—are discussed in Sections 3.1, 3.2, and 3.3, respectively, as well as in Appendixes 3 through 5. Appendix 6 then addresses the importance of considering technological change and other factors that affect catchability. These other factors include density dependence, changes in environmental, biological, and management processes that affect how, when, where, and by whom fish are caught.

3.1 Dynamics: Discounting and Optimum Yield Trajectory

The NS1 Guidelines identify B_{MSY} as the target stock level, provide a framework for determining the target time (T_{target}) to rebuild a stock, where T_{target} is the specified time period for rebuilding a stock that is considered to be as short a time as possible, taking into account the status and biology of any overfished stock, the needs of fishing communities, recommendations by international organizations in which the U.S. participates, and the interaction of the stock within the marine ecosystem. T_{target} shall not exceed T_{max}, which is determined solely by biological factors. In Section 2, we used economics to develop the concept of OSY and identified B_{OSY} as an alternative, generally more conservative and beneficial target. In this section, we address some limitations of MSY and OSY. In addition, we use economics to develop the concept of optimum yield trajectory (OYT), which is the sequence of harvests over time expected to maximize the discounted present value of the net benefit from a fishery while preventing overfishing.

In principle, such a framework can be used to address the following two questions.

1. How quickly should we rebuild an overfished stock from its current biomass level to a specific target level such as B_{MSY} or B_{OSY}? More specifically, what are the optimum yield, effort, and biomass trajectories (i.e., time paths) for attaining the target stock level, where the optimum trajectories are those expected to maximize the discounted present value of the net benefit from a fishery?

2. What are the optimum yield, effort, and biomass trajectories if the stock is not overfished or if a stable long-term biological or economic optimum does not exist because MSY or OSY is expected to change over time?

The concept of OYT is required to address those two questions because OSY and MSY are long-term sustainable yield concepts that do not reflect current stock conditions and the benefits and costs of alternative time paths to a specific biomass target level. We use the term OYT instead of dynamic MEY to eliminate confusion about how inclusive the term MEY is and to make a clear distinction between the long-term sustainable economic yield concept of OSY and the dynamic desired yield trajectory concept of OYT. Just as OSY is in practice a proxy for OY when OY is defined as a long-term economic optimum, OYT is in practice a proxy for OY when OY is defined as a desired annual yield trajectory (i.e., a series of desired annual yields that can vary annually)[14].

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[14] The NS1 Guidelines state that “While OY is a long-term average amount of desired yield, there is, for each year, an amount of fish that is consistent with achieving the long-term OY. A Council can choose to express OY on an

For clarity in this section, we develop the concept of OYT in a deterministic setting without stock interactions. In Sections 3.2 and 3.3 and Appendixes 4 and 5, we discuss the complications of uncertainty and stock interactions. Addressing those complications, which are typical of most fisheries, is key to developing more useful fishery management models.

In practice, it is difficult to account for all benefits and costs in determining OYT. Typically not included are: the opportunity cost of using living marine resources and marine habitat to harvest fish; benefits and costs beyond the harvesting sector; and equity and employment effects. For both OSY and OYT, modeling difficulties and lack of data are obstacles to generating a complete quantitative analysis. However, using qualitative analyses where quantification is not possible, as expressly provided for in EO 12866, can enhance understanding of the range of likely outcomes and facilitate informed decision-making in the absence of perfect information.

Fisheries are inherently dynamic, and it is standard practice in economics to evaluate benefits and costs over time using a technique known as "time discounting." Discounting is a complicated subject, but an important consideration in defining OYT. In general, OYT is defined in reference to a particular discount rate. The discount rate is intended to represent the rate of social time preference under the assumption that people generally prefer a reward today over the prospect of a similar reward in the future.

An important example is the simplest kind of time discounting—geometric—with a constant discount rate r. With a constant discount rate r, the discounted present value of a \$100 bill received in t years from the present is $\$100/(1+r)^t$, and the discounted present value of receiving a \$100 bill every year forever, beginning with one today, is $\$100*(1+1/r)$. As the time step becomes smaller, geometric discounting leads to exponential discounting in continuous time.

The choice of what discount rate to apply to public policy analyses can be controversial because the discounted present value of a given stream of net benefits decreases as the discount rate increases. This is particularly true when future net benefits occur so far in the future that there are inter-generational effects. In fact, the inventor of optimal economic growth models, Frank Ramsey (1928), famously described the entire practice of discounting as "ethically indefensible" and one that "arises merely from the weakness of the imagination."

Nonetheless, discounting is standard practice in federal government economic analyses that satisfy EO 12866 and other statutes. For analyses satisfying EO 12866, Office of Management and Budget Circular A-94 requires evaluation of proposed policies at a 7 percent real (inflation-adjusted) discount rate. Circular A-94 strongly encourages comparing policies using real discount rates of 3 percent and 7 percent, though analysts may use a rate other than 3 percent if it can be justified or if it is used in addition to 3 percent. Therefore, NMFS and Council analysts have some flexibility with respect to which discount rates will be used.

Because OYT is defined in terms of the discounted present value of the net benefit from a fishery, time discounting plays a more important role in determining OYT if the discount rate is comparatively high, if a stock will take many years to rebuild, and if the costs occur well before the benefits (or vice versa).

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annual basis, in which case the FMP or FMP amendment should indicate that the OY is an "annual OY." An annual OY cannot exceed the ACL." Therefore, OYT would identify the annual OYs over time and for each year the ACL should equal the annual OY, which is in part intended to prevent overfishing and rebuild overfished fisheries.

The traditional approach for estimating OYT in the bioeconomic literature is the deterministic optimal control model, as used, for example, by Clark (1990). With this approach, deterministic bioeconomic models are used to solve dynamic optimization problems, with an objective function representing the discounted present value of the stream of profits (and consumer surplus if adequate data are available). This value is maximized subject to a biological growth equation that includes the effects of the growth of individual fish, recruitment, natural mortality, and fishing mortality.

Dynamic optimization problems are generally difficult to solve and it is useful to derive analytic solutions to gain insight, so simplified functional forms have often been used. This tradition goes back at least to the quadratic yield-effort curves in Gordon (1954) and Schaefer (1954). In fact, the standard bioeconomic model is often referred to as the Gordon-Schaefer model. Solutions of models with logistic growth and extensions (e.g., Pella and Tomlinson, 1969) are well analyzed (e.g., see Clark, 1990), and applications are widespread.

For many years, most bioeconomic models used to estimate an incomplete version of OYT, which did not account for all the broadly defined benefits and costs of a yield trajectory, were based on a logistic growth function and surplus production. But as discussed in Appendix 3, age-structured bioeconomic models are increasingly the norm. For example, Kjaersgaard and Frost (2008) disaggregate effort; specify age-structured stock dynamics rather than surplus production; explicitly incorporate recruitment and selectivity; evaluate spawning stock biomass; allow discarding; specify multiple inputs, species, and fleets; spatially disaggregate harvesting; allow dynamic numerical allocation; and can perform both optimizations and feedback simulations. Bjørndal and Brasãao (2006) and Kompas et al. (2010), as well as other studies discussed in Appendix 3, incorporate age structure, explicit recruitment, and other features.

OYT with Fixed Stock-Level Targets

A dynamic optimization approach is appropriate for comparing the expected benefits, costs, and distributional effects of alternative rebuilding schedules and associated time paths of catch, biomass, and effort for attaining fixed-target stock levels (e.g., B_{MSY} or B_{OSY}) for overfished stocks. For example, Costello et al. (2012) use a dynamic bioeconomic optimization model that explicitly accounts for economics, management, and the ecology of size-structured exploited fish populations to estimate the optimal rebuilding strategy and economic returns from rebuilding for each of 18 hypothetical fisheries spanning a wide range of basic biological, harvest, and economic traits. They define the optimal rebuilding strategy as that which will provide the greatest net present value of the profits from the fishery over time. Although a broader measure of overall net benefit is required by the MSA, the NS1 Guidelines, and EO 12866, the findings of Costello et al. suggest the kinds of results that might emerge from applying such an approach to NS1[15].

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[15] Findings from Costello et al. (2012) include the following:

1. Under an optimal rebuilding strategy, stock recovery requires between 4 and 26 years (with a mean of 11 years), depending on the fishery.
2. Our results suggest that the value [of recovery from a collapsed state] can be quite large (perhaps 2–5 fold increases or greater in the value of a collapsed fishery), but the value may be strongly dependent on ecological, economic, and regulatory characteristics of the fishery.
3. A similar degree of heterogeneity exists in the economically optimal rebuilding time for a fishery (typically

Larkin et al. (2011) discuss the use of bioeconomic modeling for developing rebuilding strategies. They identify problems with the commonly held belief that fishery closures are the "maximizing" approach to successful rebuilding. In addition, they note that when economic, social, and cultural considerations are included in developing optimal rebuilding plans, the most rapid rebuilding plan is often not the optimal plan. Larkin et al. also state that "bioeconomic models, if properly used, can help managers develop objective analysis in order to select rebuilding strategies that have the best chance to maximize social welfare" and that "bioeconomic models can also be used to help managers balance the risk to protecting fishery stocks against the economic and social risks to fishermen, processors, and the communities that depend on their activities."[16]

The maximum allowable rebuilding time (T_{max}) prescribed in the NS1 Guidelines does not address economic considerations and could often preclude the use of rebuilding periods that would increase the discounted present value of the net benefit from a fishery. However, OYT, constrained by the rebuilding periods specified in the NS1 Guidelines and B_{MSY} or B_{OSY} target stock level, can be used to identify the best catch, effort, and biomass time paths given those constraints.

OYT without Fixed Stock-Level Targets

Ignoring the dynamic nature of fisheries and managing fishery resources for a nonexistent, long-term biological or economic optimum will result in inappropriate targets for yield, effort, and stock conditions and, therefore, decrease the discounted present value of the net benefit from a fishery. For example, simply excluding technological change from population and bioeconomic models can create various problems.

First, when stock assessments are based principally on catch-per-unit-of-effort (CPUE) data and do not

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8–20 years), which, according to our results, typically involves small (though non-zero) increasing harvest during the rebuilding trajectory.

4. While a biologically based rebuilding policy that does not consider economics will always be the fastest way to achieve rebuilding goals, our results show that the economically optimal policy often takes a little longer but leads to substantially higher value.

5. Efforts to rebuild and recover the world's fisheries, whether collapsed or heading towards collapse, will benefit greatly from an improved understanding of the long-term economic benefits of recovering collapsed stocks, the trajectory and duration of different rebuilding approaches, variation in the value and timing of recovery for fisheries with different economic, biological, and regulatory characteristics, including identifying which fisheries are likely to benefit most from recovery, and the benefits of avoiding collapse in the first place.

6. Getting better estimates of cost parameters and discount rates will be particularly useful given that these parameters are often poorly known and yet affect results as shown [in this paper].

7. In cases where a decision has already been made to rebuild, then it may be desirable to calculate economically optimal policies with an endogenous rebuilding constraint.

[16] These papers (Costello et al., 2012; Larkin et al., 2011) were included in an Organisation for Economic Co-operation and Development (OECD) series on the economics of rebuilding fisheries. The OECD (2012) report, *Rebuilding Fisheries: The Way Forward*, includes references to other papers in that series.

fully account for the effects of technological change, technological change is a source of upward bias in those assessments. Second, if effort controls are the principal management tools used to control catch, and technological change is not fully accounted for, the resulting effort controls will be inadequate and catch will be too high. Finally, technological change tends to increase OSY and OYT by decreasing the costs of harvesting, processing, and marketing fish, and perhaps by increasing product quality and therefore the prices of fish and seafood products. Because technological change lowers the costs of harvest, leaving fish in the water to lower harvest costs is no longer as important. Therefore, accounting for technological change and other factors that will change over time is key to effective fishery management. Squires and Vestergaard (2013) provide an excellent discussion of the importance of accounting for technological change and its effects on optimal harvest strategy. Appendix 6 addresses the importance of considering technological change and other factors that affect catchability.

The OYT of any stock that requires conservation and management is constrained by its OFL, ABC, and ACL. However, when the stock is not overfished, its OYT is not constrained by a fixed-target stock level. In such cases, and if a stable OSY does not exist, OYT can be assessed using OYT control rules; relatively short-term forecasts of the net benefits of alternative catch, effort, and biomass time paths; and adaptive management that responds to changes in stock conditions and other determinants of OYT (including our understanding of those determinants).

These dynamic optimization concepts and related decision support methods for OYT and OY control rules need to be further developed and operationalized to support fisheries management where long-term sustainable yield approaches have proved to be less useful.

3.2 Uncertainty and Fishery Management under NS1

Uncertainty is an important aspect of both preventing overfishing and attaining optimum yield, the core requirements of NS1. Harvest levels that prevent overfishing are estimated under uncertainty about stock size, stock dynamics, fisherman behavior, ecosystem effects, and other factors. Optimum yield must also be interpreted in light of these uncertainties and others such as uncertainty about costs and benefits, market dynamics, and regulations[17].

Over the past decade, incorporating uncertainty into efforts to prevent overfishing has been a focus within the US fisheries management community. The NS1 Guidelines require that scientific uncertainty be considered in setting ABC and recommend that management uncertainty be accounted for in the ACL, if an ACT or functional equivalent is not used and in the ACT if one is used. Specifically, the NS1 Guidelines stipulate that ACL cannot exceed ABC, where ABC is based on an ABC control rule that accounts for scientific uncertainty in the OFL, any other scientific uncertainty, and the Council's risk policy. The 2016 revisions to the NS1 Guidelines removed the explicit language stating that Councils could "choose to use a single control rule that combines both scientific and management uncertainty and supports the ABC recommendation and establishment of ACL and if used ACT."

The buffers between OFL and ABC, between ABC and ACL, and between ACL and ACT provide insurance against undesirable outcomes. Therefore, optimal buffer size will depend both on the cost of that buffer relative to the cost of other methods of providing the same level of protection and on the benefits of various levels of protection against the undesirable outcome. Actions that could reduce both uncertainty

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[17] Useful surveys of uncertainty in fisheries management can be found in Charles (1998) and Berkson et al. (2002).

and appropriate buffer sizes include:

- More timely and accurate catch monitoring
- More timely and accurate stock and rebuilding monitoring
- Quicker adjustments to ACLs and AMs
- Better understanding of how fishermen will respond to AMs and other management actions
- In some circumstances, the use of large marine protected areas

Estimating OY under uncertainty requires information on economic and social factors. In a static framework, such as the model of OSY depicted in Figure 2, one method for addressing uncertainty would be to estimate the sustainable revenue and cost curves in terms of expected revenue and cost, and add confidence limits to both curves. However, setting harvest levels in fisheries is by nature a dynamic problem, because current harvest affects future stock dynamics and attainable harvest. Given uncertainty in a dynamic setting, a common approach is to develop a feedback control policy using the tools of optimal control or Markov decision processes (MDPs). Such models are commonly used in ecology, engineering, genetics, and economics. They have been used for the management of animal populations since at least Reed (1974) and D. Anderson (1975), and for fisheries since at least Ludwig (1979) and Reed (1979). Under this type of approach, OYT would be defined in terms of mapping from a current observed stock level into a harvest recommendation; that is, it would be a feedback control rule (see Beddington and May (1977) for an early example of this point). We describe some of the methods available to develop such an approach in Appendix 4.

It's important to note that preventing overfishing is necessary but not sufficient for attaining OY. That is, preventing overfishing is a requirement, but satisfying that requirement does not imply that the requirement to attain OY has been met. In principle, overfishing and optimum yield would best be addressed simultaneously within a unified framework. One approach to a joint treatment of overfishing and OY would be to treat OY as an objective to be optimized subject to constraints that prevent overfishing. An alternative would be to treat OY and overfishing as dual objectives in a joint optimization framework, allowing the assessment of trade-offs between them. Developing the analytical and institutional capability to treat OY and overfishing jointly would support better fishery management in the future.

