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Editor's Choice
Food for thought: pretty good multispecies yield

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MSY principles for marine fisheries management reflect a focus on obtaining continued high catches to provide food and livelihoods for humanity, while not compromising ecosystems. However, maintaining healthy stocks to provide the maximum sustainable yield on a single-species basis does not ensure that broader ecosystem, economic, and social objectives are addressed. We investigate how the principles of a "pretty good yield" range of fishing mortalities assumed to provide >95% of the average yield for a single stock can be expanded to a pretty good multispecies yield (PGMY) space and further to pretty good multidimensional yield to accommodate situations where the yield from a stock affects the ecosystem, economic and social benefits, or sustainability. We demonstrate in a European example that PGMY is a practical concept. As PGMY provides a safe operating space for management that adheres to the principles of MSY, it allows the consideration of other aspects to be included in operational management advice in both data-rich and data-limited situations. PGMY furthermore provides a way to integrate advice across stocks, avoiding clearly infeasible management combinations, and thereby hopefully increasing confidence in scientific advice.

Keywords: economic objectives, ecosystem objectives, MEY, mixed-fisheries, operationalizing MSY, social objectives.

Introduction

The concept of maximum sustainable yield (MSY) was developed in the 1930s–1950s. In 1982, when MSY was incorporated in the United Nations Convention on the Law of the Sea, it became a global standard for managing fish stocks and fisheries. This, and the negotiations and other agreements leading up to it, resulted in the incorporation of MSY into progressively more national, regional, and international fisheries policies and legislation, including the original US Magnuson Fishery Conservation and Management Act of 1976, the New Zealand Fisheries Act of 1983, and most regional fisheries management organizations, among others. Further affirmation of MSY as the overarching fisheries objective by the 2002 Johannesburg World Summit on Sustainable Development meant that the principle was subsequently developed by the EU and written into the reformed EU Common Fisheries Policy (EU, 2013). Harvesting at or below the single-species F_{MSY} (the fishing

mortality that delivers MSY on average) is a commonly accepted fisheries objective, and many current management regimes have been built around this framework (Mace, 2001; Worm *et al.,* 2009; Dichmont *et al.,* 2010; ICES, 2014a).

The MSY principles reflect a focus on obtaining continued high catches by controlling fishing mortality to benefit the productivity of fish stocks and society in general. Fisheries management in most jurisdictions, however, has objectives other than just maximizing sustainable output. These include social objectives such as maintaining regional communities or supporting traditional lifestyles, economic objectives such as ensuring profitability, and, often, governance objectives such as ensuring flexibility or minimizing management transaction costs. In addition, there are often additional conservation objectives such as reducing the impact of fishing on key habitats or the catch of protected species.

While maximizing sustainable yield and maintaining healthy stocks addresses stock-specific aspects of sustainability, it does not address the issue that the maximum ecological, economic, or social benefit may not occur at F_{MSY} (Zabel *et al.,* 2003; Anderson *et al.,* 2015; Hilborn *et al.,* 2015) nor does it ensure sustainability in the wider interpretation, encompassing all four pillars of ecosystem, economic, social, and institutional or governance sustainability (Charles, 1994; Garcia *et al.,* 2003). While the concept of maximum social yield—which explicitly captures trade-offs between social, economic, and ecological sustainability—has been in existence since the mid-1980s (Charles, 1988), such a target has never been clearly defined and quantified (and probably varies substantially among fisheries).

The concept of "pretty good yield" (PGY) was introduced by Alec MacCall (National Marine Fisheries Service, Santa Cruz, CA, USA, retired) and further explored by Ray Hilborn in recognition that "a range of harvest policies provide good yield while also producing other desired outputs, be they biological or economic" (Hilborn, 2010). Hilborn (2010) showed that yield in a single-stock context varies comparatively little with fishing mortality near the equilibrium MSY for many population growth curves. Selecting a target fishing mortality rate within the range of PGY adheres to the principle of maximization of sustainable yield while allowing consideration of other aspects to be included in decision-making. Recently, such single-species ranges have been explored by the European Commission and the International Council for the Exploration of the Sea (ICES) for potential implementation in long-term management plans (e.g. ICES, 2015a). The fraction of MSY used to define PGY describes the degree to which it is possible to trade-off one objective (the maximization of yield) to achieve other objectives. Given the flatness of many yield curves (Pope, 1983; Hilborn, 2010), allowing ranges of fishing mortality down to 80% of MSY, as initially explored by Hilborn (2010), seems to provide a very large space within which to operate. ICES (2014b), therefore, opted for 95% of MSY. Lower percentages are unlikely to be precautionary (indeed, the 95% upper range is often not; Rindorf *et al.,* 2017), but a solution to this may be to use asymmetrical percentages setting the "lower F_{MSY}" at, for example, that corresponding to 95% of MSY and the "upper F_{MSY}" corresponding to 98% of MSY or more.

Harvested species do not exist in isolation. The catch of one species affects catches of other species through technical interactions in the fishing process, predator–prey interactions, and environmental drivers, leading to changes to stocks other than the fishery target. In mixed-fisheries, single-species MSY cannot be obtained for all or even most species at a time (Hilborn *et al.,* 2015). This

can lead to a dilemma between maximizing profits and ensuring the sustainability of less-productive stocks. The principle of halting all fishing when the catch of the least-productive stock reaches its F_{MSY}-based TAC leads to a low impact on the least-productive species, but may also lead to substantial economic and social losses. It is estimated that >50% of the potential seafood production in the North Sea, Iberian Sea, US west coast, and south-eastern Australia trawl fisheries would be lost if fishing mortality for all species in mixed-species fisheries were constrained to levels below F_{MSY} (Hilborn *et al.,* 2012; Fulton *et al.,* 2014; ICES, 2015b; Gourguet *et al.,* 2016), though this loss in volume is not necessarily accompanied by an equivalent loss in economic yield (Dichmont *et al.,* 2010). While maximum economic yield generally involves fishing mortality levels less than F_{MSY}, achieving overall economic benefits in mixed-fisheries may require some (mainly low productivity) species to be fished at higher fishing mortality rates relative to their F_{MSY} (Pascoe *et al.,* 2015). While economically beneficial, and consistent with maintaining sustainability of the more productive and valuable stocks, high rates of fishing mortality on the less-productive stocks may be risky.

