Putting Economics into Maximum Economic Yield

Abstract

Christensen (2009), Sumaila and Hannesson (2010), and Grafton et al. (2012) discuss the relationship between Maximum Economic Yield (MEY) and Maximum Sustainable Yield (MSY), including the full value-chain impact, excess capacity in the economy, consumer benefits, employment, and profitability. Many of these concerns and others, such as accounting for subsidies or costs in developing economies, are properly handled by applying economic principles and values to measure all benefits and costs, but are not yet fully incorporated into measures of MEY. Only when all economic distortions are accounted for and valued by economic (shadow) prices does MEY actually represent a full economic optimum. Further, when accounting for changes in technology and nonmarket public good benefits from biodiversity and ecosystem services, an open question remains whether the MEY resource stock exceeds, equals, or falls short of the MSY resource stock. The relationship is likely to change and fluctuate over time due to changes in technology, other sources of economic efficiency, prices, recruitment, the environment, society's economic valuation of biodiversity and ecosystem services, and other factors. The previous discussion and this paper represent extensions of MEY and fisheries management beyond its traditional focus upon the resource stock externality.

Keywords Fishing sector, maximum economic yield (MEY), maximum sustainable yield (MSY), economic prices, external benefits, technical change

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1. Introduction

The concept of Maximum Economic Yield (MEY) and its relationship to Maximum Sustainable Yield (MSY) continue to generate considerable debate, and as this paper shows, the debate is not yet over. Christensen (2009) asserts that MEY equals MSY, because heretofore MEY only considers the fish harvest and excludes the full value-chain impact. Sumaila and Hannesson (2010) in a rejoinder state that MSY differs from MEY, even when the benefits from the complete fish value chain are taken into account, and that maximizing society's economic benefits comes when resources are allocated across all uses to equalize net benefits from employing one more unit of society's resources. They further suggest that when there is excess capacity in the economy, so that all resources are not fully utilized, the multiplier effect upon incomes and employment from additional rounds of spending and zero pricing of labour could be important. Grafton et al. (2012) show how a biomass corresponding to MEY, B_{MEY}, can be used to determine relative employment and profitability measures, account for both the harvesting and processing sectors, and incorporate consumer benefits. Grafton et al. (2012) further show that including a processing and/or retail sector along with measures of consumer benefit lowers the B_{MEY}, but that there remains a broad range of parameter values for which $B_{MEY} > B_{MSY,}$ and that B_{MEY} can thereby serve conservation goals. Vieria and Pascoe (2013) survey current issues and question including the supply chain up to and including the consumer benefits in MEY.

An overlooked issue in the above discussions is the distinction between a private (financial) analysis[1] from the perspective of the consumer or producer in the value

[1] A private analysis includes only benefits and costs that are internal to, i.e. accounted for by, producers and consumers and measured by market prices, however imperfectly. In contrast, an economic analysis accounts for distorted markets and includes benefits and costs that may be external to producers and consumers throughout the value chain and consumers, i.e. economic analysis includes any external costs and benefits and distortions such as taxes as discussed further in this paper (Drèze and Stern 1986). External benefits/costs or externalities are benefits/costs to society that are not accounted for by private consumers or producers and are not fully reflected in market prices, if at all.

chain using existing market prices and an economic analysis from the perspective of society using economic prices – shadow prices – that account for all sources of economic value and missing and distorted markets (see Drèze and Stern 1986 for the theory of shadow prices).[2] The latter approach is the definition of an economic analysis common to welfare economics, cost-benefit analysis, project valuation, and a comprehensive economic analysis routinely conducted by governments and development banks (UNIDO 1978, Squire and van der Tak 1979, World Bank 1996, Asian Development Bank 1997, Just, Hueth, and Schmitz 2004, Australia Commonwealth 2006, European Commission 2008).