3.3 Additional Trade-Offs in a Fishery with Stock Interactions

When there are significant ecological interactions (e.g., predation and competition) or economic interactions (e.g., market interactions or stocks are caught together) among two or more stocks in a fishery, MSY, OSY, or OYT for the entire fishery is not the sum of the independently determined MSYs, OSYs, or OYTs of its individual stocks. Stock interactions result in a new set of trade-offs that cannot be adequately addressed in terms of differences in levels of sustainable yield and biomass for each stock. This section extends the concepts of MSY, OSY and OYT to a mixed-stock fishery with stock interactions and demonstrates that economics provides a framework for addressing those trade-offs.

3.3.1 MSY in a Fishery with Stock Interactions

Researchers have demonstrated that ignoring ecological interactions (predation and competition) among the stocks in a fishery results in incorrectly specified reference points. For example, Link et al.

(2011) note that "exploring the use of model outputs at the aggregate or systemic levels is something that is sorely needed and requires much greater attention in the near future." They recognize the need to address biological trade-offs resulting from ecological interactions. In addition, they reference a study from the Northeast Fisheries Science Center (2008) that suggests that expected aggregate yield and B_{MSY} are lower, and that overall fishing mortality rates should be lower, for stocks as a whole than single-species results suggest.

Similarly, Mueter and Megrey (2006) estimate maximum multispecies surplus production (equivalent to maximum sustainable yield) for groundfish complexes in the Eastern Bering Sea/Aleutian Islands region and the Gulf of Alaska. They find that their estimates are smaller than the sum of single-species MSY proxies from recent stock assessments for each groundfish complex. In another example, Kasperski (2015) finds that because arrowtooth flounder negatively affect the growth of other stocks, MSYs for Pacific cod and Alaska pollock—economically and ecologically important target stocks in the Bering Sea/Aleutian Islands groundfish fishery—would be greater if the arrowtooth flounder biomass was well below its B_{MSY} and possibly below its MSY-based MSST.

These results suggest that when there are significant interactions among two or more stocks, aggregate MSY reference points (MSYF) for all the stocks in a fishery should be determined simultaneously, using known interactions among those stocks. That is, MSYF should be used to determine MSY reference points for the fishery as a whole, including associated reference points for individual stocks. Given the critical role of MSY in the MSA and NS1 Guidelines, it is important to address the concept of MSY for a fishery as a whole—and the trade-offs between trying to do what is best for each stock and what is best for the fishery as a whole—in terms of maximizing sustainable yield. Because this discussion is in terms of MSY, these trade-offs reflect differences in long-term sustainable yield among the stocks in a fishery rather than trade-offs between current and future yields.

Appendix 5 provides a numerical example of the aggregate MSY for a two-stock fishery in which the only stock interactions is that both stocks are caught together. The key points of this simple example in which the independently determined MSY level of effort is greater for stock 1 than for stock 2 (i.e., $E_{MSY1} > E_{MSY2}$) are as follows:

1. The sum of the MSYs for the two stocks does not represent an attainable MSY for the fishery as a whole.

2. The level of effort that generates MSY for the fishery as a whole (E_{MSYF}) is less than the MSY level of effort for stock 1 (E_{MSY1}) but greater than the MSY level of effort for stock 2 (E_{MSY2}).

3. If the MSY reference point for the fishery as a whole (MSYF) is used, the biomass targets for stocks 1 and 2 are the sustainable biomass levels associated with the level of effort that generates MSY for the fishery as a whole (E_{MSYF}); therefore, the target level for stock 1 is greater than its B_{MSY}, the target level for stock 2 is less than its B_{MSY}, and attaining MSY and B_{MSY} for either stock would prevent the attainment of MSY and B_{MSY} for the other stock and for the fishery as a whole.

4. A choice needs to be made among the reference points that will support MSY for one stock, MSY for the other stock, or MSY for the fishery as a whole.

However, there is a potentially critical problem with the concept of an aggregate MSY. It is the implicit assumptions that an additional metric ton of sustainable yield of any stock is equally important and that its importance does not depend on the level of sustainable yield for any stock. There are at least three possible fixes if these assumptions are not valid. First, we can recognize this as an additional advantage of using aggregate OSY instead of aggregate MSY as a reference point because those assumptions are not implicit in the concept of an aggregate OSY. Second, we could apply different weights to reflect the differences in the importance of an increase in sustainable yield among stocks and among levels of sustainable yield for individual stocks. However, the determination of the appropriate weights will be a challenge. Third we can present the multi-dimensional surface (i.e., sustainable yield possibilities frontier) that depicts the various levels of sustainable yield that are simultaneously attainable for the stocks in a fishery and then determine how to select the optimum point on that surface. MSY frontiers are an area of ongoing research (e.g., Flaaten 1988).

3.3.2 OSY in a Fishery with Stock Interactions

For simplicity, we discuss the extension of the concept of OSY to a mixed-stock commercial fishery using the same two-stock fishery example we used in Section 3.3.1 and the simple model of OSY we discussed in Section 2.2.2. The main points from the numerical examples discussed in Appendix 5 are as follows:

1. If the ex-vessel prices of the two stocks differ, the levels of effort that maximize sustainable yield (E_{MSYF}) and sustainable revenue (E_{MSRevF}) for the fishery as a whole are not the same. Therefore, simply changing the objective from maximizing sustainable yield to maximizing sustainable revenue changes the maximizing level of effort for the commercial fishery as a whole, and associated biomass target levels for both stocks.

2. The cost of fishing effort is considered in determining OSY levels of effort, catch, and biomass for the fishery as a whole. Note that OSY cannot be determined separately for each stock because the same effort, and therefore the same cost, is associated with catching both stocks together.

3. E_{OSYF} is less than the E_{MSYF}; therefore, the fishery as a whole OSY-based biomass target for each stock will be greater than the associated MSY-based biomass target.

4. The E_{OSYF}-based biomass target for at least one of the stocks will be greater than its independently determined MSY-based biomass target. But, depending on the differences in prices for the two stocks and the cost per unit of effort, the E_{OSYF}-based biomass target for the other stock can be greater than, less than or equal to its independently determined MSY-based biomass target.

Interactions among stocks can be much more complex than the examples just discussed, in which the only interaction is that two stocks are caught together in a single fishery. For example, L.G. Anderson (1975) considers the ecological interactions of two stocks in the case of two single-stock fisheries where the biomass of each stock depends on the biomass of the other stock. He also analyzes technical interactions between two stocks in the case of two single-stock fisheries that each take some of each other's target species as incidental catch because neither fishery uses perfectly selective fishing gear. He notes that in both cases it is possible to discuss an MSY for both fisheries combined, and that this will occur when the sum of the yields from the two fisheries is a maximum. He presents the conditions for a combined static MEY for the two fisheries and shows that those conditions will not hold if each fishery is managed to obtain its individual MEY.

More recently, Anderson and Seijo (2010) consider four possible combinations of ecological and technical interactions and determine that static MSYs and MEYs for fisheries and/or fleets combined cannot be determined by independently estimating MSYs and MEYs by species:

- Combination 1: Each of two heterogeneous fleets harvests a different species; the two species compete with each other for an ecosystem-limiting factor such as space or food.
- Combination 2: Each of two heterogeneous fleets harvests a different species; one species is the prey of the other.
- Combination 3: Two fleets with different fishing power and unit costs of effort compete for a stock in the same fishery.
- Combination 4: A multispecies fishery where a fleet incidentally harvests the target species of another fleet in addition to its own target species.

These results suggest that when there are significant interactions among two or more stocks in a fishery, OSYF-based reference points for all stocks should be determined simultaneously using known interactions among those stocks. That is, just as MSYF should be used to determine MSY reference points for the fishery as a whole, OSYF should be used to determine OSY reference points for the fishery as a whole, including associated reference points for individual stocks in the fishery. Using OSYF-based reference points accounts for the trade-offs between trying to do what is best for each stock and what is best for the fishery as a whole in terms of maximizing overall net benefit. Because this discussion is in terms of OSY, which is a stable, long-term sustainable economic yield concept, these trade-offs reflect ongoing differences in the overall net benefit from a fishery rather than trade-offs between current and future overall net benefits.

Unlike the concept of aggregate MSY, the concept of aggregate OSY is not based on the implicit assumptions that an additional metric ton of sustainable yield of any stock is equally important and that its importance does not depend on the level of sustainable yield for any stock.

3.3.3 OYT in a Fishery with Stock Interactions

The OYT for a stock of fish is the catch trajectory (or time path) that is expected to maximize the discounted present value of the net benefit from a fishery, given current conditions for the stock and expected changes in ecological, environmental, and economic conditions; fishery technological characteristics (e.g., gear selectivity); and distribution of catch among user groups (e.g., fleets). If the OYT for a stock is determined in part by an MSY- or OSY-based target biomass level (e.g., B_{MSY} or B_{OSY}) and an MSY- or OSY-based fishing mortality limit (e.g., F_{MSY} or F_{OSY}), and if there are significant interactions among two or more stocks in the fishery, the target and limit for the fishery as a whole and associated stock-specific targets and limits attempt to capture those stock interactions. In such cases, targets and limits based on MSY and OSY for a fishery as a whole will be more useful in determining OYTs than the independently determined MSY and OSY for each stock in a fishery.

In addition to affecting the stock-level targets that constrain the OYTs of individual stocks, stock interactions mean that OYTs for individual stocks should not be determined independently. The catch trajectory of each stock can affect the discounted present value of the net benefit of catch trajectories of other stocks in a fishery. Therefore, stock interactions should be accounted for to the extent practicable to simultaneously estimate OYTs for all stocks in a fishery. The resulting OYTs for individual stocks can be substantially different than those that are determined independently, and can identify additional trade-offs among stocks in a mixed-stock fishery.

3.3.4 Concluding Remarks Concerning an Aggregate MSY, OSY and OYT for a Fishery as a Whole

The 2013 National Research Council report on the effectiveness of stock rebuilding plans includes the following relevant conclusions concerning the trade-offs between MSY-based reference points for a fishery as a whole and those that are independently determined for individual stocks.

- Fisheries management involves trade-offs among harvested species that interact, even if these trade-offs are not explicitly considered in management decisions.
- Our understanding of how ecosystems function is improving, in some cases enough to contribute to the models used in fisheries management. For example, stock assessments can be linked with multispecies models.
- If the concern is about long-term risk of recruitment failure, or, worse, extinction, then the MSST is the incorrect threshold. The specification of the MSST is not based on recruitment failure or extinction.
- Rebuilding of mixed-stock fisheries will remain challenging because of the need to weigh trade-offs among species.
- Attempting to deal with the mixed-stock problem will require analyses and modeling of fisheries and economics data to identify appropriate solutions, as well as flexibility to apply mixed-stock exceptions (where applicable).
- One challenge is the development of mixed-stock fisheries models that allow for evaluation of trade-offs.
- A second challenge is to design operational regulations with incentives for fishing practices that adequately protect weak stocks while providing fishing opportunities for healthy stocks.
- For mixed stocks, the stock-specific approach that ignores species interactions can result in fisheries forgoing yield of a healthy stock to allow rebuilding of a weak stock.
- In general, the current requirements have led to socioeconomic considerations playing a secondary role in the design of rebuilding plans.

Froese et al. (2015) note that one of the few currently uncontested tenets of EBFM is that maximum sustainable yields cannot be achieved simultaneously for all exploited stocks in an ecosystem. Therefore, alternative sustainable yield and biomass targets (or reference points) are required.

Kasperski (2015) provides additional evidence to support the use of reference points (e.g., MSYs, OSYs, and OYTs) for a fishery as a whole and the associated reference points for individual stocks. He finds that, because arrowtooth flounder negatively affect the growth of Pacific cod and pollock in the Bering

Sea/Aleutian Islands groundfish fishery, substantially increasing the harvest of arrowtooth to decrease its biomass is optimal in the multispecies model because it leads to increased growth and therefore greater potential harvests of cod and pollock. He estimates that such a harvest strategy for arrowtooth would increase the net present value of the three-species fishery by more than $5 billion for 2010 through 2040, which is about a 33 percent increase in net present value. In such a case, using an arrowtooth flounder biomass target of B_{MSY} and a fishing mortality limit of F_{MSY} would appear to be detrimental to the fishery as a whole.

Most recently, Jacobsen et al. (2017) note that "single-species assessment approaches may overestimate the availability of win–wins by failing to account for trade-offs across interacting species" and Burgess et al. (2017) "use a general analytical theory to identify (i) characteristics of fish stocks that tend to facilitate or inhibit the precision and accuracy of reference points from single-species assessments, (ii) characteristics of ecosystem components that introduce the greatest bias/imprecision into single-species reference points and (iii) warning signs within single-species frameworks that important ecosystem components may not be adequately accounted for."

NMFS recognizes the importance of the concept of an aggregate MSY or OY. For example, the Ecosystem-Based Fisheries Management Policy of the National Marine Fisheries Service (National Marine Fisheries Service 2016) encourages developing and monitoring ecosystem-level reference points. Similarly, the Supplementary Information presented with the NS1 Guidelines indicates that NMFS proposed using aggregate MSY estimates as one method to facilitate the incorporation of EBFM into U.S. federal fisheries management. In addition, the NS1 Guidelines indicate that:

- Stocks may be grouped into complexes where, for example, stocks in a multispecies fishery cannot be targeted independent of one another.

- MSY may be specified for the fishery as a whole.

- There are several types of models that can be used for estimating MSY for an aggregate group of stocks, including the fishery as a whole.

- An OY established at a fishery level may not exceed the sum of the MSY values for each of the stocks or stocks complexes within the fishery.

- Aggregate level MSY estimates could be used as a basis for specifying OY for the fishery.

- When aggregate level MSY is estimated, single stock MSY estimates can also be used to inform single stock management. For example, OY could be specified for a fishery, while other reference points are specified for individual stocks in order to prevent overfishing on each stock within the fishery.

- Exceptions to the requirement to prevent overfishing could apply under certain limited circumstances, if harvesting one stock at its optimum level may result in overfishing of another stock when the two stocks tend to be caught together. This is referred to as the mixed stock exception.

Further, in response to comment 17 in the 2016 final rule to revise the NS1 guidelines, NMFS noted that: "Fundamentally, aggregate MSY is an additional limit on the management system that encourages more conservative EBFM-based measures. Even when aggregate level MSY is estimated, stock-specific MSY must still be used to inform single stock management. Other annual reference points (within the ACL framework) must also be specified in order to prevent overfishing from occurring in single stocks" (see 81 FR 71858; 10/18/16).

NMFS received a number of questions by the Councils related to the aggregate MSY provision in the NS1 guidelines and posted responses to those questions on its website.[18] In those responses, NMFS noted that: "Given the MSA's requirement to end and prevent overfishing, individual stock SDC should be specified (as opposed to SDC for a complex as a whole), based on the best scientific information available. Further, if Councils are able to manage stocks with individual ACLs, they should do so to prevent overfishing. Even in these cases, Councils may still estimate aggregate MSY for a complex or functional group and apply such information to the management of the individual stocks within the complex or group."

The NS1 Guidelines do not specify which SDC should be used for individual stocks when an aggregate MSY is used. One possibility is to use SDC that are based on independently determined MSYs that do not account for stock interactions and that cannot be achieved simultaneously for all harvested stocks in an ecosystem. Another approach is to use SDC that are based on MSYs determined simultaneously for the individual stocks and the fishery as a whole, that account for stock interactions to the extent practicable given our current understanding of those interactions and that can be achieved simultaneously for all harvested stocks in an ecosystem. The use of an aggregate MSY with independently determined MSYs for the individual stocks is internally inconsistent because, as noted in Section 3.3.1 and earlier in this section, the sum of the independently determined MSYs cannot be attained and are not associated with the aggregate MSY. The inconsistency results from considering stock interactions in determining the aggregate MSY but ignoring them with independently determined MSYs for the individual stocks. We are not suggesting that NMFS should consider switching to a fishery management method where: 1) we manage based solely on an aggregate MSY or 2) ignore the NS1 requirements to prevent overfishing and rebuild overfished fisheries. Rather, we are questioning the use of MSYs to set SDC if those MSYs do not account for stock interactions. If MSYs and SDC are used for individual stocks, shouldn't we use MSYs and SDC that account for those interactions? The use of MSYs and SDC for individusal stocks that are based on an aggregate MSY, could eliminate the need for the mixed stock exception (i.e., exceptions to requirements to prevent overfishing*)*. When there are significant stock interactions, additional consideration is needed concerning the trade-offs between doing what is best for each stock individually and what is best for the fishery as a whole whether in terms of maximum sustainable yield, optimum sustainable yield or optimum yield trajectory. The sustainable yield possibilities frontier (i.e., MSY frontier) mentioned in Section 2 is an appropriate tool to analyze tradeoffs associated with significant ecological interactions such as predator-prey relationships and inter-specific competition. For the latter, preliminary results from our current research demonstrate the existence of points on the MSY frontier that are related to aggregate MSY where no stocks is overfished.