Species interact through biological processes in addition to technical interactions. The level of fishing that leads to MSY of prey species depends on the level of fishing imposed on prey, predators, and competitors (Gislason, 1999; Collie *et al.,* 2003; Jacobsen *et al.,* 2014). Further, the productivity of predators depends on the abundance of prey, competitors, and predators (Frederiksen *et al.,* 2005; Cury *et al.,* 2011). Therefore, the "ecosystem sustainable harvest rate" for a given species depends on that exerted on other species. For example, if high fishing pressure is exerted on one prey species, it may be preferable to be more precautionary in the exploitation of other prey species to ensure that the total amount of forage is sufficient to service higher trophic levels (Shephard *et al.,* 2014; Trenkel *et al.,* 2015). Other examples are the desire to ensure biodiversity indices above agreed levels (Levin *et al.,* 2009; Samhouri *et al.,* 2010) and the possibility of more prey fish when predator abundance is low (Frank *et al.,* 2005; Jacobsen *et al.,* 2014). The levels at which each stock is sustained can have substantial economic implications if the economic value of the predator and prey species differs widely (Voss *et al.,* 2014), leading to recent suggestions of balanced harvesting rather than targeted harvesting (Zhou *et al.,* 2010).

Several management objectives do not manifest themselves in terms of a target or desired catch level, and hence are not influential in determining "pretty good multispecies yield" (PGMY) (Table 1). Institutional objectives, where they exist, are largely concerned with ensuring that fisheries management is delivered efficiently and cost-effectively, minimizing transactions costs, ensuring mechanisms are in place to encourage compliance, ensuring systems are adaptive, and providing a mechanism for stakeholder involvement in the management process (Hanna, 1999; Jennings *et al.,* 2016). Some social and economic objectives relate to the distribution of access and benefits, regional economic performance, and fishery participation.

We investigate how the principles of a PGY range of fishing mortalities in a single-species context can be expanded to a PGY space to accommodate a multispecies situation (PGMY), where the yield from one stock affects the yield from, or sustainability of, other parts of the ecosystem. We discuss how a PGMY space can be implemented operationally in management advice in the European system both when a "sustainable space" exists and where no options are sustainable under all sustainability pillars.

Table 1. Potential impact of management objectives on PGY.

Example objectives	Effect on PGY targets
Ecological	
Sustainability of commercial stocks	⬛
Sustainability of non-target stocks	
Exploitation of forage fish compatible with species interactions	
Biodiversity	⬜ (grey)
Habitat impacts	
Economic	
Vessel/fleet profitability	⬛
Processor/supplier profitability	
Sustainable livelihoods	
Regional economic benefits to communities	
Social	
Low variability in catch advice	⬛
Employment in the fishing sector	
Associated onshore employment	
Equitable access to the resource	⬜ (grey)
Minimize conflicts with competing users	
Respect customary fishing	
Enhance community resilience	
Improve quality of life in coastal communities	
Governance/institutional	
Political	⬜ (grey)
Food security	
Foreign exchange generation	
Charter fishing/recreational use	
Legal obligations	
Good governance structure	
Effective decision-making	

Generally affects PGY targets: ⬛; potentially affects PGY targets: ▦; and generally does not affect PGY targets: □.

We conclude by providing advice on the likely trade-offs encountered in different parts of the PGMY space and considering what the potential is to expand the idea to other jurisdictions.

Principles of PGMY

We keep the original premise of MacCall that a large fraction of MSY can be obtained for a wide range of fishing mortality rates. However, rather than suggesting that all values within the PGY range of an individual stock can be used in combination with all values in PGY ranges of other stocks, the determination of the combined fishing mortality ranges of all fished stocks is restricted to enhance stock, ecosystem, economic, and possibly social sustainability in accordance with the idea of the "minimum sustainable whinge", outlined by Pope (1983). We suggest, as a starting point, defining the PGMY space as the combinations of fishing mortalities for individual stocks that provide >95% of the yield for that stock in a single-species analysis (with the underlying assumption that stocks can be targeted individually, following ICES, 2014b), but excluding combinations of fishing mortalities for individual stocks which have a greater-than-agreed risk of resulting in an ecosystem state beyond agreed reference points. Clearly, the choice of the actual percentage is a policy decision rather than a scientific option.

The variable F_{MSY} differs between species, and the differences are rarely matched exactly by differences in catchability. Because of this, managing fishing on one stock to F_{MSY} generally leads to other stocks experiencing fishing mortalities that differ from their respective F_{MSYS}. These technical interactions can be accommodated, to the

extent possible under the jurisdictions' policy arrangements, by using a fishing mortality at the high end of the PGY F-range for some species and using a fishing mortality at the low end of the PGY F-range for others. Within the PGY range, all yields are close to MSY and hence the likelihood of achieving close to MSY for all stocks is greater. Simply fishing all stocks at the upper bound of their single-species PGY F-range could deleteriously affect ecosystem status, as the problem of incompatible production rates will remain, though now at lower biomass and higher fishing effort. This may occasionally satisfy short-term societal goals such as maintaining employment. However, such a strategy, if maintained over longer periods, leads to lower economic yield. Fishing mortality combinations that result in agreed undesirable ecosystem effects are excluded from the suggested PGMY space (Figure 1). The excluded combinations include high fishing mortalities on prey species when seeking to maintain the forage biomass for predators, fishing mortalities known to be incompatible with the desire to limit bycatch of sensitive species such as seabirds, and fishing mortalities known to be incompatible with technical interactions, e.g. combinations of high and low fishing mortalities of stocks caught by the same fishery.

The multispecies yield space in a two-species theoretical example (Figure 2) is loosely based on the relationships between cod (*Gadus morhua*) and haddock (*Melanogrammus aeglefinus*) in the greater North Sea and compatible with an assumption of nearly constant fleet structure over the period considered (Murawski and Finn, 1986). The species chosen are interlinked biologically, because cod is a predator on juvenile haddock, and also technically though mixed-trawl fisheries catching both species. Consequently, there are combinations of low fishing mortality on cod, and hence resulting in higher natural mortality of haddock, which are not compatible with high fishing mortality on haddock (pretty good ecosystem yield, PGEY; Figure 2a). This comparison presupposes that the single-species, technical-analysis model, and multispecies models are comparable (e.g. that the estimates of natural mortality for the single-species model come in some way from a multispecies model), as is true for, e.g. North Sea cod and northern shelf haddock (ICES, 2015c). Technical interactions are strong in this example (Figure 2b), and only combinations where the difference in fishing mortalities of the two species is small are feasible in the mixed-fisheries for these species unless substantial changes in fleet composition take place.

Pretty good multispecies economic yield

We could account for economic considerations in PGMY as the combinations of fishing mortality rates where the total profit of the fishery exceeds a minimum specific proportion of MEY. This would be required where clear economic objectives exist, such as achieving MEY for Australian Commonwealth fisheries. Ranges of fishing mortality can be further restricted by agreed limits to sustainability such as minimum revenue in the upcoming one or more years. For example, in the cod/haddock example, cod is more valuable than haddock; therefore, the pretty good multispecies economic yield (PGMEY) space is biased towards lower fishing mortalities for haddock, because having a high fishing mortality on haddock incurs higher opportunity costs (in terms of reduced cod catches) than the value gained (Figure 2c).