Traditionally, MEY has reflected a focus upon the resource stock externality, but as we show, this focus is too narrow, because it misses other increasingly relevant externalities and other pertinent economic distortions. Accounting for economic prices and external benefits and costs helps put economics into MEY. Only when all economic distortions and externalities are accounted for and valued by economic prices does MEY actually represent a full economic optimum.

Beyond externalities, there can be further distortions in the economy that can keep an economy from reaching a full economic optimum -- or in our case, from MEY actually representing a full economic optimum, along with distortions interfering with efficient resource allocation and that require economic prices. These distortions include (Drèze and Stern 1986): (1) indirect or income taxes; (2) quantity controls; (3) controlled prices; (4) tariffs and trade controls; (5) oligopoly; and (6), imperfect information and transaction costs. Here, we largely concentrate upon the distortion most relevant to common resources, such as fish stocks, and public goods, such as biodiversity and ecosystem services, notably external costs and benefits, taxes (subsidies are negative taxes and hence considered), controlled prices, and tariffs and trade controls that can alter exchange rates in some developing countries and employment benefits.

[2] Shadow prices are also called accounting prices.

In principle, the economic (shadow) price of a good or service is defined in terms of the marginal effect on social welfare of the availability of an extra unit of the specified consumption good or service, output, or input or the social opportunity ocst in terms of social welfare of a marginal unit reduction in the production plan (Drèze and Stern 1986). In practice, economic prices are based upon demand prices through marginal willingness to pay or accept and marginal revenue product for intermediate inputs, and supply prices through marginal opportunity costs (Squire and van der Tak 1979, Sinden 1995, Just, Hueth, and Schmitz 2004). Economic prices can also be a weighted average of the demand and supply prices. Economic prices can be expected to equal market prices when markets are not missing or otherwise distorted, but a wedge arises between the two when the above distortions and externalities are present.

This note shows that MEY measures to date have been a combination of both private and economic ("social") valuations of costs and benefits in a static-in-technology fishery and mainly focused upon producer benefits and the supply side and have largely (but not totally) overlooked consumers and nonmarket benefits. As such, MEY to date has not represented a full economic optimum. Accounting for changes in technology and other sources of economic efficiency (Squires and Vestergaard 2013ab), consumer surplus (Bulte et al. 1998, Clark 2010, Grafton et al. 2012), and nonmarket external benefits (Bulte et al. 1998, van Kooten and Bulte 2000) -- notably biodiversity and ecosystem services, plus valuing costs and benefits by economic prices – shadow prices – gives a full MEY rather than a hybrid private-economic MEY.[3] Adding in processing, distribution, and retail sector expands beyond the fishery production process (Christensen 2009, Sumaila and Hannesson 2010, Grafton et al. 2012). MEY here is the sum of the discounted net consumer and producer benefits over time, where these benefits include those

[3] Here we abstract from the population dynamics, with contemporary issues, such as age-structured populations, see Tahvonen (2009), or uncertainty, see Kompas et al. (2008), or meta-populations and patchy stock issues for benthic and groundfish species, see Sanchirico and Wilen (1999), or cyclical populations for small pelagics, see Carson et al. (2010).

market benefits from consumption, processing, distribution, retail, and production plus nonmarket benefits from biodiversity and ecosystem services, all measured by market prices or economic (shadow) prices when markets are distorted, incomplete, or missing, while accounting for changes in technology and other contributors to economic efficiency and changes in the resource stock. External costs arising from the resource stock externality are routinely accounted for in MEY as a normative measure of the social-economic-ecological optimum. A social discount rate is used rather than a private discount rate such as a market interest rate, and is a point well recognized in the bioeconomic literature.