As noted in Section 3.3.1, the implicit assumptions of the simple concept of an aggregate MSY are that an additional metric ton of sustainable yield of any stock is equally important and that its importance does not depend on the level of sustainable yield for any stock. The validity of these assumptions needs to be

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[18] See NOAA Fisheries Responses to CCC NS1 Questions at: https://www.fisheries.noaa.gov/national/laws-and-policies/2016-revisions-national-standard-1-guidelines

assessed and, if they are found to be invalid, alternative aggregate concepts should be used.

In evaluating the trade-offs that occur because of interactions among stocks, it is important to recognize the following:

- The MSA requirements to prevent overfishing and to rebuild overfished fisheries are intended to ensure that the Nation will realize the full potential of its fishery resources in perpetuity.
- Those fishery resources contribute to the food supply, economy, and health of the Nation and provide recreational, social, and cultural opportunities.
- Commercial and recreational fishing constitute a major source of employment and contribute significantly to the Nation's economy.
- Many coastal areas depend on fishing and related activities, and their economies have been badly damaged by overfishing.
- Fishery resources are finite but renewable. If placed under sound management before overfishing has caused irreversible effects, fisheries can be conserved and maintained to provide optimum yields on a continuing basis.

Therefore, the objectives of preventing overfishing and rebuilding overfished fisheries are intended to help meet the goal of realizing the full, sustainable potential of the Nation's fishery resources, in part by preventing irreversible effects. However, if significant stock interactions occur, that goal could be hindered by using reference points based on independently determined MSYs for individual stocks to assess whether a fishery is overfished and should be rebuilt, or whether overfishing is occurring. On the other hand, using reference points based on MSY or OSY for the entire fishery and the associated reference points for its individual stocks accounts for those interactions as much as possible, given the available information, and could contribute to achieving that goal.

Because of technical interactions among stocks, fishermen will seldom be able to reach ACLs for all the stocks in a fishery without exceeding some ACLs. However, they will be better able to reach that goal if those ACLs are based on reference points associated with the MSY or OSY of the fishery as a whole, or if they have better incentives to change their fishing practices in ways that decrease incidental catch or bycatch of the stocks with the ACLs that constrain total catch for the fishery. If bycatch is monitored adequately and if all catch is counted against fishermen's quotas, individual fishing quotas (IFQs) and other catch share programs can provide incentives for developing and using fishing practices that reduce bycatch rates and associated fishing mortality for constraining stocks. For example, the evaluation of the West Coast Groundfish IFQ (National Marine Fisheries Service 2013) includes the following statement concerning this potential benefit:

1. Results from 2012 indicate a substantial reduction in the amount of bycatch, which occurs when fishermen are fishing for one species, but unintentionally catch other creatures that live near that species. Because fishermen have more flexibility under a catch shares program, they can be more selective in the areas they target. Two years into the catch shares program, catch of unwanted species, or bycatch, remains lower than the two prior years structured under trip limit management. This is good news for certain species that need rebuilding and for fishermen who can focus on their target species.

2. At the same time, results show that the groundfish fleet was able to catch a greater percentage, 29%, of their target species (other than whiting), which is up from 24% in 2011. This result highlights the increased diversity of the landings and the fishermen's ability to target new areas and markets.

In addition to affecting technical interactions among stocks, management regimes can affect the cost of effort, ex-vessel prices, the distribution of catch among user groups (e.g., fleets), and other determinants of MSY, OSY, OYT, and the overall net benefit provided by a fishery.

4. Conclusions

Since the 2007 MSA reauthorization, NMFS and its partners in the federal fishery management community have developed and implemented a framework for preventing overfishing and rebuilding overfished fisheries, yet the economic content of this framework has received relatively little attention. In this paper, we argue that economic ideas and analyses are relevant to both preventing overfishing and achieving OY, the dual objectives of NS1, where achieving OY includes rebuilding overfished fisheries.

Because preventing overfishing and rebuilding overfished stocks imply opportunity costs and behavioral responses from affected people, they have an important economic component. Similarly, achieving optimum yield necessarily includes an economic dimension because optimum yield reflects the value of fish and fishing to people.

In addition to being relevant to each of NS1's objectives, economics provides a framework for considering how the two objectives relate to one another: preventing overfishing often requires harvest reductions, and optimum yield is best understood as an answer to the question of how to manage these and other trade-offs.

Though we argue that the economic content of NS1 deserves more attention, we recognize that progress in this area will require a major effort, similar to that mounted for developing the ACL framework. New models and new data sources will be needed. Dynamics and discounting, uncertainty, and stock interactions are significant challenges to economic analysis. In the appendices that follow, we explore these challenges in more detail.

4.1 Key Points

The most important points we make in this paper are included in the Executive Summary and repeated here.

1. Economic concepts and analyses can contribute to understanding of the trade-offs inherent in fisheries management decisions that aim to prevent overfishing while achieving OY. For example, understanding how fishermen and others involved in the fisheries are likely to respond to alternative management actions is critical to determining or modifying those trade-offs.

2. Because uncertainty is inherent in fisheries, preventing overfishing is meaningful only in probabilistic terms. A greater probability of preventing overfishing generally comes at greater cost, in terms of forgone yield. In other words, reducing yield is a form of payment to insure against overfishing.

3. Optimum yield is defined by the MSA in terms of benefits to the Nation. Including economic benefits generally leads to harvest policies that imply higher levels of biomass and overall net benefit and lower levels of effort and catch. For example, OSY is normally a more conservative reference point than MSY and it results in greater overall net benefit to the Nation.

4. Measures to achieve the joint goals of preventing overfishing and attaining OY are more likely to succeed if they account for system dynamics, uncertainty, stock interactions, and the effects of alternative management regimes.

4.2 Important Topics for Future Work

Developing the analytical and institutional capability to treat OY and overfishing jointly would support better fishery management in the future.

1. We expect steady progress in overcoming the modeling challenges associated with estimating OSY and OYT. However, the data requirements for developing models that are increasingly useful for policy discussions are formidable. Given the current paucity of economic data—and particularly cost data—in many of our federally managed fisheries, the development of new data collection programs is at least as important as modeling innovations to defining and managing for OY.

2. The maximum allowable rebuilding time (T_{max}) prescribed in the NS1 Guidelines has no economic content and could often preclude the use of the rebuilding periods that would increase the discounted present value of the net benefit from a fishery. However, the OYT, constrained by both the rebuilding periods specified in the NS1 Guidelines and the B_{MSY} or B_{OSY} target stock level, can be used to identify the best catch, effort, and biomass time paths given those constraints.

3. Accounting for technological change and other sources of variability in the catchability coefficients used in population and bioeconomic models is important to developing more useful fishery management models.

4. The NS1 guidelines describe a framework for specifying ABC, ACLs, and accountability measures. The guidelines require ABC control rules that are used to specify ABC and that account for uncertainty in the OFL and for the Council's risk policy. The guidelines also note that: 1) ACTs can be used to account for management uncertainty and 2) if an ACT, or functional equivalent, is not used, management uncertainty should be accounted for in the ACL. The following points concern the determination of these buffers, which are key elements of the effort to address uncertainty and prevent overfishing:

    a. Further research is required to determine when it would be appropriate to assess all sources of uncertainty and variability together to establish the buffer between OFL and ACT, if one is used, or between OFL and ACL if an ACT is not used. Such research would help determine if the explicit option for "A Council to choose to use a single control rule that combines both scientific and management uncertainty and supports the ABC recommendation and establishment of ACL and if used ACT", which the 2016 NS1 Guidelines eliminated, should be included again. All sources of uncertainty and variability can be treated simultaneously for estimating OSY and OYT.

    b. The buffer provides insurance against an undesirable outcome. Therefore, optimal buffer size will depend both on the cost of that buffer relative to the cost of other methods of providing the same level of protection and on the benefits of various levels of protection against the undesirable outcome. To determine optimal buffer size, it is important to decide whether the undesirable outcome we should insure against is: 1) Occasionally exceeding an ACL or even the OFL; or 2) Stock collapse and not rebuilding overfished fisheries.

    c. The following methods could reduce both uncertainty and appropriate buffer sizes: more timely and accurate catch monitoring; more timely and accurate stock and rebuilding monitoring; quicker adjustments to ACLs and AMs; a better understanding of how fishermen and others will respond to AMs and other management actions; and the use of large marine protected areas. The best mix of the alternative methods for dealing with uncertainty will depend on the effectiveness and cost of each method and each feasible mix of methods.

5. The management regime will affect the trade-offs and challenges that confront fishery managers, as well as their success in preventing overfishing while achieving OY. The management regime (e.g., managing with race for fish versus a catch share system) affects harvest costs, ex-vessel prices, fish utilization rates, product quality, gear selectivity, bycatch, safety, compliance, management costs, and other outcomes that determine OY. Therefore, changes to the management regime beyond simply implementing the NS1 Guidelines can be critical for meeting the NS1 challenge. These changes could include taking management actions to address the perverse incentives that increase the difficulty of meeting that challenge.

6. Recognizing the importance of MSY, OSY, and OYT reference points for a fishery as a whole—as well as the associated reference points for individual stocks—is an important step toward both EBFM and the use of reference points that are critical for meeting NS1. However, developing such reference points requires more information and better models than are currently available for most, if not all, fisheries. For example, it will require better estimates of the opportunity cost of using living marine resources and habitat to harvest fish.

Overcoming these challenges will be the work of years. However, advances in our ability to meet the dual objectives of NS1 and to move toward EBFM can be made with improved data and models and increased recognition of the need to go beyond the use of stable, single-species, long-term sustainable biological yield concepts and models.

APPENDIX 1. A More Comprehensive Model of OSY

The simple model of OSY presented in Section 2 has several limitations, including the following:

1. It is based on the assumption that the ex-vessel price of fish and the marginal cost of effort are constant.
2. It considers only a subset of the costs and benefits that determine overall net benefit to the Nation for each sustainable level of yield and associated sustainable levels of biomass and effort. Specifically, it does not consider external costs of harvesting fish; benefits or costs in post-harvest sectors (e.g., fish dealers, processors, wholesalers, and retailers); net benefits to consumers; fishery management costs (e.g., monitoring, reporting, enforcement, and management decision-making costs); or distributive impacts and equity.
3. It is designed for a stock of fish that is taken only in one commercial fishery and not in any recreational or subsistence fisheries.
4. It does not show how a change in the fishery management regime will affect OSY through its effects on the ex-vessel price and the marginal cost of effort.
5. It is designed for a single stock that has no significant ecological or economic interactions with other living marine resources.
6. It considers neither uncertainty nor the dynamic nature of fisheries.
7. It ignores technological change and other factors that affect catchability.

This appendix explores extensions to the Section 2 model to address the first three limitations. We discuss the fourth limitation in Appendix 2; the fifth limitation in Section 3.3 and Appendix 5; the sixth limitation in Sections 3.1 and 3.2 and Appendixes 3 and 4; and the final limitation in Appendix 6. The last two limitations apply to the concept of OSY itself, not just the simple version of OSY discussed in Section 2.

A1.1 Addressing Assumptions of Constant Ex-Vessel Fish Price and Marginal Cost of Effort

Economic research is necessary to determine the extent to which the price of fish is expected to increase as the sustainable level of catch decreases from MSY. It may be appropriate to assume a constant price for a fishery that accounts for a small part of the total supply of a species, or if there are other species (or other sources of food) that are very good substitutes for that species for the post-harvest sectors and consumers. However, if neither of those conditions is met, prices will be higher for lower levels of sustainable catch. In addition, reductions in revenue that would otherwise result from lower levels of catch can be partially, fully, or more than fully offset by the price increase. Vieira and Pascoe (2013) note the following:

> Given that most empirical studies (in Australia and elsewhere) have found that fish prices are generally inflexible, a default position may be to estimate MEY as the yield that maximises industry profits at the prevailing price—as is current practice. However, where there is evidence of price flexibility, research needs to be undertaken to derive more appropriate catch–price

relationships to further refine the model and ensure that the target reference point reflects the yield that maximises total benefits to the broader society (industry and consumers).

The age structure of a stock associated with a set of sustainable levels of catch, effort, and biomass can affect the size composition of the catch, which will in turn affect the average ex-vessel price if the price is size dependent. The management system can have much stronger impacts on price than those associated solely with quantity landed or size of fish. The timing of landings, their disposition, and quality may be much more important and have less to do with the ACL or even gear and area restrictions than with the incentives created by the management system. For example, moving from a race for fish to an individual fishing quota (IFQ) in the Alaska halibut fishery led to substantial price increases because it increased quality, eliminated supply gluts, and allowed more fish to be sold fresh.

The assumption of constant marginal cost is less problematic because we are discussing a stable long-term sustainable economic yield model for which all inputs are variable; however, economic research is required to assess this assumption for specific fisheries. Nonetheless, it should be noted that the regulatory approach also impacts costs. Controlling catch with a competitively fished ACL that creates a race for fish may lead to higher marginal costs than a regulatory approach like IFQs or cooperatives that provide incentives for efficient harvest (see Appendix 2).

A1.2 Including a More Complete Set of Benefits and Costs for Commercial Fisheries

The benefits to the Nation from the commercial, recreational, and subsistence harvest of fish include income, employment,[19] consumption, recreational, and existence benefits. This section focusses on the benefits and costs provided by a commercial fishery. Sections A1.3 and A1.4 address the benefits and cost provided by recreational and subsistence fisheries, respectively.

For a commercial fishery, the associated costs include the costs of the fuel, labor, boats, equipment, facilities, and other market inputs used to harvest fish and to provide them to consumers. The cost of using any of these market inputs is the value of the highest-valued alternative use of that input; this is referred to as the opportunity cost of that input. In the absence of significant market failure, the market price of an input provides a useful estimate of its opportunity cost, and it is not necessary to adjust the market price to estimate the opportunity cost of a market input.

External Costs

Living marine resources and their habitats are also used to harvest fish. Because the Nation derives benefits from competing consumptive and nonconsumptive uses of those marine resources, or simply from their existence, there are opportunity costs associated with using marine resources to harvest fish. Typically, society bears these opportunity costs while producers and consumers of seafood do not, and the costs are not captured by market prices. These external costs are thus imposed on others rather than on each fishing operation or consumer based on use.

The external cost that has received the most extensive treatment in the fisheries economics literature is the stock externality: an interaction among fishermen over time in which a (private) unit of catch at one point in time tends to lower reproductive output and reduce the stock in current and future periods,

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[19] Broadly defined income and employment benefits include those for the harvesting and post-harvesting sectors, as well as resulting indirect and secondary income and employment impacts.

thus reducing catch per unit of effort and raising costs for each fishing operation for a given level of catch. In the absence of an effective fishery management regime, this stock externality will result in overfishing, overfished fisheries, and a substantial reduction in the overall net benefit that fisheries provide to the Nation. The simple model of OSY depicted in Figure 2 accounts for the stock externality related to the effect of catch on sustainable yield. Five examples of external costs that are not accounted for in that model are presented below. Some of these costs are associated with forgone benefits from public goods.[20]

1. Bycatch mortality of fish, sea turtles, marine mammals, and seabirds eliminates other uses of and benefits from these living marine resources. The opportunity cost of using these living marine resources to harvest fish should be included as one of the external costs of harvesting fish.