Pretty good social yield

Of the many possible objectives that could be included in the concept of PGY and PGMY, not all can be directly articulated into
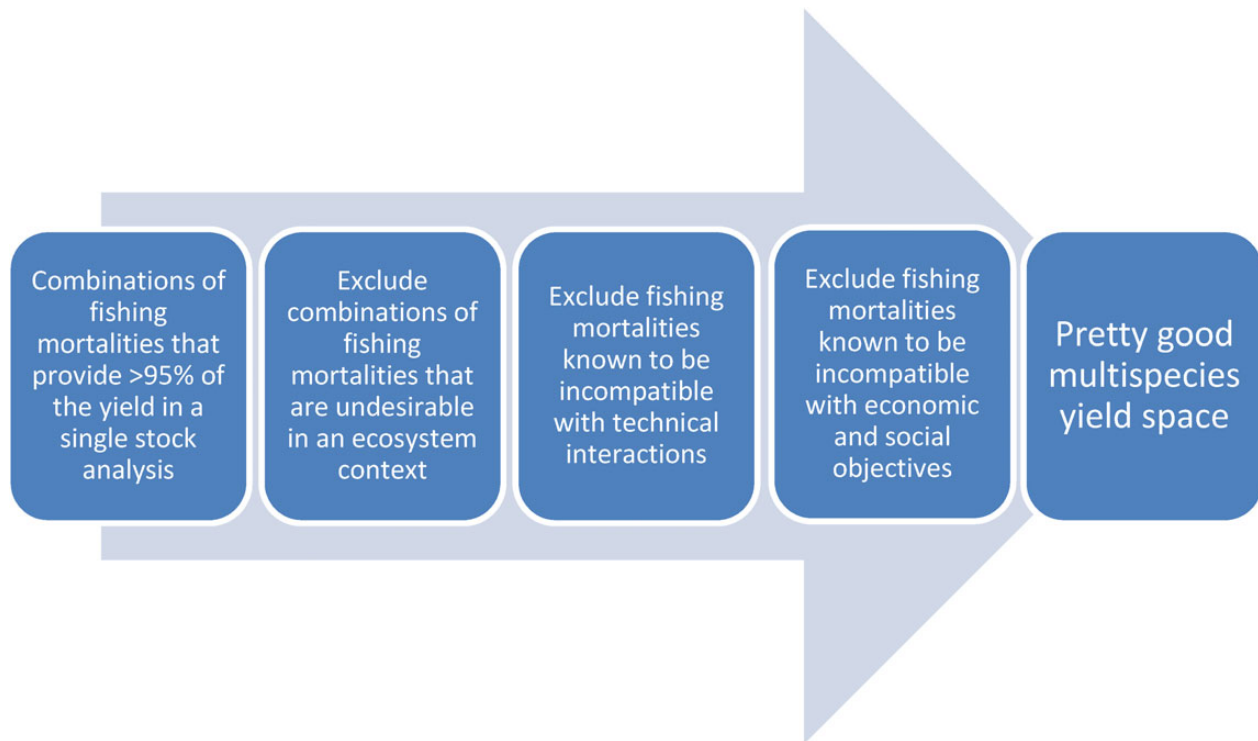
Figure 1. The stages in defining PGMY.

factors that could be included in the calculation of PGY or PGMEY. Instead, some would affect how the TAC was distributed or other controls such as when or where the catch can be taken (Table 1). Social yield would be expected to be less dependent on long-term fishing mortalities and more dependent on, for example, year-to-year variation in yield. An example of short-term social considerations that may affect the PGMY may be to keep the catch opportunities similar to those from previous years. Other social factors, such as distributional issues, may not directly affect the target yield, only how it is administered. Similarly, most governance objectives would not directly affect the target yield, only how it was taken (Table 1).

There are likely several ways of defining the pretty good social yield (PGSY) space by generalizing the PGMY approach (see Pope, 1983). However, it is clear that the addition of further objectives may narrow the sustainable space to the point where no set of fishing mortalities exists that satisfies all objectives. For example, while the options that meet social objectives, such as maximizing employment at the same time as ensuring all participants can make an adequate living, may be a desirable objective, it may not be compatible with other objectives. This can also be seen in our example, where the space defined by the hatched green area in Figure 2 is less than that defined by the solid green area. If articulated, it is possible that social considerations can be included to further reduce the PGMY space, as suggested in Figure 3, but more often, social objectives can be achieved through other means, such as which policy instruments are implemented.

Tactical and strategic PGMY considerations

MSY and hence PGY are, by definition, long-term strategic goals. However, tactical (short-term) considerations are also important when implementing MSY approaches. Fishing mortality within

the PGY F-range may be too high at a given point in time if the stock has experienced a series of years of poor recruitment or poor individual growth. Similarly, social indicators aiming to provide long-term benefits to local communities rely on those communities still existing when the benefits can be harvested. Hence, the implementation of PGMY requires both a strategic long-term component and a tactical shorter term component, with the strategic step of identifying the PGMY space and the tactical decision related to where to operate within that space. In some cases, tactical considerations will mean that it is impossible to find short-term solutions within the PGMY space (Figure 4).

Operational implementation of pretty good multispecies multiobjective yield in the European system