This note starts by first discussing that induced effects – secondary benefits – when there is persistent excess capacity in the economy are properly captured when economic costs and benefits can be valued using economic measures of value -- shadow prices -- rather than input-output multipliers (although the latter can be used). Second, MEY can capture all economic benefits to society from consumption and production throughout the value chain including processors, distributors, retailers, chandlers, etc., if general equilibrium inverse demand functions are used to price landed fish and shadow prices are used to value all inputs in the harvesting process (Just et al. 2004). An key assumption is that the landed fish is explicitly treated as an essential input in the value chain into final seafood commodities. The Grafton et al. (2012) approach of adding the net benefits from this sector to consumer and producer surplus into the objective function is appropriate when an equilibrium demand curve for fish is not used and if there are not price changes in multiple markets leading to path dependency for consumer but not producer benefits (Just et al. 2004). This paper presents an alternative approach suitable when there are multiple markets and price changes that is also possibly more easily implemented. The third major point is that following standard cost-benefit and project evaluation principles, when using economic prices, the impact of subsidies and taxes (non-Pigouvian), distorted exchange rates in developing countries, controlled prices such as fish price floors or ceilings or minimum wages or informal labor and capital markets, and other distorting effects on market prices are readily incorporated into economic – as opposed to private – costs and benefits and thereby comprehensive measures of MEY. Fourth, consumer welfare should be incorporated into measures of MEY (Bulte et al. 1989, Clark 2010, Grafton et al. 2012), since these are economic benefits to society. Fifth, nonmarket external benefits from the public goods[4] of biodiversity and ecosystem services are important components of an economic – as opposed to private – measure of MEY and extend MEY towards an ecosystem based fisheries management basis. Sixth, fisheries are not immune to changes in technology and other sources of changes in economic efficiency, and these changes should be incorporated into the analysis (Squires and Vestergaard 2013ab).

When some or all these proper components of an economic – as opposed to private – analysis are missing, the measured MEY is not the full economic optimum MEY. Moreover, unless a fishery is absolutely devoid of technological or environmental change, the relationship between MEY and MSY is unclear, and this relationship changes over time i.e. there is *not* a no-growth steady-state equilibrium and requires non-autonomous bioeconomic models.[5] Finally, MEY has only considered one source of dynamic economic efficiency, dynamic scale efficiency, and excluded technical and allocative efficiency (Squires and Vestergaard 2013ab). We define these terms as we discuss them below.

We will not in this note discuss the conceptual issues related to MSY and MEY when there are technical interactions and biological interactions. When there are technical interactions and therefore the production is a multi-output, then the yield curves have to be added and total MSY/MEY can be defined, but it might lead to under- and overexploitation of the involved species (Caddy and Sharp 1986). An

[4] Public goods are those that are nonexcludable and nonrival, i.e. all can freely enjoy without diminishing the amount available to others.
[5] Dichmont et al. (2010) advocate constant updating with autonomous bioeconomic models, i.e. adaptive management, to account for changing market prices.

example could be a mixed groundfish fishery. When there are biological interactions (e.g. predator-prey there will be a trade-off curve of yields (like the well-known production possibility curves) and hence multiply MSY levels, but only one MEY-level depending of relative prices and cost, which beside the biological conditions also depends on economic parameters such as relative prices and costs (Flaaten 1988). Nonetheless, we note that these results also depend upon the state of technology, because technological progress can reduce technical interactions by increasing selectivity.

2. Economic and shadow prices and secondary benefits

Before entering into the heart of our discussion, we first observe that economic values have to be assessed in terms of a well-defined criterion or objective, which is referred to as ‘social welfare’ (Drèze and Stern 1986). The evaluation of social welfare is based on assessments of the well-being (utility) of individual households, which can in principle be supplemented by interpersonal comparisons of well-being. The latter are embodied in ‘welfare weights’, in which the marginal increments in net benefits for some individuals or households receive greater weight than others according to some set of criteria established by society (Squire and van der Tak 1979, Drèze and Stern 1986). Although not implemented in practice, in principle, differential weights can also be given to the incremental net benefits received by the private and public sectors. When distribution becomes an issue, for example, different groups can receive different relative weights, reflecting their relative position in society as viewed by the social planner. The use of such weights alters the level of MEY. Thus, using shadow wage rates and weighting those labour groups of most concern can accommodate employment effects, especially in countries with substantial and persistent excess capacity, unemployment, and distributional imbalances. For the moment, we simply note that in measuring MEY the standard practice is to (implicitly) assign equal weight to the marginal incremental net benefits enjoyed by all individuals and households, which is also standard practice in economic analyses. Such a specification contains several implicit assumptions, such as marginal utilities of income equal across all individuals, so that the marginal gain in consumer well-being (utility) with a one unit increase in income is equal across all individuals or households regardless of income and wealth levels (Squire and van der Tak 1979, Drèze and Stern 1986).