2. Fishing can adversely affect the productivity of fish habitat and the habitat of other living marine resources. The forgone benefit to the Nation resulting from decreased habitat productivity is an opportunity cost that should be included as one of the external costs of harvesting fish.

3. Each sustainable level of biomass for a stock will affect the productivity of other stocks in the fishery and large marine ecosystem. If a lower sustainable level of biomass for a stock decreases the productivity of other stocks, the forgone benefit to the Nation resulting from the decrease in fishery productivity is an opportunity cost of fishing. Conversely, if a lower sustainable level of biomass for a stock increases the productivity of other stocks, there are benefits associated with that increased productivity. Such costs and benefits should be included in any analysis of net benefit to the Nation.

4. Each sustainable level of catch and the associated sustainable levels of biomass and effort for a stock of fish will have ecosystem effects that could change levels of biodiversity and ecosystem services and the benefits derived from them. Any measurable decrease or increase in those benefits should be included in the estimate of the cost or benefit of a lower sustainable level of biomass and a higher sustainable level of effort. Biodiversity and ecosystem services are public goods (Bulte et al., 1998; Van Kooten and Bulte, 2000).

5. Any costs associated with harvesting-sector accidents that are not reflected in the harvesting costs depicted in Fig. 2 should be considered.

Many of these types of external costs can be difficult to estimate because they are difficult to observe or because they occur outside of markets. However, they tend to be higher at higher sustainable levels of effort and catch and lower levels of biomass. Thus, they typically result in higher marginal harvesting costs and lower OSY and, therefore, higher B_{OSY}, lower E_{OSY}, and decreased commercial harvesting-sector profit. Therefore, including these external costs, which is both required and appropriate, typically results in an even more conservative reference point.

External costs can also cause misalignment between the interests of individual fishermen and consumers and the objective of sustainable fisheries. They can result in various (often co-occurring)

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[20] A public good is a good for which: 1) The use of the good by one individual does not diminish its use by or value to others; and 2) Use or enjoyment by others cannot be excluded. That is, it is a good that is both nonrivalrous and nonexcludable.

undesirable outcomes, including overfishing and excessive levels of bycatch, habitat degradation, and fishing capacity.

Benefits and Costs beyond the Harvesting Sector

As noted earlier, the simple model of OSY depicted in Figure 2 does not address benefits and costs in the post-harvesting sectors, net benefits to consumers, or distributive impacts and equity. Economic benefits beyond the harvesting sector can be measured in terms of profits in those sectors and consumer surplus.[21] Typically, the ex-vessel-level analogue to consumer surplus provides a useful approximation of net benefit to the post-harvesting commercial sectors and to final consumers (see Just et al., 2004). Therefore, an estimate of ex-vessel demand for fish can be used to approximate that set of net benefits. Such an approximation can be used to replace the sustainable revenue curve in Figure 2 with a curve that also captures net benefits for each sustainable level of effort and its associated sustainable levels of catch and biomass. However, if this method is not useful for a particular stock of fish, or if it is important to know the distribution of net benefits beyond the commercial harvesting sector, separate estimates of the net benefits for each post-harvesting sector and for final consumers would be useful. Such estimates would require substantially more information.

If the price is lower for a higher sustainable level of catch (i.e., if the ex-vessel demand curve slopes down to the right), the sum of post-harvesting-sector profits and consumer surplus will increase as the sustainable level of catch increases, and the difference between MSY and OSY will decrease. Alternatively, if the price of fish is not affected by a change in the sustainable level of catch, neither is that sum nor OSY.

Therefore, including post-harvesting-sector profits and consumer surplus in the determination of OSY will either increase OSY toward MSY or not change it. Grafton et al. (2012) show that including post-harvesting-sector profits and consumer surplus increases dynamic MEY toward MSY, but that there remains a broad range of parameter values for which dynamic MEY < MSY and dynamic $B_{MEY} > B_{MSY}$. Similarly, Vieira and Pascoe (2013) demonstrate that when the price of fish is determined by level of catch, and ex-vessel demand for fish is used to estimate net benefits beyond the commercial harvesting sector, considering these benefits increases MEY but does not increase it to MSY.

In addition to direct effects, the harvesting and post-harvesting sectors can experience secondary effects on income and employment. These effects are measures of economic activity and not of economic benefits in the sense of the earlier discussion (e.g., in Section 2.2). As a result, they can affect overall net benefits through their distributional or equity effects. These secondary impacts can be estimated using regional input-output models; computable general equilibrium (CGE) models (Seung and Waters, 2006; Norman-López and Pascoe, 2011); or economic ("shadow") prices (Squires and Vestergaard, 2016). The traditional input-output model approach assumes that excess capacity persists in the harvesting and post-harvesting sectors and that additional workers employed come from the ranks of the unemployed. Conversely, CGE models assume full employment, so in these models an increase in catch transfers labor, capital, and other inputs from other sectors.

These secondary economic impacts typically increase as sustainable catch increases, meaning that including these impacts in the determination of OSY tends to increase it toward MSY. In fact,

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[21] Consumer surplus is the difference between the benefits consumers receive from a good (e.g., seafood) and what they must give up to attain it.

Christensen's (2010) conclusion that MEY = MSY is based on the assumption that "the more jobs and the more value generated, the higher the benefit to society." However, as noted by Sumaila and Hannesson (2010), this conclusion ignores the costs associated with increasing sustainable catch to MSY. Although these economic impacts are not useful measures of the benefits and costs throughout the post-harvesting sectors, they do provide information concerning the distributive effects of alternative sustainable catch levels. As stated in EO 12866, distributive impacts and equity should be considered in determining broadly defined net benefits. In fact, the intra- and inter-generational distributions of benefits and costs associated with fishery management actions are often critical to determining the preferred alternative.

If society determines that benefits and costs to different groups or individuals should receive different weights, the overall net benefit to the Nation from each sustainable catch level (and its associated sustainable levels of biomass and effort) depends on the magnitude and distribution of its associated costs and benefits. OSY can account for these distributional effects by applying appropriate welfare weights to benefits and costs to generate social prices (Little and Mirrlees, 1974; Squire and van der Tak, 1979). The net effect on OSY of considering external harvesting costs, benefits and costs beyond the harvesting sector, and distribution of benefits and costs will vary by fishery.

Fishery Management Costs

Fishery management costs (e.g., monitoring, reporting, enforcement, and management decision-making costs) should also be considered in determining the overall net benefit of a fishery to the Nation. For example, if fishery management costs increase as fishing effort increases, those costs affect the marginal cost of effort and should be accounted for in determining OSY. Similarly, if fishery management costs differ significantly among alternative fishery management approaches, those differences can be important factors in selecting which approach to use. The costs of monitoring and reporting can be substantial if the management approach and fishery require observer coverage.

There are several reasons a single measure of a fishery's overall net benefit to the Nation cannot typically be provided:

- Both quantitative and qualitative estimates are used when the former are not available for all benefits and costs.
- Net benefits include potential economic, environmental, public health and safety, and other advantages that cannot always be readily valued in monetary terms.
- It can be difficult to determine the weights that should be given to the benefits and costs that accrue to different groups or individuals.
- Levels of uncertainty often differ for projections of different types of costs and benefits, and there is often no good way for analysts to account for those differences in monetary terms.

Therefore, the analysis of the costs, benefits, and distributional effects of alternative sustainable catch levels (and associated sustainable levels of biomass and effort) might include projections of various types of impacts at each level, rather than a single measure of overall net benefit to the Nation. Therefore, an analyst provides information to fishery management decision-makers, but those decision-makers, not the analyst, are responsible for determining which alternative will provide the greatest overall benefit to the Nation.

A1.3 Extending the Model to Account for Net Benefits from Recreational Fisheries

Net benefit in the recreational sector can be thought of as the sum of profits from for-hire businesses, which offer fishing trips to anglers, and net benefit to anglers from for-hire fishing and all other modes of fishing, as measured by consumer surplus or compensating variation[22] associated with their fishing experiences.

Revealed preference and stated preference models have been used to estimate net benefit to anglers, whether their catch is retained or released. For example, Lew and Larson (2012) used data from a stated preference survey to estimate the economic value anglers place on, or their willingness to pay for, saltwater boat fishing trips in Alaska. Data from these surveys was also used to assess anglers' responses to changes in such fishing trip characteristics as number of fish caught, bag limit, and fish size. An important implication of this study, and many other studies concerning the benefits anglers receive from recreational fishing, is that the benefits depend on trip characteristics that reflect much more than level of catch. This means that changes in the size composition of the stock, as well as changes in other determinants of trip characteristics, can affect the benefits received by recreational fishermen under each set of sustainable level of catch and biomass. As with commercial fisheries, external costs and benefits need to be accounted for.

A1.4 Extending the Model to Account for Net Benefits from Subsistence Fisheries

As with recreational fisheries, revealed preference and stated preference models can be used to estimate net benefit to subsistence fishermen, their families, and their communities. Such benefits can include the perceived value of a range of traditional uses of harvested fish by subsistence fishermen; increased food quality; sharing of subsistence resources within social networks; combining time and money of multiple households to increase harvesting efficiency; lack of reliance on market economies; maintenance of cultural traditions; and the other values of the subsistence fishing experience (Berman, 1998; Schumann and Macinko, 2007; Gerlach and Loring, 2013). Cost survey data can then be used to estimate harvesting and household-processing costs. These costs include the cost of fuel, equipment, and other fishing inputs needed to harvest fish; times and modes of travel for fishing; and the costs of processing and preparing the catch for consumption in the home (Gerlach and Loring, 2013; Himes-Cornell et al., 2013). Other costs that should be accounted for include any external costs and benefits, and the opportunity costs of labor and other inputs that are not necessarily given full economic values by the market.

As with recreational fisheries, the characteristics and uses of subsistence fishing trips affect the benefits of subsistence fishing. Therefore, the benefits received from subsistence fishing for each set of sustainable level of catch and biomass are determined by a large set of variables.

When a stock is harvested in more than one type of fishery (e.g., commercial, recreational, and subsistence), the overall net benefit to the Nation for a given sustainable level of catch (and associated levels of biomass and effort) will depend on the distributions of catch and effort among those fisheries. The same is true when multiple fleets or multiple types of commercial, recreational, or subsistence fisheries generate different net benefits per unit of catch.

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[22] Compensating variation measures how much compensation an angler would require to prevent a decrease in his or her utility if the fishing experiences were not available.

APPENDIX 2. The Management Approach and Its Effects on OSY

The regulatory approach used to manage catch, and the incentives it creates, can strongly affect both the benefits and costs of harvesting fish. Changes in marginal cost and marginal revenue affect not only the net benefits from the fishery but the OSY and the associated levels of biomass (B_{OSY}) and effort (E_{OSY}). The regulatory approach and the specific design of the system can also impact other outcomes such as safety, bycatch, habitat destruction, fishery management costs, and distribution of catch among sectors. These outcomes also affect the overall net benefits derived from the fishery. Differences in net benefits, OSY, B_{OSY}, and E_{OSY} are generally most profound when moving from a race for fish allocation system to a catch share system that creates incentives for individuals to maximize the value they can generate from their exclusive catch privilege by reducing their harvesting costs and/or increasing their ex-vessel revenue.

In this appendix we focus primarily on how the management system affects net benefits, OSY, B_{OSY}, and E_{OSY}, where, as with the simple model of OSY presented in Section 2.2, net benefits are narrowly defined as the difference between revenue and costs in a commercial fishery. We begin by discussing examples of fisheries in which catch share systems were implemented to illustrate how those management changes can impact harvest costs, fish prices, and utilization rates. We then use a simple Gordon-Schaeffer model to illustrate how those changes affect OSY, B_{OSY}, and E_{OSY}. We conclude with a discussion of broader impacts of these types of management changes on net benefits and distribution of those benefits and implications for OSY. The potential for the management system to affect MSY, B_{MSY}, and E_{MSY} though its effects on the determinants[23] of those three variables is noted here but not discussed elsewhere in this appendix.

A2.1 Ending the Race for Fish

When fisheries are managed solely by closing a fishery each year after the total allowable catch (TAC) (i.e., ACL or ACT) is caught, but fishing capacity is not constrained, and catch is allocated based on who can land it first, a race for fish ensues. This approach often leads to excessive fleet capacity and fishing effort that increases harvest costs, creates supply gluts, and reduces product quality, the price and the net value of catch (National Research Council (NRC) 1999; Homans and Wilen, 2005). A catch share system allocates exclusive privileges to harvest a portion of the TAC to individuals (e.g., an IFQ) or groups (e.g., fishing cooperatives). Those holding catch shares have the incentive to maximize the net value they can generate with them. Often these systems enable the season length to be extended and eliminate supply gluts, enabling more careful handling of fish and potentially additional fresh or even live sales of catch - all of which can substantially increase the value of the catch (Homans and Wilen, 2005). Individual vessels may be able to reduce costs by operating more efficiently. In addition, costs may be reduced further if transferability of catch privileges allows consolidation of catch by fewer, more efficient vessels. Later in this section we discuss several real-world examples that highlight these changes.

Perhaps the best examples of an extreme race for fish and the effects of ending it with a catch share system are the Pacific halibut fisheries in British Columbia (BC) and Alaska. In both cases, the fisheries

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[23] The definition of MSY presented in the NS1 Guidelines and reproduced in Section 2.2 of this paper identifies the following determinants of MSY: prevailing ecological, environmental conditions and fishery technological characteristics (e.g., gear selectivity), and the distribution of catch among fleets. As noted elsewhere in this paper, regulatory and market condition can affect gear selectivity and the distribution of catch among fleets.

had been managed with limited seasons that had constrained catch and conserved biomass. However, these measures had led to continually decreasing season length culminating in short derby fisheries, reduced product quality, and supply gluts as well as safety concerns, gear conflicts, lost gear, ghost fishing, and other negative effects of the race for fish (National Research Council 1999). An individual vessel quota (IVQ) system was implemented in the BC halibut fishery in 1991, and an individual fishing quota (IFQ) system was implemented in Alaska in 1995. In the first 3 years of the IVQ system, the BC halibut fishery enjoyed more than a 50 percent increase in price relative to the Alaska fishery, which was still operating under a race for fish (Casey et al., 1995). Herrmann (1996) estimates IVQs increased the value of landings of BC halibut by over C$23 million in the first 4 years of the IVQs. In 1995, an IFQ system was implemented in the Alaskan halibut fishery and lengthened its season from a few days to 245. Alaska enjoyed a smaller price increase (only about 10 percent) and induced a price drop in the BC Halibut fishery, which now had to compete in the fresh market against Alaskan halibut (Herrmann and Criddle, 2006). Although a decrease in the number of boats participating in the Alaska halibut fishery may have reduced costs, consolidation in the fishery was purposely constrained to maintain or increase the small owner–operator nature of the fishery and protect remote fishing communities.

In other Alaskan fisheries in which catch shares were implemented, reduction in capacity and related cost savings were major objectives and outcomes. Both the Bering Sea Aleutian Island (BSAI) pollock and crab fisheries were initially managed with hard TACs and seasonal closures that led to a race for fish and excess harvesting and processing capacity. The introduction of catch shares (cooperatives in the pollock fishery and IFQs in the crab fishery) lead to substantial reductions in the number of vessels participating and higher capacity utilization, with accompanying reductions in fixed costs and increases in technical efficiency (Felthoven, 2002; Schnier and Felthoven, 2013). Abbott et al. (2010) also found that productivity and remuneration of crew increased post-IFQ for the BSAI crab fishery.

Changes that occur after introduction of catch shares are complex and not always uniform across sectors. Dupont et al. (2005) found that implementation of IFQs in the Scotia-Fundy mobile gear groundfish fishery increased prices, which benefited all vessels. However, only larger vessels saw productivity gains and reduced harvest costs. IFQs reversed a declining trend in productivity for the large vessels, but productivity continued to decline for the smaller vessels. A meta-analysis of U.S. catch share systems by Birkenback et al. (2015) found strong evidence that catch shares tend to increase season length but cause mixed results regarding changes in prices. Many factors can impact prices, making it difficult to identify the impact the catch share system had. Catches, revenues, and costs are also strongly influenced by exogenous factors that influence fishery productivity and cost and thus profit. Also, many catch share systems did not have a substantial race for fish prior to implementation so expectations of price gains would be lower. Nevertheless, there is substantial empirical and theoretical evidence to suggest that implementing catch shares in a fishery where catch had been allocated through a race for fish can substantially increase profits either through increasing revenue, decreasing harvest costs, or both.