The overarching fishing objective of the European Common Fisheries Policy (CFP) is to exploit stocks at levels compatible with long-term maximum yield [Article 2 (2), EC, 2013] while remaining precautionary in management [Preamble (10) EC, 2013] and ensuring that fisheries management is consistent with the objectives of achieving economic, social, and employment benefits and of contributing to the availability of food supplies [Article 2 (1), EC, 2013]. The latest revision to the policy gradually implements a discard ban in all European fisheries (EC, 2013). Under this ban, discarding fish of any size from stocks with official quota regulations will not be allowed, and all catch must be landed and counted against the TAC for the stock. This has greatly increased the attention given to mixed-fisheries aspects as there are several fisheries where large percentages of yield will be lost if fishing has to cease once the first TAC is exhausted. The European Commission has previously given priority to economic short-term considerations over ecosystem sustainability through the practice of
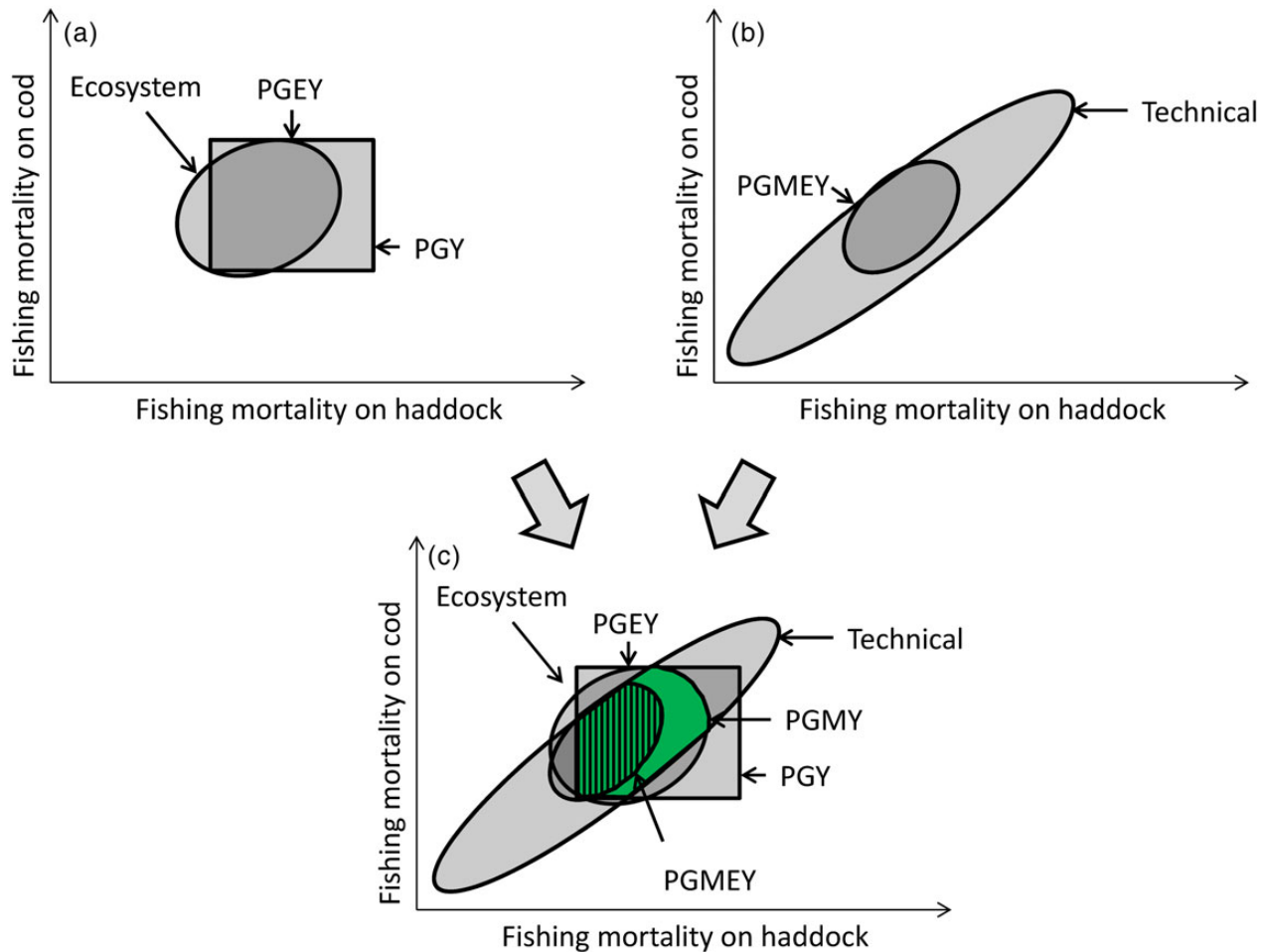
Figure 2. Hypothetical PGMY and PGMEY space for two groundfish species caught in a mixed fishery, loosely based on the relationships between cod and haddock in the greater North Sea. The two species are interlinked biologically and technically as cod is a predator on juvenile haddock and mixed-trawl fisheries target both species. Combinations of fishing mortality leading to PGMY (the space consistent with PGY and ecosystem considerations in (a) and technical interactions for the two species in (b) are indicated. The combinations of fishing mortality rates where the total profit of the fishery exceeds a minimum specific proportion of MEY (PGMEY, striped). Shaded forms indicate the areas of desirable multispecies or ecosystem combinations, technical interactions, and the single-species PGY that is compatible with maintaining stocks above biomass limits. It is assumed that the desirable area is defined elsewhere. However, if this is not the case, similar figures can be plotted giving isopleths rather than single shapes for each consideration as done here.

providing single-species TACs where catches of stocks for which TACs were exhausted were legally required to be discarded. Under this previous system, all disadvantage caused by technical interactions was carried by the less-productive stocks, and there was no incentive to avoid them. An economic loss provides substantial incentive on behalf of the fishery to avoid the less-productive species in landings. As this can be ensured either by avoiding the catch of the species or through illegally discarding catches, the system is likely to require a high-intensity control system. One way to limit this is to change the advice for all stocks to avoid clearly infeasible combinations (e.g. high fishing mortality combined with low fishing mortality for two species caught in mixed-fisheries). However, the exact definition of infeasible combinations requires consideration, as it is essential to retain the incentives for the fishery to release more yield by being more selective in fishing or by changing fleet composition (Murawski and Finn, 1986).