In addition to differentially weighting different social groups, MEY can readily account for social benefits from employment and account for informal labour markets by valuing labour at its "shadow wage rate" (UNIDO 1978, Squire and van der Tak 1979, Sinden 1995, World Bank 1996, Asian Development Bank 1997, Just et al. 2004). When fisheries are managed with an employment objective in mind, the use of shadow wage rates and welfare weights for different labor groups (discussed below) provides a theoretically rigorous approach to measuring MEY that places greater social value upon employment and provides an alternative to multi-objective analysis.

This economic price for labour is an imputed economic value that captures the economic value to society from the last unit of labour employed in the fisheries sector plus any disutility of worker effort, both measured in shadow prices to account for distortions elsewhere in the economy.[6] This shadow wage rate is based upon the benefits foregone by labour when employed, i.e. its social opportunity cost, which accounts for the forgone marginal product, the marginal social value (disutility) of foregone leisure, the value of employment that is not directly paid a wage but nonetheless contributes to the economy – such as self-employment, the value of unemployment benefits, and other factors, all measured in shadow prices to account for distortions elsewhere in the economy (Squire and van der Tak 1979, Sinden and Thampapilai 1995, World Bank 1996, Asian Development Bank 1997, European Commission 2008).

[6] The economic value of disutility of effort in shadow prices that account for distortions elsewhere in the economy depends on relative employment conditions and whether or not a worker already is employed, and can be measured by the difference between labor's supply price for the new and old jobs (Squire and van der Tak 1979)..

The shadow wage rate also accounts for any government-induced distortions in labour markets including minimum wage laws, unemployment insurance, income taxes, and legal impediments to labour mobility. Market-induced distortions include union market power over wages or restricted entry into a particular market.

Labour always has an opportunity cost, even if there is high unemployment and idle labour, since people do not work for free, and there is always a forgone output or leisure that forms the reservation wage plus disutility of effort, even if not occurring in a market. Not only might seemingly unemployed labor be employed in the informal economy or be self-employed and receive payments in kind, but unemployed labor (in the market economy) displays a reservation wage necessary to activate the unemployed in any particular area. This reservation wage, the minimum cost of hiring an unemployed person, is the controlling element for a worker with no productive alternative, since even that person demands a minimum amount as a condition of employment (Powers 1981). In contrast, Sumaila and Hannesson (2010, page 2), state, …"further activities in the fish value chain would not be costs, such as when this would employ otherwise idle labour." Using a shadow wage rate and shadow cost of labour lowers the net economic benefits compared to treating unemployed labor as free, but provides a more accurate measure of net economic benefits.

The shadow wage rate captures any induced effects -- secondary benefits -- in the economy from additional employment, such as additional rounds of spending that can occur, that increase income and employment when there is persistent excess capacity in the economy (Squire and van der Tak 1999, World Bank 1996, Asian Development Bank 1997, Australia Commonwealth 2006). Employment thereby has indirect benefits through additional rounds of spending from the employed fisheries labour when there is excess capacity. The total effect of this chain reaction of spending can be summarized by multiplier analysis of input-output analysis as observed by Sumailla and Hannesson (2010) and implemented by Norman-López and Pascoe (2011). Nonetheless, "text-book" economic analysis correctly captures these economic benefits by using economic prices, i.e. the shadow wage rate for labour, opportunity costs or marginal revenue product for other inputs in the production process, and willingness to pay or accept for consumer benefits, under conditions discussed next (Squire and van der Tak 1999, World Bank 1996, Asian Development Bank 1997, Australia Commonwealth 2006).