A2.2 Prices, Costs, and OSY

The Gordon-Schaeffer model, introduced earlier in this paper, can be used to demonstrate how changes in harvest costs or prices induced by management changes can alter OSY, $B_{OSY,}$ and E_{OSY}. Figure 3 shows two sustainable revenue curves with the solid line representing sustainable revenue (price * annual yield) in the initial unregulated open access (UOA) fishery and in the final catch share (CS) fishery. The dashed sustainable revenue curve shows the result of prices decreasing as a result of compressed seasons, supply gluts, and reduced quality induced by containing total catch to the MSY level with a race for fish that produces a derby (DB) fishery. The underlying relationship between effort and catch is not changed, but the revenue curve is lowered at every point due to the lower ex-vessel price of fish. The figure also shows the total cost lines with the solid line representing costs per unit of fishing effort in the unregulated open access and catch share fisheries. The dashed total cost line has an increased (doubled) slope representing the increased cost associated with the excess fishing capacity and race for fish induced by the derby fishery. The assumption is that fishing capacity continues to increase in the derby fishery until it drives costs up to the point where profits are fully dissipated. The model assumes, conservatively, that marginal costs and prices return to unregulated open access levels under a catch share system, though we might expect prices to rise and costs to fall further relative to open access levels.

The effort level and revenue move from point *A* under unregulated open access (the point at which effort has risen to where revenues equal costs in the unregulated fishery), to point *B* under the derby fishery with a TAC set to achieve MSY. This assumes costs have risen until they equal revenues in the derby fishery and a new bioeconomic regulatory equilibrium has been established. Effort and revenue then move to point C when the catch share system is implemented. This assumes that harvest is set at the level that maximizes equilibrium profit and that the marginal cost and prices returned to the levels that prevailed in the unregulated open access fishery. Note E_{OS} under the derby fishery (though never observed because the TAC was set to achieve MSY[24]) had shifted far left from 40 to 25 given the lower revenue and steeper cost curves associated with the derby fishery. E_{OSY} is higher and B_{OSY} is lower with the catch share system than with prices and costs associated with the derby fishery. In general, increases in ex-vessel prices or decreases in marginal cost tend to move OSY closer to MSY.

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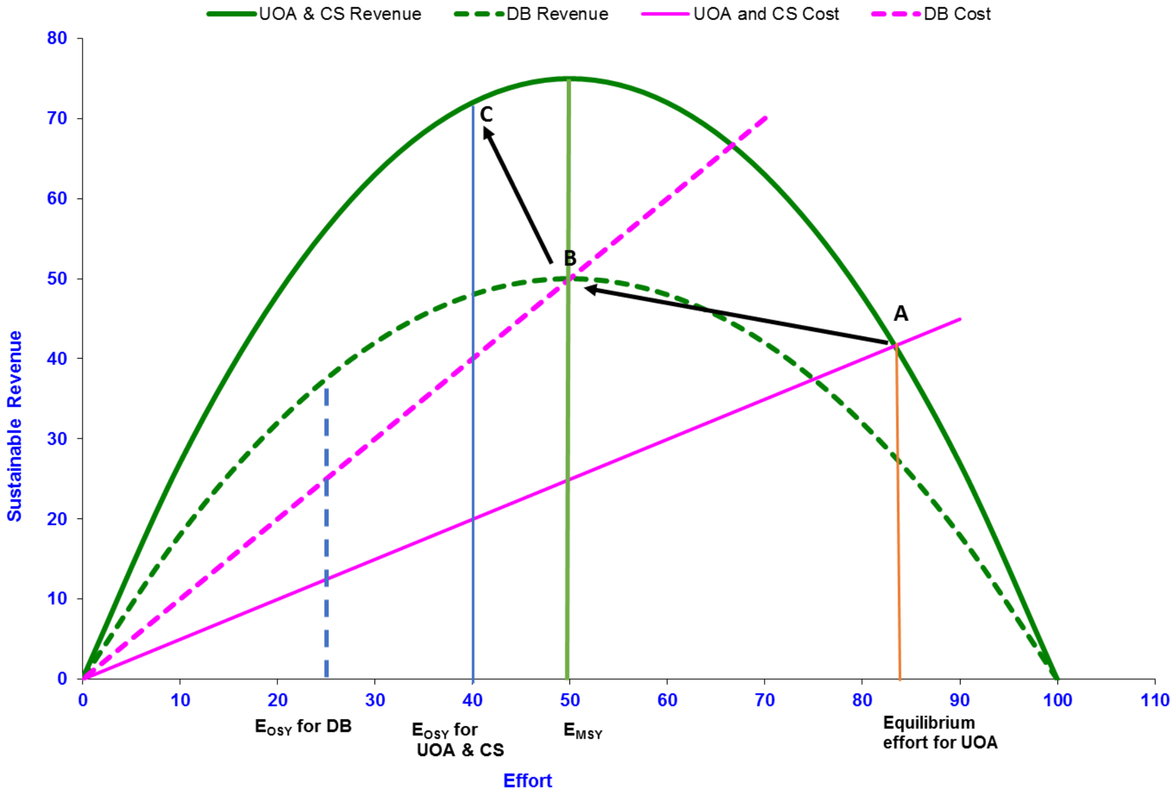
[24] If the catch had been set lower (at the OSY level given the harvest costs and prices that prevailed under a TAC set at MSY), we would expect the harvest costs to rise and prices to fall until again there were no profits. Otherwise, incentives to increase capacity to get a bigger share of the catch would persist, again shifting E_{OSY} left.

Figure 3: Sustainable revenue, total cost, and optimum sustainable yield with increasing prices and decreasing costs (cost and revenue are in millions of dollars).



A2.3 Conclusions

Controlling catch with only seasonal closures may be successful at constraining catch and rebuilding biomass and increasing sustainable harvest. However, that method of controlling catch can lead to a race for fish that drives up costs and decreases revenue. The fishery examples discussed here illustrate that catch share systems can increase prices and revenues and decrease costs, thereby greatly increasing fishery profits. The exposition with the Gordon-Shaeffer model demonstrates that those changes in costs and prices can also alter the OSY effort, harvest, and biomass levels, where in this case OSY is determined based on a narrow measure of net benefit (i.e., maximize sustainable profit). Catch share systems may also have broader effects that impact net benefits from fisheries, including reducing gear conflicts and bycatch, but also distributional effects that may not always be considered positive.

APPENDIX 3. Dynamics and Discounting

Many bioeconomic models are based on a logistic growth equation, which lacks age structure and other realistic features included in the modern stock assessment models that are often used to estimate MSY. Age-structured population dynamics are, however, increasingly incorporated as constraints in bioeconomic models (Gulland, 1983; Deacon, 1989; Bjørndal and Brasão, 2006; Tahvonen, 2009a, 2009b; Kjaersgaard and Frost, 2008; Kompas et al., 2010; Tahvonen et al., 2012; Quaas et al., 2013). Age-structured estimates of OSY allow more useful comparisons of OSY to MSY for stocks managed using age-structured stock assessments. Ideally, we would want to compute OSY using the exact population model that is used to compute MSY; in practice, this ideal may be difficult to achieve.

Using alternative population models to compute OSY is an area of active research. In this section, we consider a simple class of models called Deriso-Schnute Biomass Models (Quinn and Deriso, 1999). These models contain an explicit representation of age-structured population dynamics with age-dependent growth, and thus provide a rigorous foundation for a general theory for analyzing age-structured catch and effort data (e.g., Schnute and Fournier, 1980; Fournier and Archibald, 1982; Schnute, 1985).

An objective function must be specified in the definition of OYT, which is usually assumed to be additive over time (i.e., time separable). The class of objective functions we consider here is restricted to a set of time-separable quadratic objective functions from which OYT is defined subject to a linear constraint that represents population dynamics under the assumption that recruitment is an exogenous process. Linearity in population dynamics based on age structure and reproduction is based on Leslie (1945).

Because OYT depends on both an economic objective and a biological growth equation, the meaning of "optimum" can be ambiguous or, worse, ill posed. Under the conditions outlined here, dynamic optimization of expected economic profits, subject to a (restricted) linear growth equation, is a well-posed problem because: 1) A unique solution to the problem exists; and 2) The solution can be represented as a system of linear difference equations. The bioeconomic model and theory described here are abstract; they contain restrictive assumptions with respect to both biology and economics. These assumptions are necessary to reach a compromise between an analytically tractable dynamic model under uncertainty and one in which age structure is an explicit feature, with growth based on biological principles.

Models in fisheries economics deal with uncertainty in many ways, including simply ignoring its presence, as in the simple OSY model depicted in Figure 2. Rational expectations models represent another approach. In these models, uncertainty is represented with random variables. Decisions in the model are based on mathematical expectations of these random variables, conditional on information available to the decision-maker at the time a decision is made. In other words, decisions in the model are based on mathematically optimal (i.e., rational) forecasts. However, solving this type of maximization problem can be difficult or impossible, especially if the objective function or constraints contain random variables or stochastic processes. Therefore, a first priority is to verify that the maximization problem under uncertainty that defines OYT is well posed in that a unique solution exists and is computable.

We assume that there is a known objective function, such as expected profits over time in present-value terms. For example, an objective function with discount factor $0 < \beta < 1$, variable cost parameter α , positive adjustment cost parameter ψ , and positive parameters ϕ and ξ that represent stock and congestion externalities in terms of catch c_t and biomass b_t , could be specified as

$$\text{Max E}\left[\sum_{t=0}^{\infty}\beta^t\left((\alpha+\phi b_t-\xi c_t)c_t-\frac{1}{2}\psi(c_t-c_{t-1})^2\right)\right]. \quad (1)$$

The quadratic dynamic adjustment cost term in the previous equation is essentially a penalty on variability in catches. Suppose that recruitment r_t is an exogenous stochastic process that may be affected by other processes, such as climate. The simplest assumption is that biomass b_t , catch c_t , and recruitment *r* are related by a linear growth equation, which includes a coefficient $0 \le \theta < 1$ on the right-hand side such that

$$b_t = \theta b_{t-1} - c_t + r_t . \quad (2)$$

The set of linear growth functions that are admissible in the linear-quadratic class of rational expectations models includes autoregressive and moving average stochastic processes. Equation (2) can serve as a linear constraint in a stochastic dynamic optimization problem with a quadratic objective function, as in equation (1). A theory of quadratic eigenproblems has been developed in the applied mathematics literature (e.g., Higham and Kim, 2001) to handle multivariate versions of equation (2) as constraints in dynamic optimization. However, whether the set of linear growth equations included in the linear-quadratic class of rational expectations models can handle an age-structured population is an open research question.

The application of Bayesian methods to rational expectations models is not straightforward because it involves imposing an analyst's subjective beliefs on the model. Unrestricted vector autoregressions, a natural empirical alternative to a theoretical rational expectations model, are readily adapted to Bayesian analysis. However, the relationship of Bayesian analysis to rational expectations is complicated and beyond the scope of this document. Instead, the models under consideration here are treated in a classical likelihood framework.

In the case of a single endogenous state variable (the stock) and no constraints, a linear-quadratic stochastic dynamic optimization problem is solved by factoring a characteristic polynomial. In the case of a single control variable, the quadratic formula is used to derive these factors, which are a conjugate pair. In general, adding a constraint like (2) to a linear-quadratic stochastic dynamic optimization problem adds a degree to its characteristic polynomial so that it becomes cubic instead of quadratic. A technique for solving cubic equations, usually referred to as Cardan's formula, is directly relevant to single-stock cases. However, in cases of multiple stocks, a cubic characteristic polynomial (which is a matrix polynomial) presents a major hurdle because a general theory of cubic eigenproblems does not currently exist.

Clark (1990) describes some elements of bioeconomic theory with age-structured populations using a cohort model. An empirical application of this theory is available in Clark (1976). Deriso (1980) follows this approach and analyzes OYT harvesting strategies in a classical delay-difference population model. Quinn and Deriso (1999) review these models and describe them as representing a middle ground between simple (but unrealistic) production models and more complicated (i.e., vector-based) age-structured population models. The first group of delay-difference models reviewed in Quinn and Deriso

(1999) is based on Leslie matrices, with population dynamics represented in age-specific linear projection matrices. This first approach does not explicitly consider effects of individual growth; however, it does satisfy equation (2).

The review in Quinn and Deriso (1999) also refers to a second set of delay-difference models called Deriso-Schnute Biomass Models, based on work in Deriso (1980) and Schnute (1985). These models explicitly consider the effects of individual growth through a second-order difference equation that relates age-dependent growth increments over time (i.e., Ford's equation). This particular mathematical structure is important because second-order difference equations often represent market dynamics and optimal dynamics in economic models. Representing both types of dynamics is important in analyzing fisheries because externalities typically cause actual outcomes to deviate from socially optimal outcomes.

The starting point for the bioeconomic theory posited here is Ricker's (1975) exposition of von Bertalanffy's equation and its relation to Ford's growth equation. Schnute (1985) expressed the latter in terms of $w_{a,t}$, the weight of fish at age *a* in period *t*, with the assumption that Ford's growth coefficient is a fraction, $0 < \rho < 1$. Under this assumption, the annual weight increment decreases by a constant factor in each period according to a simple second-order difference equation,

$$w_{a+1,t+1} - w_{a,t} = \rho(w_{a,t} - w_{a-1,t-1}), \tag{3}$$

for all $t \geq 1$ and w_{a0} given for $a > 0$. A solution of this difference equation can be found in Appendix A of Schnute and Fournier (1980). Second-order difference equations can be used to describe dynamics in many economic models. For example, Ford's growth equation has a natural economic interpretation: The annual rate of return (in terms of growth) of leaving an individual fish in the water is a geometrically decreasing function of its age.

Though a formal proof is beyond the scope of this paper, a linear growth equation that is equivalent to equation (2) exists that is both a delay-difference model that can be derived from Ford's growth equation (3) and compatible with optimal control theory for linear-quadratic systems. A derivation of this linear growth equation from a set of first principles for delay-difference models, as expressed in the works cited previously, involves some restrictive compromises. Familiar restrictions on delay-difference models—for example, those found in Schnute (1985)—apply here. These restrictions include known (i.e., extrapolated) prerecruitment weight, knife-edged recruitment, infinitely lived individuals, constant natural mortality, and knife-edged selectivity. In addition, recruitment is simplified here and assumed to be an exogenous stochastic process. This assumption omits effects of any type of known (i.e., expected) compensatory response. The most important compromise in the approach outlined here involves a survival fraction $0 < \sigma < 1$, which Schnute (1985) interprets as the share of fish not caught in the fishery that survives to the next period (i.e., escapement). Unfortunately, that algebraic form does not simplify in the solution of the associated dynamic optimization problem.

The approach described here treats fishing and natural mortality as simultaneous processes. Therefore, instead of treating survival to the next period as conditional on survival in the fishery, the treatment here assumes that fishing and natural mortality are additive (hence separable) for each point in time, as in Baranov's catch equation. In other words, the age-dependent survival fraction applies to the entire population of each cohort in a period, which determines the total number in that cohort for the next period.

Treating fishing and natural mortality as concurrent additive processes produces symmetry in the growth model, which can be expressed simply in terms of state variables. Traditionally, the set of state variables in delay-difference models has been the number of individuals in a cohort at the start of a season, before fishing occurs. Here, state variables instead represent the numbers of fish in each cohort net of fishing mortality. An advantage of the latter representation of the system is that analyzing its limiting behavior and calculating probabilities of various events are straightforward undertakings.