The thoughts of the European Commission on how to implement the F_{MSY} approach in the ICES Area under the new CFP have been clarified as fishing mortalities leading to 95% of MSY (EU, 2014: ICES, 2014a; STECF, 2015). Species identified as non-target species are limited by the need to ensure that their exploitation rates are sustainable, but without reference to maximization of yield. This decision to implement PGY ranges has led to concern that, if all TACs are calculated based on the upper end of the F_{MSY} ranges, mixed-fisheries problems will persist at higher levels of fishing mortality, with the result being continued discarding, similar or reduced catch, reduced stock size, and higher operating costs (STECF, 2015). Fortunately, considerable scientific effort has already been dedicated to identifying the effect of different combinations of fishing mortality on the expected catch (ICES, 2015d,e; Ulrich *et al.*, 2017) and identifying operational indicators for ecosystem effects of fishing (ICES, 2014c, 2015f). Agreed economic and social objectives and indicators have yet to be specified, but as a first step, advice can be given on general aspects such as the directional change of effort and hence employment and economic yield.
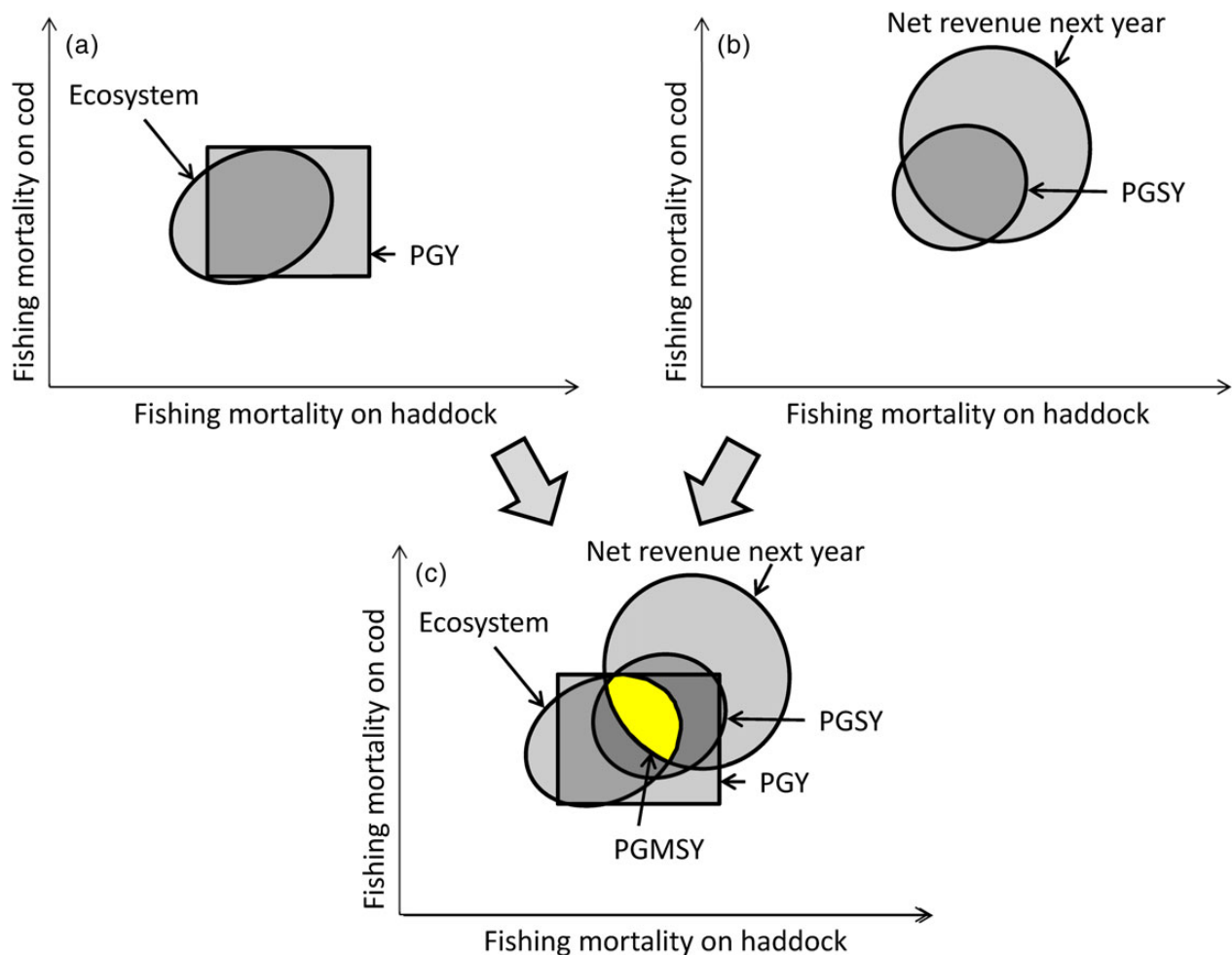
Figure 3. PGY and ecosystem space (a), pretty good social yield (PGSY) space (b), and pretty good multiobjective yield (PGMSY) (c) for two groundfish species caught in a mixed fishery. Shaded forms indicate the area of the single-species PGY that is compatible with maintaining specific requirements such as stocks above biomass limits, desirable multispecies, or ecosystem combinations, the social objective to keep net revenue relatively stable between years and "pretty good" social yield (PGMSY).

In this context, advice on annual catch including ranges for mixed-fisheries could have four steps: (i) single species, (ii) multi-species and ecosystem, (iii) economic, and (iv) social. Each step may include strategic long-term and tactical short-term aspects. The scientific basis for implementing these steps is available in several systems, and some steps have already been implemented (Table 2).

A key issue in the implementation of PGMY is whether such a space exists at all. In the North Sea, recent studies and advice given from ICES demonstrate this for cod and haddock. For cod and haddock, single-species PGY ranges are 0.22–0.49 and 0.25–0.52 year^{-1}, respectively (ICES, 2015a; Figure 5). Due to the cannibalistic nature of cod, $F < 0.28$ year^{-1} leads to cod yields <95% of MSY as well as increased risk of prey stocks falling below biomass reference points, whereas $F > 0.32$ year^{-1} leaves other stocks at risk by allowing piscivorous mid-level predators such as haddock to increase, producing cascading effects on forage fish (Vinther *et al.*, 2016). One prey stock that is particularly sensitive to low cod fishing mortalities is North Sea whiting (*Merlangius merlangus*), which currently suffers increased natural mortality from grey gurnard (*Eutrigla gurnardus*) and marine mammal predation as