If there is persistent excess capacity in the sector and accompanying unemployment, the supply price of labour (rather than the demand price) is used, because the affected labour would otherwise have been persistently unemployed, and hence there is increased availability, and the alternatives to the project would not also have made use of the idle labour. When the economy is at full capacity or the labor to be used is currently fully employed, the project or policy displaces existing labour, which requires use of a demand price (from a firm's derived demand for labour) rather than the labour supply price, where the demand price is obtained from the derived demand schedule and is the firm's marginal revenue product of labour (Squire and van der Tak 1999, World Bank 1996, Asian Development Bank 1997, Australia Commonwealth 2006).

The shadow wage rate may be less than the market wage rate or even the crew share, provided that the risk and uncertainty incorporated in the crew share are also incorporated into the shadow wage rate. Because the shadow wage rate is often lower than the prevailing market wage rate (risk and uncertainty adjusted), the economic benefits to society from employing this otherwise unemployed or underemployed labour (and accounting for foregone leisure and self-employment) will be incorporated into the producer benefits. An example of this situation can be found in Vestergaard, Stoyanova and Wagner (2011), where the crew share wages are assessed to be above shadow wages rate even when adjusted for risk. However, the shadow wage rate is only employed if the excess capacity in the sector is expected to persist over long time periods. When the excess capacity is due to the normal business cycle or a limited economic downturn, and hence not expected to persist, accounting for secondary benefits is not typically recommended (Squire and van der Tak 1999, World Bank 1996, Asian Development Bank 1997, Australia Commonwealth 2006). Intuitively, secondary benefits capture the impact of a policy, not the net-benefit, because the expenses in one part of the economic system are income in another part in the system unless there is persistent excess capacity and formerly underemployed or unemployed resources are not utilized, so that genuinely new net benefits are created rather than transfers or effects canceling each other out.

Some approaches to the shadow wage rate, notably Little and Mirrlees (1974), Squire and van der Tak (1979), and Ray (1984), accommodate the wider consequences of income distribution, so that increases in income of relatively disadvantaged are counted as a social benefit that is offset against employment cost (Curry and Weiss 1993, Dinwiddy and Teal 1996).[7] That is, the social benefit of additional income (usually measured by the benefit of additional consumption) of favored labor groups is subtracted from the shadow wage rate measured as the marginal output foregone and marginal disutility of labor. The trade-off between Pareto efficiency and increased employment is reflected in the weight given to the marginal benefit of additional income (consumption). Distribution weights given to those above and below some norm, such as per capita income or the official poverty level, vary by the functional form of the social valuation function. These weights may be based upon an individual choosing the savings level such that the diminishing marginal utility of income equals the marginal utility of an extra dollar saved or consumed, so that an increase in income leads to an increase in consumption and savings and an equal decline in the marginal utility of each (Campbell and Brown 2003). Welfare weights attached to additional consumption by an individual are then based on the marginal utility received at that individual's income level relative to a base level. The higher the level of income and consumption, the lower is the distributional weight. With weights, the shadow wage

[7] This is intrageneral income distribution. Inter-generational income distribution is accommodated by different relative weights for savings/investment and consumption; see Squire and van der Tak (1979).

rate generally lies between the opportunity cost, measured by the foregone marginal product, itself measured by a shadow price to reflect distortions in other markets, plus the disutility of labor effort also measured by a shadow price to reflect distortions in other markets, and the market wage rate. Standard practice, as noted, is to apply unitary weights, so that all labor receives equal weights.[8]