Under the interpretation above, an approximation can be made that yields $\theta \approx \sigma(1+\rho)$, and that because ρ and σ are positive, and $\theta < 1$ by assumption (to ensure that the growth model is stable), there is an upper bound on biological growth and survival parameters such that $(1+\rho) < 1/\sigma$. A slight modification implies $\rho < (1-\sigma)/\sigma$. In words, Ford's growth coefficient must be smaller than a ratio of rates, with natural mortality in the numerator and survival from natural mortality in the denominator. According to the condition on θ that precedes equation (2), this bound is a necessary and sufficient condition for stationary dynamics in a linear bioeconomic model.

This abstract bioeconomic model is obviously not plausible in every setting. Some parts of the model may be relaxed. For example, Ford's growth equation could be modified to include a dynamic forcing function such as climate change, or the assumption of knife-edged selectivity could be replaced by a more flexible functional form. Any major modification to the model would probably preclude closed-form solutions. The problem may still be well posed but the analytical approach would be replaced by a numerical procedure for computing the solution. In such cases, recursive methods based on dynamic programming (e.g., Bellman's equation) are popular, and are formally equivalent to an approach based on Euler equations.

With respect to estimating OSY, the economic component of the model described here does well in representing the negative externalities that are thought by economists to be prevalent in fisheries. Multivariate versions of the model described here could be used to define OSY for mixed-stock fisheries. On the other hand, perhaps the most important shortcoming of the model here in terms of economic analysis is its simple approach to variable commercial operating costs: Only a single linear term, which is proportional to catch (or effort), is present to represent these market-based costs. Although such a simple approach may be adequate in an abstract model, it misses interesting and important questions, such as how a change in fuel prices, bag limits, or ESA interactions would affect OSY. Consequently, in addition to relaxing key restrictions on biology and selectivity, another high priority for future work is to extend the cost structure of the bioeconomic model outlined here to explicitly account for variable inputs across the suite of users and uses. Mathematically, the most convenient way of extending this cost structure might be to estimate a static system for derived input demand and to incorporate this structure directly into the model.

Such a static demand system, and outputs from the model outlined here, could be used as inputs to a CGE model of a regional economy to examine OSY on a broader scale. In that approach, a CGE model could represent the value to the overall economy of a particular region from economic activity directly, and indirectly, related to fishing (Waters et al., 2014). Then the CGE model—instead of the more traditional and restrictive objective based on net benefits (i.e., profits) to the fishing industry—would be the basis for computing OSY.

APPENDIX 4. Modeling Uncertainty

The previous appendix introduced stochastic stock dynamics, which are an important source of uncertainty in the setting of harvest control rules. Other uncertainties important to fisheries management include process error (such as stochastic stock dynamics, environmental conditions, catch prices or non-market values); observation error (such as inexact knowledge of stock biomass); and model error (such as uncertainty about the proper specification of stock-recruitment relationships).

In a modeling context, incorporating uncertainty into management decisions requires that the uncertainty have a formal representation and that the decision-maker's attitude toward risk be defined.

Uncertainty and risk are important subjects in many fields, and the concepts and terminology surrounding them are not consistent across or even within fields. Most models build on an assumption that uncertainties can be meaningfully represented as probabilities, though other approaches exist (see, for example, Regan et al. [2005] and Prato [2009]). In economics, an influential tradition has been to distinguish between risk as a situation in which probabilities of outcomes are known and uncertainty as a situation in which the probabilities are not known.[25] However, recognition that the classical approach to decision-making under uncertainty (which was developed with respect to gambling problems) is not well suited to many decision problems led to the development of the theory of subjective probability (Savage, 1954) and the preference state approach (Arrow, 1964).

Here, we apply the term "uncertainty" to any situation in which a random variable appears, whether a probability distribution is assigned to its possible realizations or not. We treat risk as a reflection of the importance of uncertainty to decision-makers. Risk attitudes or risk preferences capture managers' attitudes toward possible realizations of values that are a function of underlying random variables. Thus, risk may be represented as statistics regarding outcomes such as expected loss or maximum possible loss, or as the probabilities of particular undesired outcomes (e.g., the probability of overfishing).

Risk is significant to the development of harvest control rules because it affects a choice among actions in relation to managers' objectives. For example, one very conservative approach to management under uncertainty is the maximin strategy, whereby a policy is designed to achieve the best outcome in the worst possible realization of model states or parameters. The probabilities of outcomes need not be considered in the maximin strategy. If probabilities of outcomes are available, functions of uncertain outcomes and their probabilities can be calculated. A decision-maker is risk neutral if he or she wants to maximize the expected value of a variable (or function thereof) without respect to other moments of the distribution. In most bioeconomic analyses, the assumption is that fisheries managers are risk neutral, though other risk preferences, such as risk aversion, may be represented. This is significant because the MSA seems to suggest a risk-averse posture toward overfishing, and the NS1 Guidelines even more so.

One general approach to the representation of risk preference is a utility function, which represents the value of possible outcomes to decision-makers. For example, a commonly used risk-averse utility function is the mean of a random variable less a penalty for that variable's variance. Utility curves, which are broadly applied in economics and engineering, have been applied in fisheries, including, for example, by Mendelssohn (1982) and Mäntyniemi et al. (2009). Another common approach to risk management is

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[25] This distinction is generally attributed to Frank Knight (1921), although some authors argue that the distinction is based on a misunderstanding of Knight's work (see, for example, Langlois and Cosgel [1993]).

based on constraining the probability of a given undesired outcome to no greater than some acceptable level, as in Shertzer et al. (2008). When an objective function is also specified, at least implicitly, this approach amounts to solving a chance-constrained program; for example,

$$\text{maximize } f(X)$$

$$\text{subject to } p(X \leq K) \leq L$$

where X is a random variable, K is a limit on X, and L is a limit on the probability that X exceeds K. For example, fisheries managers may seek to maximize expected profitability in a fishery subject to the constraint that the probability of overfishing does not exceed 10 percent. (Note that utility and chance-constrained approaches are not mutually exclusive: The function $f(X)$ could be a utility function and the problem could be solved subject to chance constraints.)

Because a traditional focus of dynamic optimization in fisheries has been on stochastic state dynamics, it will be convenient for us to frame the discussion here in terms of Markov decision processes. The general idea of a Markov decision process is to identify a control rule, known as the optimal policy. This policy specifies, for any given realization of a random state variable, the action that maximizes system performance in expectation. Formally, a Markov decision process is a collection of sets $\{A, S, P, W\}$, where A is the set of actions available to a decision-maker, S is a set of random state variables, P is a set of Markov transition probabilities that govern the evolution of the variables in S, and W is the rewards realized by the decision-maker for taking a particular action in a particular state. Given a suitably defined objective—usually the expected sum of periodic values or utilities—the solution of an MDP is a function $\pi(S)$, which gives the optimal action for a realized state. Dynamic programming methods are used for this type of analysis to compute decision rules and value functions (Rust, 2008).

Observation error, or uncertainty about true state value, has received less attention than process uncertainty in the optimal control literature. Sethi et al. (2005) address observation uncertainty within the MDP framework, an approach that yields a mapping from current observed state to optimal harvest. Moxnes (2003) treats observation error by applying the Kalman filter in the framework of stochastic optimization in policy space, an alternative to stochastic dynamic programming. An alternative approach to incorporating observation uncertainty is the partially observable Markov decision process (POMDP), a Bayesian framework in which a policy maps beliefs into actions. The POMDP is essentially a Bayesian approach to optimal control of a hidden Markov model. A preliminary application of the POMDP to fisheries management is Tomberlin (2008).

Model uncertainty—that is, uncertainty about model parameters or, more generally, model structure—has received little attention in the bioeconomics literature. Walters (1986) describes a model-averaging approach to model uncertainty in fisheries. In the larger dynamic optimization literature, robust optimization, in which expected performance is maximized under the worst-case model realization, has received considerable attention (Nilim and El Ghaoui, 2005; Woodward and Shaw, 2008). Woodward and Tomberlin (2014) apply robust dynamic optimization as a framework for precautionary management of a fishery when population growth parameters are uncertain.

Delage and Mannor (2010) present a percentile optimization to Markov decision processes under both reward and state dynamics uncertainties. Basically, this approach provides an intermediate ground between the solution of the dynamic optimization problem-based nominal (point-estimate) parameter set and the robust alternative, which yields very conservative policies. Percentile optimization provides a choice parameter reflecting the degree of risk decision-makers are willing to assume, and the sensitivity of solutions to this parameter can be explored.

Reinforcement learning is another technique that may be applied to problems with observation and model uncertainty. This technique has been broadly applied in engineering and computer science, but we are aware of only one application to natural resource management (Fonnesbeck, 2005).

Though the work of Delage and Mannor (2010) is specifically directed at the problem of model uncertainty, it is similar in spirit to the Prager and Shertzer (2010) probability-based approach to ACLs. Both might be considered instances of chance-constrained programming, an approach to constrained optimization under uncertainty in which a solution is valid as long as the probability of constraint violation is within an acceptable range.

Another approach to constrained optimization under uncertainty is stochastic programming with recourse, in which the potential to undo damages from a current action (e.g., overfishing due to an overly optimistic biomass estimate) by counteracting future actions (e.g., reducing next year's harvest) is considered at the time of the original decision. Whether such recourse is available in a fisheries management context will depend on the biological and institutional setting, and is complicated by the reality that in many cases the option of recourse will itself be uncertain. As mentioned earlier, utility theory provides another approach to decision-making under uncertainty. There does not seem to be clear correspondence between chance-constrained programming and utility theory except in very simple cases.

In summary, stochastic dynamic optimization models provide a way to estimate OYT under various types of uncertainty and for deriving risk metrics associated with particular harvest levels. Because these models can be difficult to implement, it is worth considering whether they are worth the effort. Specifically, we would like to know: 1) whether the management implications of stochastic models differ enough from deterministic models to warrant the extra modeling effort; and 2) whether nonoptimizing approaches may serve just as well in particular cases.

With regard to the first question, Andersen and Sutinen (1984) note that differences between policies derived from deterministic and stochastic models are often not great, whereas Sethi et al. (2005) find that under some conditions the differences are substantial. We do not expect a general answer to this question to emerge soon. With regard to the second question, stochastic simulation models of a small set of candidate policies (Kjaersgaard and Frost, 2008; Semmens, 2008) may often conform more closely to the Council process than general optimization models, and may be more easily implemented than a full optimization model.

To reiterate an earlier point, estimation of OYT is based on maximizing overall net benefits to the Nation subject to biological and, in principle, other (e.g., ecological, environmental, and social) constraints. For purposes of estimating OYT, scientific and management uncertainties as well as risk metrics can be captured independently of the process of defining ABC or ACL (though either of these may appear as explicit constraints on OYT). Thus, it is possible to estimate OYT without developing sequential buffers for scientific and management uncertainty, and an argument can be made that treating these uncertainties simultaneously is preferable. For example, based on stochastic simulation of Gulf of Mexico red snapper and grouper fisheries, Semmens (2008) concluded, "Importantly, the results suggest that all sources of uncertainty and variability should be assessed together to determine the appropriate buffer." Further research is required to determine under what circumstances it would be appropriate to assess all sources of uncertainty and variability together to establish the buffer between OFL and ACT, if one is used, or between OFL and ACL if an ACT is not used. Our point is that regardless of how scientific and management uncertainty are treated in the development of ABCs and ACLs, they can be treated simultaneously for the purposes of estimating OYT.

APPENDIX 5. Numerical Examples of Aggregate MSY and OSY in a Two-Stock Fishery with a Technical Interaction

Ecological interactions occur due to predation and competition; and those interactions tend to affect the overall net benefit derived from the use and existence of living marine resources and their habitat. For example, increasing the biomass of a prey species for an endangered marine mammal could provide non-market benefits that exceed the loss in market benefits in the fishery for that prey species. Technical and market interactions are the two types of economic interactions. Technical interactions occur when two or more stocks are caught together. Market interactions occur either when the ex-vessel prices of two or more stocks are interdependent or when the input prices (e.g., the price of labor or the lease price of a fishing vessel) for harvesting one stock are dependent on the harvest levels of other stocks. This appendix presents numerical examples of aggregate MSY and OSY in a two-stock fishery with a technical interaction.

A5.1 MSY Example

As depicted in Figure 4, the sustainable yield for each stock and the associated sustainable stock biomass are functions of the fishing effort that is jointly applied to both stocks.[26] Therefore, the sustainable yield curve for the fishery is the vertical summation of the sustainable yield curves for the two stocks.

In this example, the following occur as effort increases (see Table 1 and Figure 4):

1. As effort increases from 0 to 60:
    - The sustainable level of biomass for each stock decreases.
    - The sustainable yields of both stocks and the fishery increase.
    - The sustainable yield of stock 2 reaches its maximum (MSY2) of 3,600 metric tons (t) and its MSY level of effort (E_{MSY2}) of 60.

2. As effort increases from 60 to 92:
    - The sustainable level of biomass for each stock continues to decrease.
    - The sustainable yield of stock 2 decreases because the difference between the actual level of effort and E_{MSY2} increases; and because the difference between the stock 2 biomass level that supports MSY2 (B_{MSY2}) and the actual stock 2 biomass also increases.
    - The sustainable yields of stock 1 and the fishery as a whole continue to increase.
    - The sustainable yield for the fishery as a whole reaches its maximum (MSYF) of about 42,300 t and its MSY level of effort (E_{MSYF}) of 92. At that level of effort, the increase in the sustainable yield for stock 1 is exactly offset by the decrease for stock 2, and the biomasses of stocks 1 and 2 are at levels that support MSYF (B_{MSYF1} and B_{MSYF2}). Therefore, B_{MSYF2} is less than $B_{MSY2.}$

3. As effort increases from 92 to 100:

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[26] This model assumes that the relative catchability of the two species is fixed and partly depends on a specific regulatory approach. Therefore, a change to the regulatory approach can substantially alter relative catchability. For example, a catch share system may provide incentives for fishermen to alter gear, timing, or location of fishing in ways that reduce catch rates of the weaker stock, enabling a higher level of sustainably catch from the stronger stock without overfishing the weaker stock.

- The sustainable level of biomass for each stock continues to decrease.
- The sustainable yields of stock 2 and the fishery as a whole decrease because effort exceeds E_{MSY2} and E_{MSYF} by larger amounts, the biomass of stock 1 decreases farther below B_{MSYF1}, and the biomass of stock 2 decreases farther below both B_{MSY2} and B_{MSYF2}.
- The sustainable yield for stock 1 continues to increase (but by less than the decrease in sustainable yield for stock 2). It reaches its maximum (MSY1) of 40,000 t and its MSY level of effort (E_{MSY1}) of 100. Therefore, B_{MSYF1} is greater than $B_{MSY1.}$

4. As effort increases beyond 100:
    - The sustainable level of biomass for each stock continues to decrease.
    - The sustainable yields of both stocks and the fishery as a whole decrease because E_{MSY1}, E_{MSY2}, and E_{MSYF} are being exceeded by larger amounts and because the biomasses of stocks 1 and 2 are decreasing farther below B_{MSY1}, B_{MSYF1}, B_{MSY2}, and B_{MSYF2}.

The main implications of this example are as follows:

1. The level of effort that generates MSY for stock 1 (E_{MSY1}) exceeds the level of effort that generates MSY for stock 2 (E_{MSY2}); therefore, the sum of the MSYs for the two stocks is not attainable.

2. The level of effort that generates MSY for the fishery as a whole (E_{MSYF}) is less than E_{MSY1} and greater than E_{MSY2}.

3. If the MSY reference point for the fishery as a whole (i.e., the aggregate MSY reference point) is used, the biomass targets for stocks 1 and 2 are the sustainable biomass levels associated with E_{MSYF}; therefore, the target level for stock 1 (B_{MSYF1}) is greater than B_{MSY1}, the target level for stock 2 (B_{MSYF2}) is less than B_{MSY2}, and attaining MSY and B_{MSY} for either stock would prevent the attainment of MSY and B_{MSY} for the other stock and for the fishery as a whole.

4. A choice needs to be made among the reference points that will support MSY for stock 1, MSY for stock 2, or MSY for the fishery as a whole.