well as mixed-fisheries (ICES, 2014d). Within the narrower bio-logical interaction range of cod fishing mortalities, haddock fishing mortalities in the original PGY range are precautionary with respect to haddock biomass reference points, but only the upper part of the range provides yields >95% MSY in a multispecies environment (Vinther *et al.*, 2016). These multispecies combinations of fishing mortalities are unfortunately not in accordance with current technical interactions, as can be seen by the fact that the current realized fishing mortalities are 0.39 and 0.24 year^{-1} for cod and haddock, respectively (ICES, 2015c), though the space around these possible fishing mortalities is not accurately known in a mixed-fisheries context (ICES, 2015d; Ulrich *et al.*, 2017). These values are within or just below the PGY range for both stocks, but below the ecosystem PGMY range for haddock. Being below the PGMY range for haddock is likely to increase natural mor-tality on haddock prey and hence may require a decrease in fishing mortality on these stocks to ensure that biomass remains above limit reference points. In total, there appears to be a need to develop the fisheries to be more selective for haddock and less for cod if ecosys-tem and technical PGMY spaces are to overlap in a joint PGMY. The fisheries for cod and haddock impact a number of non-target species
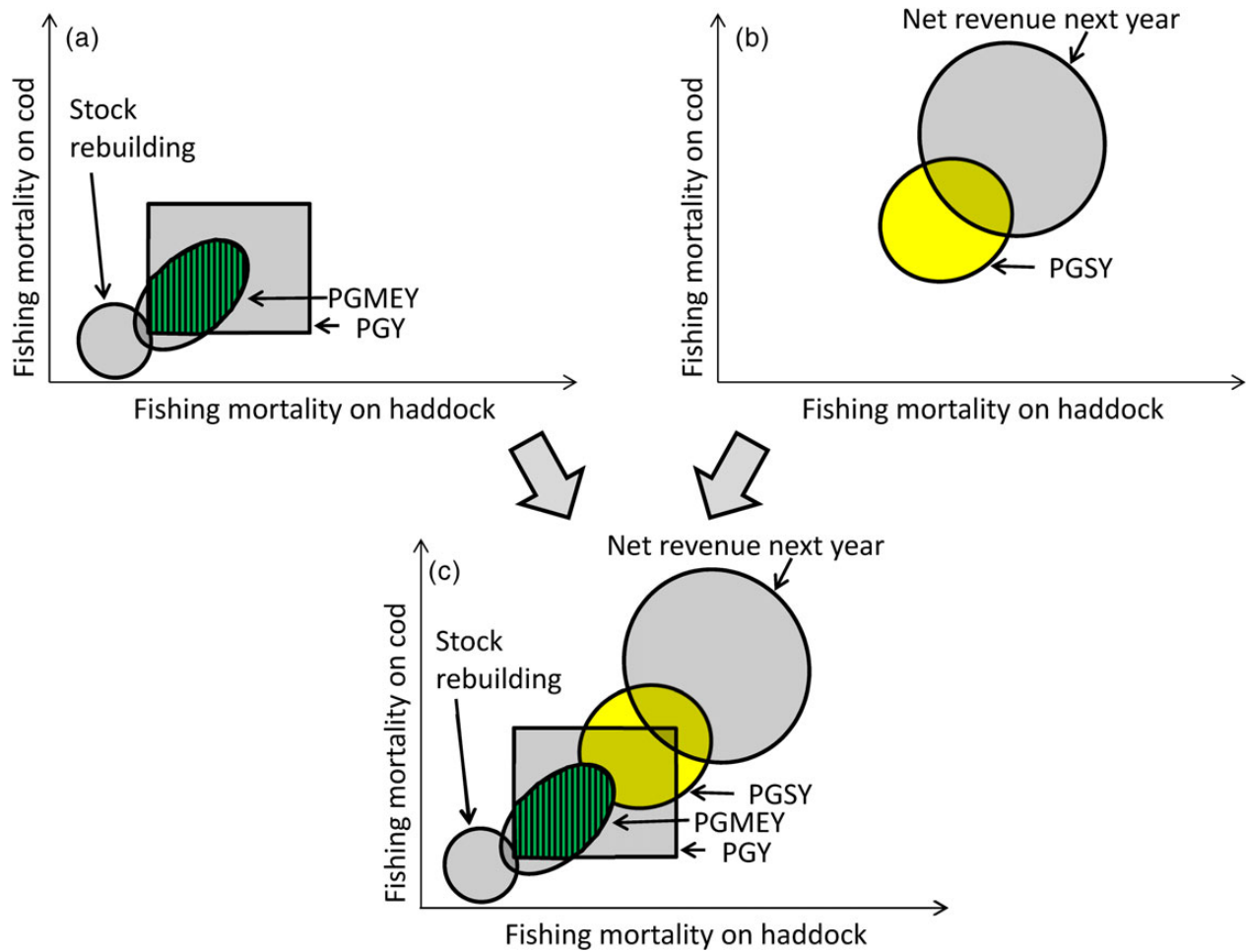
Figure 4. PGMY and pretty good social yield (PGSY) space for two groundfish stocks under rebuilding. Shaded forms indicate the area of the single-species PGY that is compatible with maintaining stocks above biomass limits in the long-term, the area compatible with stock rebuilding, and giving PGMEY in the long-term (striped), and combinations leading to PGMY, the social objective to keep net revenue relatively stable between years and "pretty good" social yield (PGSY). In this case, there is no set of fishing mortalities that satisfies tactical as well as strategic objectives.

such as slow-growing bony fish and elasmobranchs taken as bycatch in towed gear, benthic organisms impacted in the path of towed gear, and harbour porpoises (*Phocoena phocoena*) taken as bycatch in fixed nets aimed at flatfish, and, to a lesser extent, cod. The effects on these groups will depend on the distribution of effort across fisheries and hence cannot be directly plotted in Figure 5. Limits to fishing pressure have not yet been defined for the protection of any of these species. However, moving to the PGY area will decrease the general fishing pressure by >45% compared with the fishing pressure in year 2000 for both species. Unless this is accompanied by substantial effort re-allocation to fisheries with higher impact, this will provide a substantial decrease in the fishing pressure on non-target species and hence should substantially increase biodiversity indicators (Levin *et al.*, 2009; Samhouri *et al.*, 2010).

Framing the desirable operating space within the PGMY

Though specific advice on the trade-offs in different parts of the PGMY space require data and detailed modelling, some general considerations are possible that can be used to frame the desirable operating space in both data-rich and data-limited systems. Here, we assemble guidance on the fraction of MSY that is used when defining PGY, which part of the PGMY space is likely to be most desirable in a strategic perspective in single- and mixed-species fisheries, and how ranges can be addressed in data-limited fisheries. Further, we discuss the governance implications of using PGMY ranges, the case where no PGMY space exists, how to accommodate directional change, variability, and uncertainty in the implementation of the PGMY space, and constraints imposed by predator or prey species that require rebuilding.

Studies of trade-offs between economic and social objectives have found relatively asymmetrical relationships, with proportionally a greater reduction in employment required to achieve economic objectives (Pascoe and Mardle, 2001). This also implies that substantial gains in employment may be possible with relatively low losses in economic profits. For example, 25% higher employment could be achieved with a 10% reduction from the maximum fishery profit in the multispecies, multifleet, and multigear English Channel, and potentially 95% of employment could be maintained with profit levels 30% lower than at the economic optimum, provided the right combination of fishing vessels were operating in the fishery (Pascoe

Table 2. The current scientific basis for implementing PGMY in an European context.