When calculating MEY for any country with distorted foreign exchange rates due to e.g. import and export tariffs, taxes, quotas or multiple exchange rates the shadow exchange rate (SER) rather than the official exchange rate (OER) should ideally be used to value traded inputs and outputs in the UNIDO approach to project valuation (UNIDO 1978, Squire and van der Tak 1979, World Bank 1996, Asian Development Bank 1999, European Commission 2008).[9] Inputs and outputs -- the so-called nontradables -- that do not enter into international trade may be shadow priced for domestic market distortions but are not shadow priced by the SER. The SER is an economic price that differs from the official price of foreign exchange by the amount of the foreign exchange premium. The SER is the value of an additional unit of foreign exchange that accurately reflects the consumption worth of an extra unit of foreign exchange in terms of the domestic currency, given the trade policies that are expected to prevail over the life of the project (UNIDO 1978). The SER may be calculated as the weighted average of the demand price (for

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[8] Assigning equal weights is usually coupled with the Kaldor-Hicks potential compensation test, in which as long as there is at least a Pareto improvement the gainers can potentially compensate the losers and there remains a net gain to society as a whole. Fiscal policies are typically counted upon to account for losers or those of lower incomes.

[9] UNIDO is the United Nations Industrial Development Organization. The UNIDO approach is sometimes called the domestic price approach. The numéraire is domestic consumption prices in domestic currency and the discount rate is the consumption rate of interest (UNIDO 1978, Dinwiddy and Teal 1996). Sometimes, rather than using a shadow exchange rate on tradables, the foreign exchange premium is added to net benefits. An alternative approach, the world price approach, also called the Little-Mirrlees-Squire-van der Tak synthesis, is essentially the inverse of the domestic price approach and uses conversion factors to bring domestic prices to border price equivalents (foreign exchange equivalent values) in units of domestic currency, or more accurately border parity prices (accounting for resources used to place production at the project site), which is the numéraire or unit of account (Squire and van der Tak 1979, Dinwiddy and Teal 1996). Both approaches provide the same relative project rankings, and hence we utilize the more widely applied UNIDO approach in our discussion.

displacement of foreign exchange from current uses) and supply price (for increased availability of foreign exchange) of foreign exchange to the country. In general, the SER equals the OER only if all trade distortions, such as import duties and export subsidies, are eliminated. When the SER exceeds OER, society place a higher value on a unit of foreign exchange than is given by the OER typically due to more quotas, taxes, and tariffs on imports than exports or an overvalued OER.

The use of economic (shadow) prices and properly accounting for production subsidies that are not “Pigouvian”, i.e. that are not related to the expected undersupply of (impure or pure) public goods and free riding, provides economic rather than financial or private benefits and costs, i.e. from the perspective of society and not the individual firm or consumer. Cost subsidies lower costs faced by firms or consumers (i.e. financial or private costs), but can be transfer payments and a cost to society, so that adding these subsidies to the private costs gives the economic costs. Revenue subsidies increase financial revenues, but can also be a transfer payment and cost to society, so that removing them from the revenue stream (or equivalent adding them as a cost to the cost stream while keeping the subsidies in the revenue stream so that they cancel out) gives the economic costs.

The above approach assumes that subsidies are a pure transfer payment, so that the transfer from one party to another cancels out from a society-wide perspective and does not represent the use of real resources. It further assumes that all project or sector demand increases for inputs or outputs are fully met by increases in supply and not by displacement of demand elsewhere in the economy (UNIDO 1978, Squire and van der Tak 1979, World Bank 1996, Asian Development Bank 1997, European Commission 2008). If there is both displacement of existing usage and increased supply (the pure transfer assumption), then accounting for the subsidies requires estimating an economic or shadow price that is a weighted average of the demand and supply prices, where the weights are price elasticities (proportional changes in quantity demanded or supplied with a one percent change in price). Similar considerations hold for taxes.