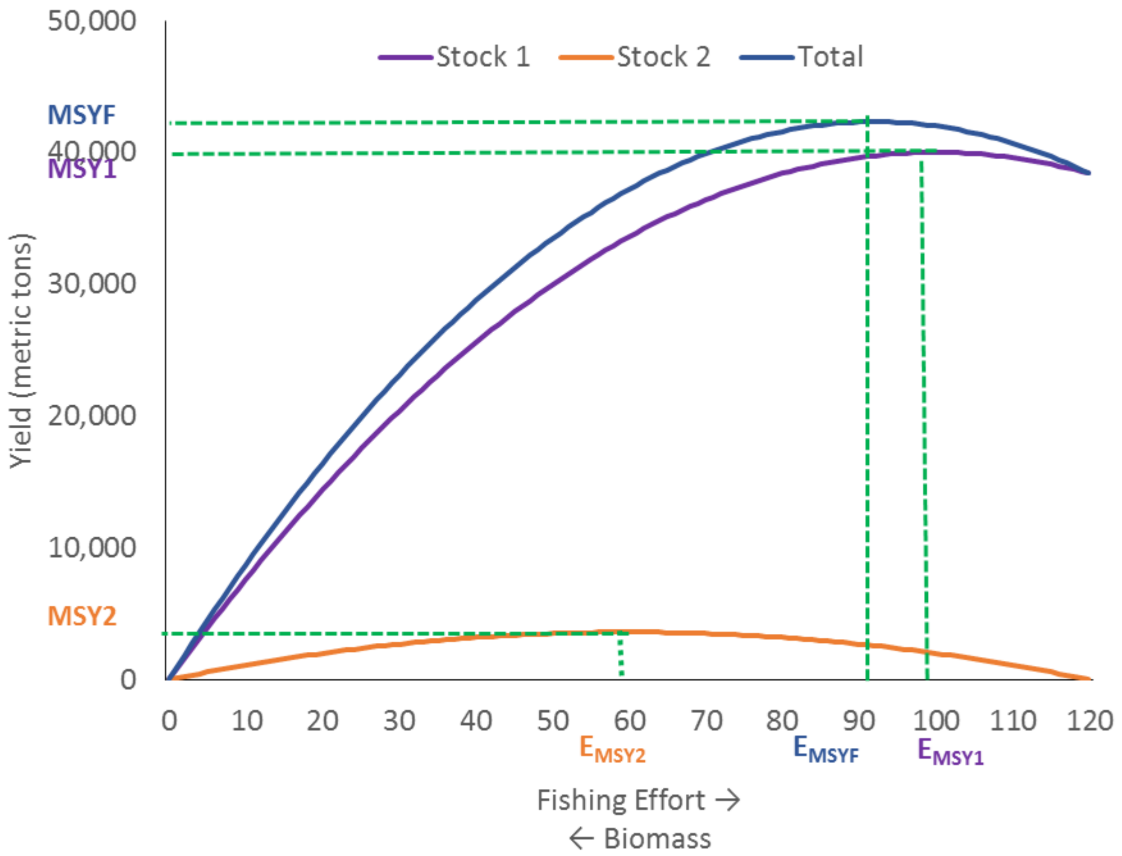
However, as noted in Section 3.3.1, there is a critical problem with the concept of an aggregate MSY if the following implicit assumptions are not valid: 1) an additional metric ton of sustainable yield of any stock is equally important and 2) that its importance does not depend on the level of sustainable yield for any stock. Section 3.3.1 also includes three possible fixes if these assumptions are not valid.

Table 1. Sustainable yield when MSY1, MSY2, and MSYF levels of effort are jointly applied to both stocks in a two-stock fishery with a technical interaction that results in the stocks being caught together (catch in metric tons).

	MSY1	MSY2	MSYF
Fishing effort	100	60	92
Catch for stock 1	40,000	33,600	39,744
Catch for stock 2	2,000	3,600	2,576
Total catch	42,000	37,200	42,320

Notes:
MSY1 is the independently determined MSY for stock 1.
MSY2 is the independently determined MSY for stock 2.
MSYF is the MSY for the fishery as a whole when the interaction between the stocks is considered.

Figure 4. MSY for a two-stock fishery as a whole when both stocks are caught together.



A5.2 OSY Examples

For the OSY examples, we use the same sustainable yield curves as in the MSY example and the simple model of OSY we discussed in Section 2.2.2. In Figure 5, we replaced the sustainable yield curves in metric tons for the two stocks from Figure 4 with sustainable revenue curves in dollars of ex-vessel revenue. We also added a total cost curve for harvesting both stocks together.

Sustainable revenue and associated sustainable levels of biomass for each stock, as well as the narrowly defined measure of overall net benefit, are functions of the fishing effort that is jointly applied to both stocks. Therefore, the sustainable revenue curve for the fishery as a whole is the vertical summation of the sustainable revenue curves for the two stocks. The OSY level of effort for the fishery as a whole is that with the greatest difference between the total revenue and total cost curves. As in Figure 2, this is the level of effort at which marginal cost and marginal revenue are equal.

CASE 1

For this example, we use ex-vessel prices of \$100 and \$5,000 per metric ton, or about \$0.05 and \$2.27 per pound for stocks 1 and 2, respectively, to transform the sustainable yield curves in Figure 4 into the sustainable revenue curves in Figure 5. In addition, we use a cost of \$100,000 per unit of fishing effort to generate the total cost curve. Table 2 presents the sustainable yield, revenue, and cost, and a narrowly defined measure of overall net benefit for Case 1 and each of five levels of effort. The five levels of effort are those associated with:

1. MSY1,
2. MSY2,
3. MSYF,
4. maximum sustainable revenue for the fishery as a whole (MSRevF), and
5. OSY for the fishery as a whole (OSYF).

Because the same underlying sustainable yield functions are depicted in Figures 4 and 5, the E_{MSY1} and E_{MSY2} are 100 and 60, respectively, in both figures. In addition, because the only difference between the sustainable yield curves in Figure 4 and the sustainable revenue curves in Figure 5 is in their vertical scaling based on the ex-vessel price of each stock, the levels of fishing effort that maximize sustainable revenue for stocks 1 and 2 (E_{MSRev1} and E_{MSRev2}) are equal to E_{MSY1} and E_{MSY2}, respectively. Therefore, B_{MSY1} and B_{MSRev1} are equal; and B_{MSY2} and B_{MSRev2} are equal.

However, because the ex-vessel prices of the stocks differ, the levels of effort that maximize sustainable yield (E_{MSYF}) and sustainable revenue (E_{MSRevF}) for the fishery as a whole are not the same. In this example, a large difference in prices in favor of stock 2 resulted in a large difference between the E_{MSYF} of 92 and the E_{MSRevF} of 63, which is much closer to the E_{MSY2} of 60. Because E_{MSYF} is greater than E_{MSRevF}, B_{MSYF1} is less than $B_{MSRevF1}$, and B_{MSYF2} is less than $B_{MSRevF2}$. This example demonstrates that simply changing the objective from maximizing sustainable yield to maximizing sustainable revenue can substantially change the maximizing level of effort for the commercial fishery as a whole, and associated biomass target levels for both stocks.

The cost of fishing effort is considered in determining OSY levels of effort, catch, and biomass. In this example, the fishing effort that produces the OSY for the fishery as a whole (E_{OSYF}) is 54, because at this level of effort the slopes of the revenue and cost curves are equal (i.e., marginal revenue is equal to marginal cost). This is less than the E_{MSY2} of 60, the E_{MSRevF} of 63, the E_{MSYF} of 92, and the E_{MSY1} of 100. Therefore, B_{OSYF1} is greater than B_{MSY1}, and B_{OSYF2} is greater than B_{MSY2}. These results mean that, in this example, OSYF is a more conservative reference point than MSY and MSRev for the commercial fishery as a whole or than MSY1 and MSY2, and that MSRevF is a more conservative reference point than MSYF. In this example of two stocks that are caught together, OSY cannot be determined separately for stocks 1 and 2 because the same effort, and therefore the same cost, is associated with catching both stocks together.

Table 2. Sustainable yield, revenue, and cost, as well as a narrowly defined measure of overall net benefit, for Case 1 when MSY1, MSY2, MSYF, MSRevF, and OSYF levels of effort are applied jointly to both stocks In a two-stock fishery (catch in metric tons and both revenue and cost in millions of dollars).

Case 1	MSY1	MSY2	MSYF	MSRevF	OSYF
Fishing effort	**100**	**60**	**92**	**63**	**54**
Catch for stock 1	40,000	33,600	39,744	34,524	31,536
Catch for stock 2	2,000	3,600	2,576	3,591	3,564
Total catch	**42,000**	**37,200**	**42,320**	**38,115**	**35,100**
Revenue for stock 1	$4.0	$3.4	$4.0	$3.5	$3.2
Revenue for stock 2	$10.0	$18.0	$12.9	$18.0	$17.8
Total revenue	**$14.0**	**$21.4**	**$16.9**	**$21.4**	**$21.0**
Total cost	**$10.0**	**$6.0**	**$9.2**	**$6.3**	**$5.4**
Revenue - cost	**$4.0**	**$15.4**	**$7.7**	**$15.1**	**$15.6**

Notes:
MSY1 is the independently determined MSY for stock 1.
MSY2 is the independently determined MSY for stock 2.
MSYF is the MSY for the fishery as a whole when the interaction between the two stocks is considered.

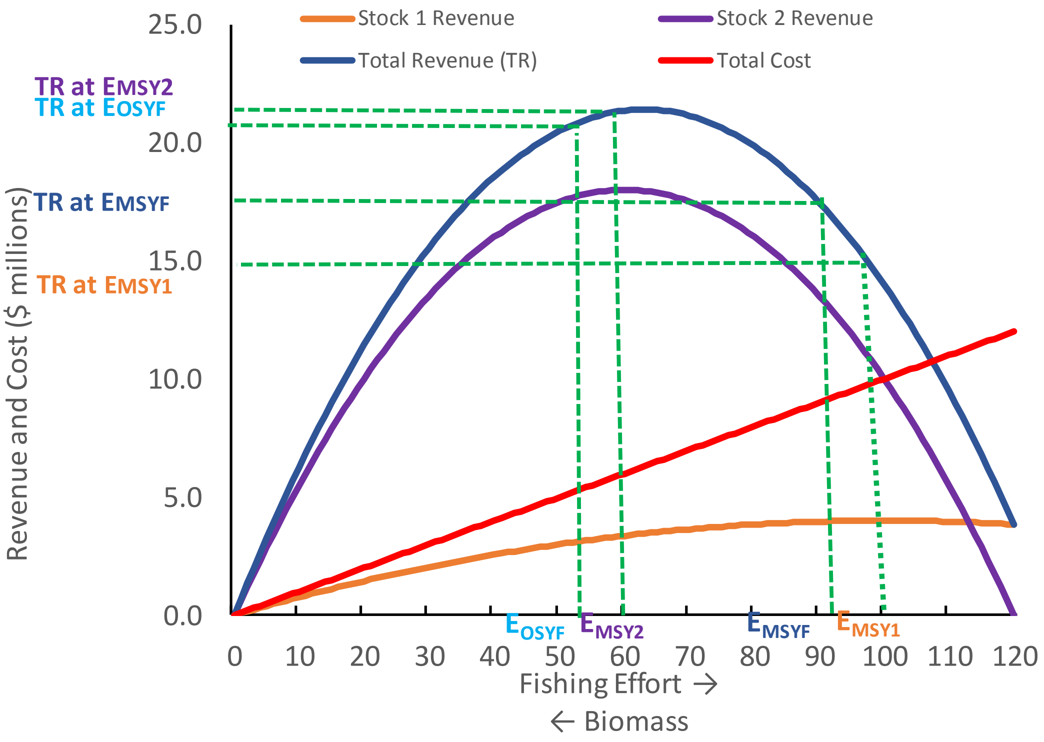
MSRevF is the maximum sustainable revenue for the fishery as a whole when the interaction between the two stocks is considered.

OSYF is the optimum sustainable yield for the fishery as a whole when the interaction between the two stocks is considered.

The sustainable revenue curves are based on ex-vessel prices of $100 and $5,000 per metric ton for stocks 1 and 2, respectively. A cost of $100,000 per unit of fishing effort was used to generate total cost.

To prevent the labeling in Figures 5 – 7 from becoming too complicated, only the levels of effort for MSY1, MSY2, MSYF, and OSYF and the associated levels of total sustainable revenue are labeled. However, because levels of both effort and biomass are arrayed on the horizontal axis, the positions of E_{MSY1}, E_{MSY2}, E_{MSYF}, and E_{OSYF} on that axis identify the corresponding positions of B_{MSY1}, B_{MSY2}, B_{MSYF}, and B_{OSYF}, respectively.

Figure 5. MSY and OSY for a two-stock fishery as a whole when the two stocks are caught together; the price of stock 2 is substantially greater than that of stock 1 (i.e., \$5,000 versus \$100 per metric ton); the cost of a unit of effort is \$100,000; and overall net benefit is narrowly defined (Case 1).



CASE 2

If the ex-vessel prices of stocks 1 and 2 are changed substantially in favor of stock 1 from \$100 to \$300 per metric ton and from \$5,000 to \$100 per metric ton, respectively, the E_{OSYF} increases from 54 to 58 and the E_{MSRevF} increases from 63 to 97. However, because the sustainable yield curves do not change, the E_{MSYF} of 92, the E_{MSY1} of 100, and the E_{MSY2} of 60 do not change (Table 3 and Figure 6). Therefore, in this case, $E_{OSYF} < E_{MSY2} < E_{MSYF} < E_{MSRevF} < E_{MSY1}$. This means that, as in Case 1, $B_{OSYF1} > B_{MSY1}$ and $B_{OSYF2} > B_{MSY2}$. Therefore, in both Case 1 and Case 2, OSYF is a more conservative reference point than the MSY and MSRev for the fishery as a whole, MSY1, and MSY2. However, Case 2 differs from Case 1 in that MSRevF is a less conservative reference point than MSYF.

Table 3. Sustainable yield, revenue, and cost, as well as a narrowly defined measure of overall net benefit, for Case 2 when MSY1, MSY2, MSYF, MSRevF, and OSYF levels of effort are applied jointly to both stocks in a two-stock fishery (catch in metric tons and both revenue and cost in millions of dollars).

Case 2	MSY1	MSY2	MSYF	MSRevF	OSYF
Fishing effort	**100**	**60**	**92**	**97**	**58**
Catch for stock 1	40,000	33,600	39,744	39,964	32,944
Catch for stock 2	2,000	3,600	2,576	2,231	3,596
Total catch	**42,000**	**37,200**	**42,320**	**42,195**	**36,540**
Revenue for stock 1	$12.0	$10.1	$11.9	$12.0	$9.9
Revenue for stock 2	$0.2	$0.4	$0.3	$0.2	$0.4
Total revenue	**$12.2**	**$10.4**	**$12.2**	**$12.2**	**$10.2**
Total cost	**$10.0**	**$6.0**	**$9.2**	**$9.7**	**$5.8**
Revenue - cost	**$2.2**	**$4.4**	**$3.0**	**$2.5**	**$4.4**

Notes:

MSY1 is the independently determined MSY for stock 1.

MSY2 is the independently determined MSY for stock 2.