Step	Sustainability pillar	Required activity		Current activity	
		Strategic (long-term) objectives	Tactical (short-term) management advice	Strategic (long-term) objectives	Tactical (short-term) management advice
1	Single stock	Set ranges for single-species PGY. Update as needed	Each year, eliminate *F*-options that are incompatible with maintaining the stock above biomass limits	Ranges for single-species PGY defined by ICES for selected stocks in 2015 (ICES, 2014b, 2015a)	Values used for advice are adjusted according to current stock status yearly by ICES (ICES, 2015c,g)
2	Multispecies and ecosystem	Filter predicted PGY combinations to avoid undesirable multispecies and ecosystem effects	Filter predicted PGY combinations to avoid undesirable multispecies and ecosystem effects given current stock sizes of prey and predators	Evaluations of the sustainability of combinations of fishing mortalities on interacting stocks have been performed (ICES, 2013b). Advice on direction of change within the space can be given for other ecosystem indicators (ICES, 2013c, 2015e)	The effect of changes in prey and predator stocks is studied for a number of stocks in the Barents Sea (ICES, 2015h), North Sea, and Baltic Sea (ICES, 2010)
3	Economic	Evaluate which combinations are practically feasible in mixed-fisheries. Evaluate the economic yield for these combinations	Limit options to those practically feasible in mixed-fisheries given current stock sizes and compatibility with economic viability of the fleets	An evaluation of which combinations are practically feasible in mixed-fisheries was completed for the North Sea and western waters by STECF (2015)	Options practically feasible in mixed-fisheries given current stock sizes are evaluated every year for the North Sea demersal stocks in the ICES advice (ICES, 2015b)
4	Social	A strategic social objective could be to maintain social and employment benefits, and to contribute to the availability of food	Evaluate the status of agreed indicators such as the difference between the current catch and the catch resulting from each combination of fishing mortalities. Large differences are likely to be undesirable from a social perspective, at least in the short term	The aim to keep catches less variable than the stock has been demonstrated to lead to decreased average yield and the willingness to sacrifice absolute yield for stability remains unclear. Direct studies on the effects of the MSY approach on local communities are rare	The difference between the current catch and the catch resulting from each combination of fishing mortalities is evaluated annually by the ICES Working Groups advising on mixed-fisheries issues (ICES, 2015b). Advice on other indicators is likely also possible once these have been agreed

and Mardle, 2001). In the North Sea, a best compromise (satisficing) solution involved a 15% reduction in both employment and fishery profits in the short term (Mardle and Pascoe, 2002). In contrast, achieving optimal long-run outcomes would require a greater loss in the short term. Given this, the potential operating space around economic and social targets may need to be larger than those suggested for biological targets, possibly aiming for ≥80% of the single objective target (e.g. MEY).

The desirability of different regions of the PGMY space depends on whether the fishery is mainly a single- or mixed-species activity, and/or uses single or mixed gear. In a single-species fishery, very little long-term yield is lost by fishing at the lower end of the PGY range, and most likely this also results in higher levels of fishery profit due to lower levels of effort and cost. In addition, there are substantial gains in the form of lower stock variability and a lower risk of violating limit reference points. There may be short-term gains in economic and social indicators by initially fishing at higher fishing mortalities. However, these gains jeopardize long-term gains (Mardle and Pascoe, 2002) and so should be adopted with care (ICES, 2013a; STECF, 2015). In mixed-fisheries, it may be economically beneficial to exert higher fishing mortality on less-productive "choke" species. However, there is no ecosystem or economic benefit in fishing all or most species in the upper

part of the PGY range. Rather, there are benefits in fishing at the lower part of the PGY range for more valuable and productive species (Pascoe *et al.*, 2015). Further, yield may increase if technical solutions or changes in fleet composition can decrease catchability of the less-productive stock. Hence, it is important that the incentive to avoid less-productive stocks is retained.

The development of the PGMY space draws on knowledge from data-rich systems, but the definitions can readily be generalized to data-limited situations. Expert judgment or industry knowledge can be incorporated in the absence of quantitative models to define single-species F_{MSY}s and the combinations of fishing mortalities which are not feasible (Zhou *et al.*, 2012; Rindorf *et al.*, 2017). However, data-limited PGMY should be considered in the context of the potentially increased uncertainty and risk of overfishing inherent in many data-limited approaches (Dichmont *et al.* 2015). As fishing beyond F_{MSY} cannot generally be considered to be precautionary with respect to maintaining stocks above limit reference points with an acceptable probability, this should not be advised without good monitoring and strict management measures that apply if limits are violated.

Using the upper part of PGY ranges ($F > F_{MSY}$) incurs specific requirements on the efficiency of the governance system, particularly monitoring and enforcement. If the ranges are used as
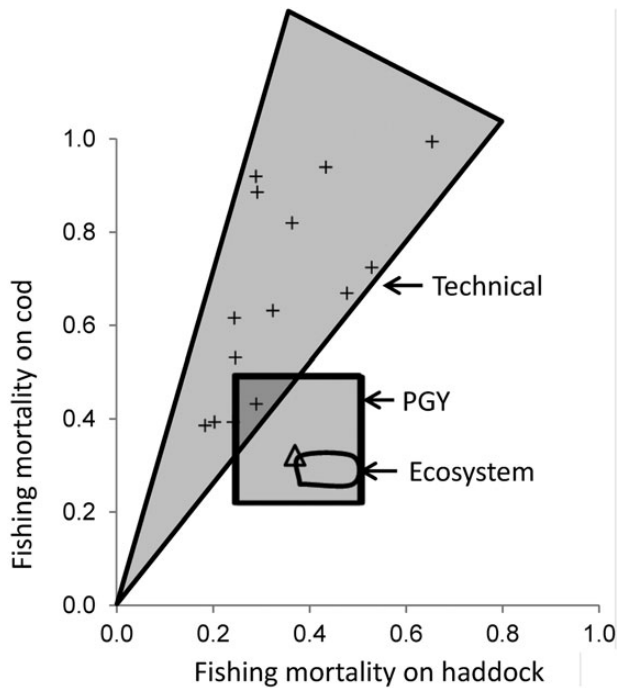
Figure 5. PGMY spaces for North Sea cod and northern shelf haddock caught in mixed-fisheries. Combinations leading to PGMY are indicated in dark shading; shaded forms indicate the areas of desirable multispecies or ecosystem combinations, technical interactions indicated by the area of observed combinations of observed fishing mortalities from 2001 to 2014 (+, from ICES, 2015c), and the single-species PGY that is compatible with maintaining stocks above biomass limits. Δ indicates the current single-species F_{MSY} point estimates.

single-species ranges in combination with a lack of control of unreported catches, this may result in fishing mortalities well above the PGY ranges for less-productive stocks. The combination of limited data and governance systems resulting in substantial unreported catches is particularly risky, and using F_{MSY} or the upper part of the ranges as a target in these cases should definitely be avoided. In data-limited systems, alternative approaches such as effort restrictions and seasonal or spatial closures (e.g. Plagányi *et al.*, 2013) are often used rather than directly controlling fishing mortality through TACs. In these cases, PGMY may be defined in dimensions of effort (Murawski and Finn, 1986; Dichmont *et al.*, 2008) or the extent of area closures.

As the number of restrictions on PGMY and hence the number of conflicting objectives increases, the operating space is diminished until, at some point, no set of fishing mortality rates satisfies all restrictions. In this case, the PGMY space does not exist within the bounds set, and broader ranges may need to be investigated. In this case, scientific advice should carefully describe the ecosystem, economic, social, and institutional trade-offs in different regions of the combinations of fishing mortality levels of different stocks (Gibson, 2006).

Both the PGMY space and our location within it are determined with (sometimes substantial) uncertainty, and furthermore all the processes on which the PGMY and PMGEY space is based vary in time to some degree and often show trends as a consequence of environment change, changes in predatory stocks, or changes in fisheries costs caused by changes in fleet spatial distribution and composition. The uncertainty in current estimated fishing mortalities and the boundaries around the PGMY space would indicate that the centre of the PGMY space will likely provide the highest likelihood of being within the true space. However, this desire to be certain of being within the PGMY space conflicts with the necessity of defining a non-zero space to allow the fulfilment of multiple objectives. Further, the risks in different parts of the PGMY space to the multiple objectives are not likely to be symmetrical around the centre. Constraint on the PGMY space is that it may not be appropriate to use the single-species PGY as a tactical target for stocks that are deemed to be overfished and in need of rebuilding. The need to implement low fishing mortality to facilitate rebuilding for one or more target or bycatch species may profoundly constrain the options for all other species fished in association (Figure 4).

As key processes vary over time, the PGMY space must be updated regularly to remain relevant with respect to objectives of both yield maximization and sustainability. In addition to the change in biological, technical, economic, and social conditions and processes, updates need to address increased knowledge and certainty. Although this is also the case when the target reference points are identified separately for each species, the task is complicated under PGMY by the many dependent factors entering the estimation and hence the substantial workload required for an update. Whereas biology is often used to set strategic goals (such as MSY), strategic economic and social aspects may change substantially from year to year as prices, costs, employment, etc., change. Because of the amount of work involved, there is likely to be reluctance to frequently update the PGMY space, a fact which may be especially problematic for economic and social targets.

The concept of PGMY presented here can theoretically be applied in any jurisdiction, subject to the interpretation of relevant legislation. There are, however, key jurisdictional differences in two important respects: setting limits to stock sustainability and the approach to addressing harvesting of less-productive species. In the USA, Australia, and New Zealand, the implemented biomass limit is one-half B_{MSY}, and the upper target to fishing mortality of all stocks is either the single-species F_{MSY} (USA and New Zealand) or F_{MEY} (Australia). Because the PGMY space is smaller when using F_{MSY} or F_{MEY} as an upper limit, the safe operating space is substantially smaller in the USA, Australia, and New Zealand. Ecosystem sustainability is implemented in a way similar to the approach here in the tier system suggested by Fogarty (2014), which eliminates management combinations that are unsustainable from a systems perspective. In the Australian implementation of MEY, technical interactions are considered, all habitats and affected species/species groups in Australia need to undertake a risk assessment (Hobday *et al.*, 2011) and some form of action to ensure they are not fished beyond their limit reference point (AFMA, 2016).

In contrast to the conceptually similar implementation of limit biomass and fishing mortality reference points (although set from different principles), the implementation of the MSY approach to less-productive species varies greatly among jurisdictions. This seems to be connected to the differing weight given to the considerations of ecosystem sustainability vs. economic and social aspects and long-term vs. short-term considerations. In the USA and Australia, priority is given to long-term ecosystem sustainability, which means that F_{MSY} (or F_{MEY}) cannot be exceeded for any stock. This potentially leads to substantial economic loss (Hilborn *et al.*, 2012; Fulton *et al.*, 2014) in both the short- and long-term, though exceptions to this also exist (Dichmont *et al.*, 2010; Gourguet *et al.*, 2016). Economic loss provides substantial incentive on behalf of the fishery

to avoid landing less-productive species but also adds to management costs to cover monitoring and surveillance.

The degree to which indicators exist to guide management towards objectives differs among the four pillars as does both the relevant time and spatial scale. In their current use, fisheries management decisions often rely on well-established stock and ecosystem indicators, whereas the use of economic and social indicators is less clear. Often, these latter objectives are poorly defined, with each stakeholder having different interpretations as well as priorities (Mardle *et al.*, 2002). Objectives are often in conflict as economic efficiency dictates concentration of fishing effort on fewer vessels and hence lower employment, whereas social objectives to maintain local communities often focus more on maintaining employment. The long-term conflict between economic and social sustainability on the one side and stock objectives on the other seems much less, as both long-term economic and social sustainability rely on stock sustainability.

The size of the PGMY space will reduce as more restrictions are imposed until no area exists that ensures all aspects of sustainability. The reaction to this should not be to give no advice, as this will simply lead to decision-makers being uninformed of the actual trade-offs and lack of transparency in decision-making. Instead, advice for the PGMY space for each sustainability pillar can be demonstrated separately when the conflict is between pillars, or the conflicting objectives within each pillar can be demonstrated where the problem is within individual pillars (Figure 4). Providing advice separately for each pillar will avoid the case where scientists are weighing off different sustainability measures according to their own considerations, and hence keep the policy choices in the policy domain.

A particular challenge in implementing PGMY in practical management is how to identify a PGMY space that is technically sufficiently restrictive to ensure that combinations of fishing mortalities, which are practically impossible, are excluded while ensuring that the industry has sufficient incentive and room to change catchabilities in the direction away from the less-productive species. If the space is restricted too much, there is no incentive to improve selectivity. If the space is not restricted enough, the advice can be seen as mutually inconsistent (and scientific credibility may suffer), and the incentive to misreport catches of the less-productive species increases.

It seems technically possible to provide advice on acceptable parts of the PGMY space in some jurisdictions, at least with respect to aspects such as species interactions, ecosystem considerations, mixed-fisheries issues, and profitability. However, it remains to be seen whether this highly complex information can be delivered in a format that managers find useful in setting annual quotas.

Conclusions

The principles of a PGY can be expanded to PGMY space in a multispecies and multiobjective situation, which accounts for the fact that not all combinations within single-species PGY *F*-ranges are compatible with biological and technical interactions and a multiobjective approach. As PGMY provides flexibility while adhering to the principles of MSY, it allows consideration of other issues and objectives to be included in operational management advice in both data-rich and data-limited situations. It provides a way to integrate advice across stocks and avoid clearly infeasible combinations, thereby increasing the usefulness of scientific advice. The PGMY space must be updated regularly to account for changes in species interactions, environmental, economic, and social change, and

increased knowledge of the systems. Clear and simple graphical methods to convey this complex information to managers need to be investigated further, a particularly challenging task as the complexity of examples involving more species and frequent non-linearities substantially complicates communication. However, these issues should not halt our progress in this area, where advice as a minimum can include definitions of undesirable parts of the single-species PGY space.

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