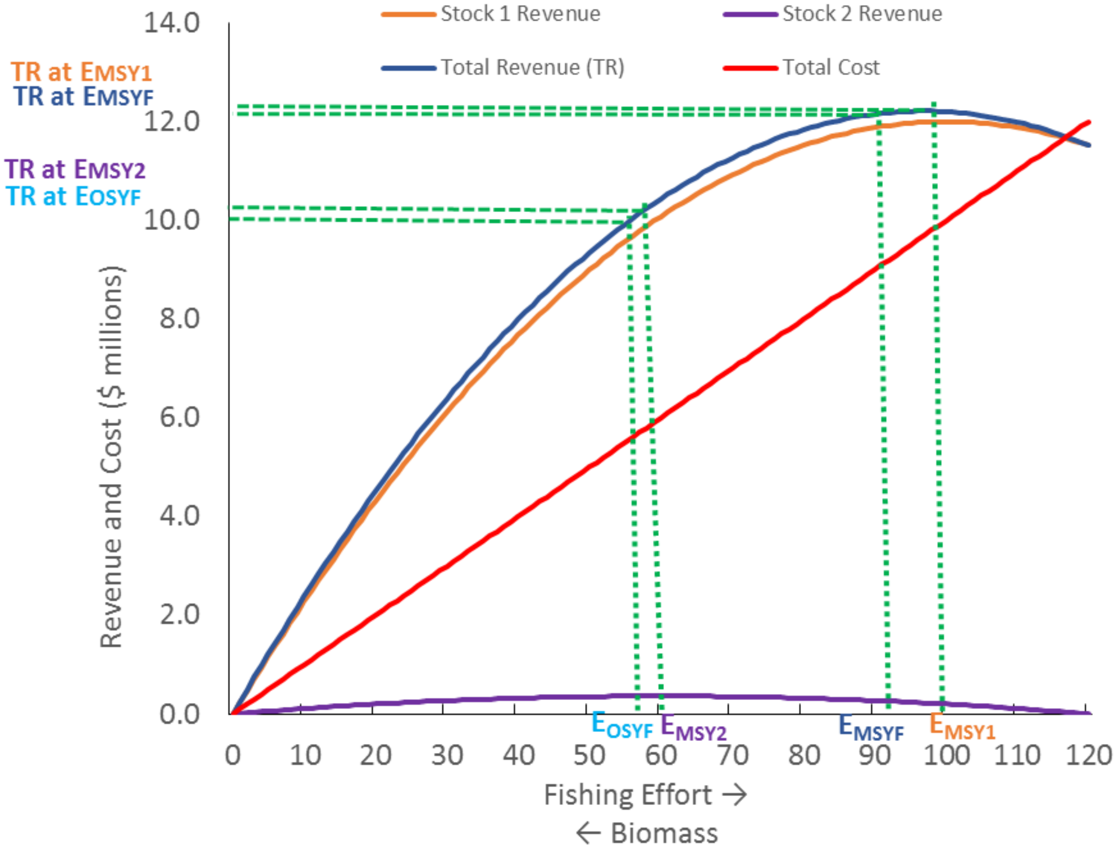
MSYF is the MSY for the fishery as a whole when the interaction between the two stocks is considered.

MSRevF is the maximum sustainable revenue for the fishery as a whole when the interaction between the two stocks is considered.

OSYF is the optimum sustainable yield for the fishery as a whole when the interaction between the two stocks is considered.

The sustainable revenue curves are based on ex-vessel prices of $300 and $100 per metric ton for stocks 1 and 2, respectively. A cost of $100,000 per unit of fishing effort was used to generate total cost.

Figure 6. MSY and OSY for a two-stock fishery as a whole when the two stocks are caught together, the price of stock 1 is greater than that of stock 2 (i.e., $300 versus $100 per metric ton), and the cost of a unit of effort is $100,000 (Case 2).



CASE 3

In Case 3 (Table 4 and Figure 7), the ex-vessel prices are the same as in Case 2, but the cost per unit of effort is decreased from $100,000 to $75,000. In this case, E_{OSYF} increases to 68, but because the sustainable yield and revenue curves are the same as for Case 2, the E_{MSRevF}, E_{MSY1}, E_{MSY2}, and E_{MSYF} remain at the same levels. Therefore, for Case 3, $E_{MSY2} < E_{OSYF} < E_{MSYF} < E_{MSRevF} < E_{MSY1}$. Consequently, $B_{OSYF1} > B_{MSY1}$ but $B_{OSYF2} < B_{MSY2}$. Thus, in Case 3, OSYF is a more conservative reference point than MSRevF, MSYF, and MSY1, but it is a less conservative reference point than MSY2. This means that there are trade-offs among MSYs for the two stocks, the MSY for the fishery as a whole, and the OSY for the fishery as a whole. Therefore, a choice needs to be made among the reference points that will support MSY for stock 1, MSY for stock 2, and MSY or OSY for the fishery as a whole.

As noted in Section 3.3, the NS1 Guidelines recognize the importance of the concept of aggregate MSY for a group of or all the stocks in a fishery. However, the NS1 Guidelines do not address the use of reference points related to aggregate MSY or OSY as alternatives to independently determined and stock-specific reference points when the former are associated with greater effort and, consequently, lower biomass for one or more stocks.

Table 4. Sustainable yield, revenue, and cost, as well as a narrowly defined measure of overall net benefit, for Case 3 when MSY1, MSY2, MSYF, MSRevF, and OSYF levels of effort are applied jointly to both stocks in a two-stock fishery (catch in metric tons and both revenue and cost in millions of dollars).

Case 3	MSY1	MSY2	MSYF	MSRevF	OSYF
Fishing effort	**100**	**60**	**92**	**97**	**68**
Catch for stock 1	40,000	33,600	39,744	39,964	35,904
Catch for stock 2	2,000	3,600	2,576	2,231	3,536
Total catch	**42,000**	**37,200**	**42,320**	**42,195**	**39,440**
Revenue for stock 1	$12.0	$10.1	$11.9	$12.0	$10.8
Revenue for stock 2	$0.2	$0.4	$0.3	$0.2	$0.4
Total revenue	**$12.2**	**$10.4**	**$12.2**	**$12.2**	**$11.1**
Total cost	**$7.5**	**$4.5**	**$6.9**	**$7.3**	**$5.1**
Revenue - cost	**$4.7**	**$5.9**	**$5.3**	**$4.9**	**$6.0**

Notes:

MSY1 is the independently determined MSY for stock 1.

MSY2 is the independently determined MSY for stock 2.

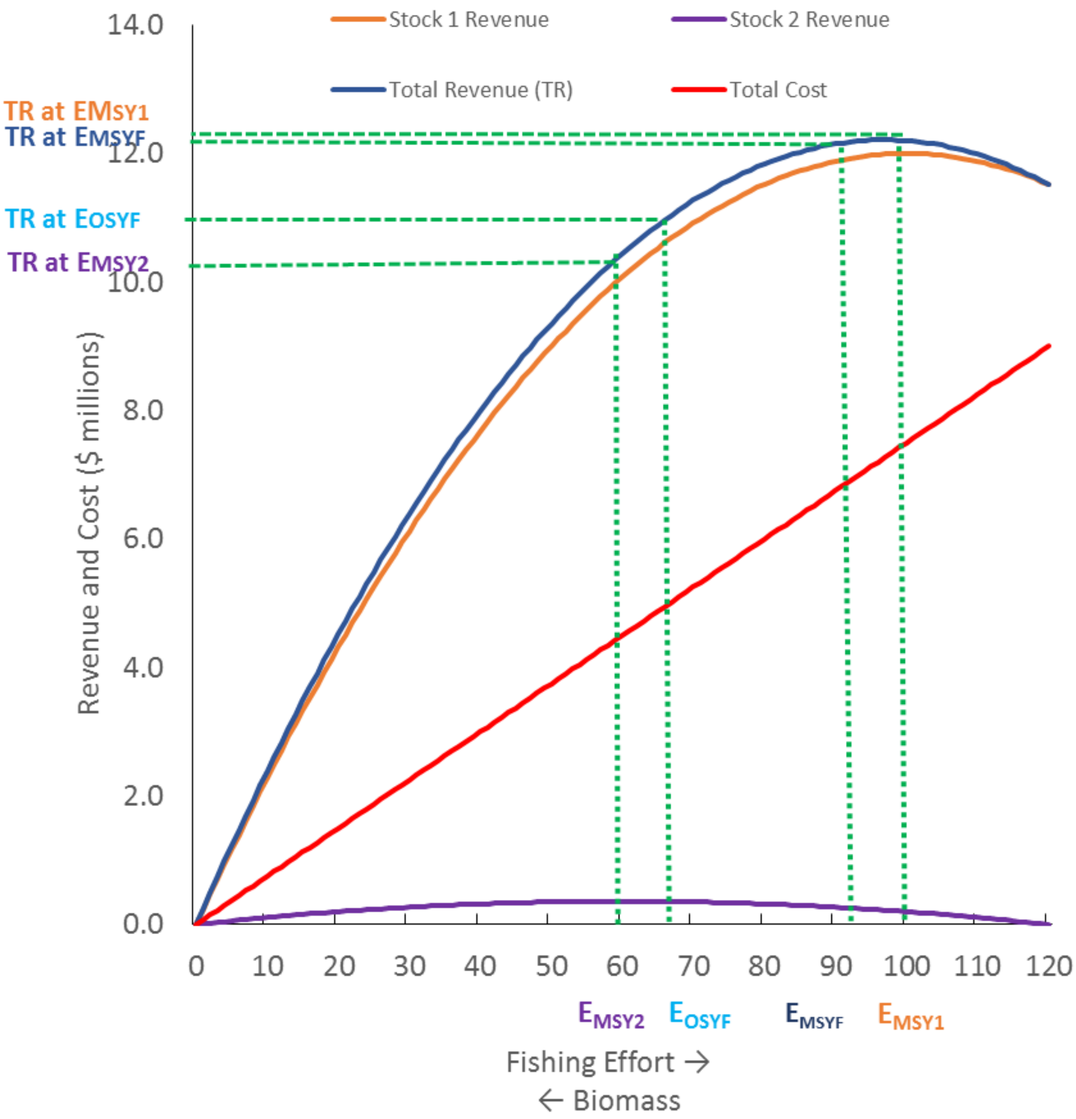
MSYF is the MSY for the fishery as a whole when the interaction between the two stocks is considered.

MSRevF is the maximum sustainable revenue for the fishery as a whole when the interaction between the two stocks is considered.

OSYF is the optimum sustainable yield for the fishery as a whole when the interaction between the two stocks is considered.

The sustainable revenue curves are based on ex-vessel prices of $300 and $100 per metric ton for stocks 1 and 2, respectively. A cost of $75,000 per unit of fishing effort was used to generate total cost.

Figure 7. MSY and OSY for a two stock fishery as a whole when the two stocks are caught together, the price of stock 1 is greater than that of stock 2 (i.e., \$300 vs. \$100 per metric ton), and the cost of a unit of effort is reduced to \$75,000 (Case 3).



APPENDIX 6. Catchability: A Critical Parameter in Stock Assessment and Bioeconomic Models

Catchability is a critical parameter in most stock assessment and bioeconomic models. It is the parameter (either a constant or variable) that relates an index of relative abundance to population size (absolute abundance). Equivalently, it is the proportionality parameter between fishing effort and fishing mortality—or the portion of the stock captured by one unit of effort where CPUE, based on fishery-dependent or fishery-independent data,[27] is the index of relative abundance (Wilberg et al., 2010).

In addition to these definitions of catchability, Wilberg et al. (2010) provide a useful review of the theory and evidence for time-varying catchability, its effects on stock assessment estimates, and methods of including time-varying catchability in stock assessments. Their review indicates that there is strong evidence that time-varying catchability is common for most fisheries in which fishery-dependent data are used to estimate CPUE, as well as for many fisheries in which fishery-independent survey data are used to estimate CPUE. Wilberg et al. state that trends in catchability over time can cause biased estimates of stock size and fishing mortality rates in stock assessment models that do not compensate for such trends. They therefore recommend that time-varying catchability be assumed and that multiple methods of including it be applied.

With few, if any, exceptions, CPUE is estimated with fishery-dependent data or fishery-independent data for only part of the range of a stock, and fishing and surveying locations are not randomly selected. Fishermen use a variety of criteria (e.g., convenience, familiarity, expected costs and revenue, and safety) to decide which areas to fish and which to avoid. Similarly, various factors determine which areas are surveyed. For example, surveys are less likely to occur in areas that cannot be surveyed successfully with available survey gear and in areas that are too expensive to survey. If fish do not behave the same in both fished and unfished areas, or in both surveyed and unsurveyed areas, CPUE estimates will be biased, and changes in actual population size will not be proportional to changes in CPUE (i.e., catchability is not constant). Even if data were available for the whole population, other factors can explain why catchability would not be constant or, equivalently, why there is a nonlinear relationship between the index (CPUE) and the actual population.

Hannesson (1983),[28] Squires and Vestergaard (2015), Hilborn and Walters (1992), Walters (2003), and Wilberg et al. (2010) address the implications of density-dependent catchability. For example, if there are area-specific differences in fish density, density-dependent catchability contributes to the problems associated with not having CPUE data for the entire range of a stock and is one reason there is a nonlinear relationship between the index (CPUE) and the actual population. The explanations of density-dependent catchability include the following: 1) Gear saturation can occur in some areas; 2) Fish behavior can include density-dependent gear avoidance; and 3) As a stock's size changes, its spatial and intra-annual distributions can change.

Density dependence is just one reason catchability can vary over time. Changes in environmental, biological, and management processes may also drive changes in catchability, in part by affecting how,

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[27] Fishery-dependent data are collected from fishing vessels during normal fishing operations as opposed to fishery-independent data that are, for example, collected during a scientific survey cruise.

[28] Hannesson (1983) is the earliest, theoretically rigorous economics paper on time-varying and density-dependent catchability we are aware of. However, it was not the first paper on this topic. For references to other papers on this topic, see Wilberg et al. (2010).

when, where, and by whom fish are caught (Hannesson, 1983; Wilberg et al., 2010; Vestergaard and Squires, 2013 and 2015).

If catchability increases as abundance declines—because of density dependence or other reasons—CPUE can remain high despite decreases in abundance. This condition can cause hyperstable CPUE. If a stock assessment model does not account for this increase in catchability, the hyperstable CPUE masks a decline in stock abundance and thus contributes to overfishing and increased chances of the stock becoming overfished. However, when a stock is actually recovering, hyperstable CPUE understates the rate and level of recovery and can unnecessarily prolong the use of relatively low quotas. Conversely, if CPUE decreases more rapidly than stock size, catchability exhibits hyperdepletion (Wilberg et al., 2010).

Sources of time-varying catchability that tend to increase catchability over time become increasingly problematic if they are not accounted for in stock assessment and bioeconomic models. In the remainder of this appendix, we discuss one source of time-increasing catchability: increases in productivity resulting from technical change and increased technical efficiency. However, many of our conclusions apply to other sources of increases in catchability over time.

Various problems can arise by excluding technological change and increased technical efficiency from stock assessment and bioeconomic models. First, when stock assessments are based principally on fishery-dependent CPUE data, and the effects of technological change and increased technical efficiency are not fully accounted for, those changes are a source of increasing upward bias in estimates of population size. Second, if effort controls are the principal management tools used to control catch, and if technological change and increased technical efficiency are not fully accounted for, the resulting effort controls will be inadequate and catch will be too high.

Finally, technological change and increased technical efficiency tend to affect OSY and OYT by decreasing the cost of harvesting, processing, and marketing fish. These factors may also increase product quality and therefore the prices of fish and seafood products.[29] When technological change and increased technical efficiency lower the costs of harvest, leaving fish in the water to lower harvest costs (the traditional marginal stock effect) becomes less important. Moreover, not accounting for technological change and increased technical efficiency creates an opportunity cost of forgone resource rent and consumer benefit that increases over time. Therefore, accounting for technological change, increased technical efficiency, and other factors that will change over time is necessary for effective fishery management.

For example, technological change and increased technical efficiency affect the rent-maximizing levels of resource stocks, and can cause dynamic B_{MEY} to be less than B_{MSY}. This result is counter to the conclusions that: 1) Dynamic B_{MEY} or B_{OYT} is greater than B_{MSY} when technological change and increased technical efficiency are not accounted for; and 2) Static equilibrium B_{OSY} is greater than B_{MSY} (Squires and Vestergaard, 2013 and 2015). Technological change and increased technical efficiency lower the costs of finding and harvesting fish over time, and therefore decrease the benefit of leaving unharvested fish in the water to lower costs. The distance between dynamic B_{MEY} and B_{MSY} is determined by the rate of intrinsic growth, the discount rate, and the rates of technological change and increases in technical efficiency. The marginal stock effect has no impact on the final result, and affects only the approach path to dynamic B_{MEY}, which is determined by biological and economic parameters.

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[29] Other effects of technological change and increased technical efficiency (beyond decreasing harvesting costs) affect OSY and OYT but do not affect catchability.

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