3. **General equilibrium demand functions**

MEY can capture the total net economic benefits throughout the supply chain if the derived demand curve for fish at the ex-vessel level entering the bioeconomic model is specified as an inverse general equilibrium derived demand curve (Just, Hueth, and Schmitz 2004). That is, a demand curve for fish is derived from the processing-broker level in the value chain that includes not just the price and quantity of the fish concerned, but the relevant price or quantity for other species that are substitutes or complements and priced elsewhere in the supply chain. This derived demand is generally specified as price dependent, leading to an inverse rather than direct demand (Barten and Bettendorf 1989). This general equilibrium specification for an essential input allows capturing the net economic benefits of downstream markets in the supply chain and accounts for multiple price changes in multiple markets without path dependency. If the demand curves for multiple markets are not general equilibrium, then the changes in consumer surplus with price changes in multiple markets differ according to which market's welfare is first assessed, called path dependency. Unlike consumer surplus, measures of producer welfare are path independent because are measuring profits not unobserved utility with budget constraints and income effects. Further, without appropriate separability assumptions, in principle all important goods and services, not just fish, would have to be included. In the commercial sector, an interrelated set of demand and supply functions are linked through different levels of markets from the vessel level to that of the final consumer (Thurman and Easley 1992). Harvested fish are then an essential input into the production of the processing sector throughout the retail sector to the consumer final demand in the whole supply chain. When properly specified and estimated as "Hicksian" rather than "Marshallian", the consumer welfare measures are the preferred compensating and equivalent variations. These measures may differ little from Marshallian consumer surplus when the income effect from a price change is small, as expected in many markets but not for lower income groups or when fish forms an sizeable part of consumption, see Just Hueth, and Schmitz (2004).

The general equilibrium approach has focused on the supply chain of related markets, but this approach can also be applied to the ecosystem, where there is also up- or downward linkages and many of the relevant prices will be economic (shadow) prices. Hence, changes in harvest in one species will, via ecosystem interactions, impact other species and other users of the ecosystem. This general equilibrium approach can include the biomass changes of the other species. An example is the forage fish fishery.

4. **Changes in technology and other sources of economic efficiency**

If $\delta > 0$ is a constant denoting the continuous social rate of discount, *P* denotes a constant *market* product price, B_t denotes the biomass, Y_t denotes the yield or catch, *t* denotes time, *q* denotes the catchability coefficient, *c* denotes the constant unit cost measured in *market* prices, λ denotes the rate of disembodied technical change (not embodied in physical capital), *M* denotes the cost share of physical capital, ψ denotes the rate of embodied technical change, $-\mu(t, Z)$ denotes technical inefficiency or the deviation from the best practice frontier that shifts with changes in technology and *Z* defines a vector of explanatory variables associated with technical inefficiency , then the objective is to maximize the discounted present value of producer benefits from the harvesting sector (Squires and Vestergaard 2013b):

$PV(\pi) = \int_0^\infty \pi[Y_t, B_t]\, e^{-\delta t} dt$ subject to $dB/dt = F(B_t) - Y_t$ and $B_0 = B(0)$, where

$\pi = \left[P - \frac{c}{qB_t e^{(\lambda + M\psi)t - \mu(t,Z)}}\right] Y_t$ is the producer benefit or economic rent measured in market prices. Solving this optimization problem leads to sustainable biomass, rent, yield and effort that varies with changes in technology, and thereby does not attain a no-growth steady-state equilibrium, although it does asymptotically approach a limit stock in which the marginal productivity of the resource stock equals the social discount rate.

MEY as discussed in the literature simply measures dynamic scale efficiency, in which the marginal cost of effort equals the marginal benefit of effort. However, two other sources of economic efficiency, technical and allocative, are excluded (Squires and Vestergaard 2013b). Full Debreu-Farrell economic efficiency, i.e. technical, allocative, and scale efficiency, is obtained by accounting for technical efficiency in $\pi = \left[P - \frac{c}{qB_t e^{(\lambda+M\psi)t-\mu(t,Z)}}\right] Y_t$ and allowing for allocative efficiency in the formation of the composite input index, effort, so that economic costs are minimized in effort's formation[10] and allocative efficiency in the formation of any composite output index, catch, so that economic revenues are maximized[11] .

B_{MEY} can often be expected to fall below B_{MSY} over time with the relentless march of technological progress, because technological change lowers the costs to fishers from searching and harvesting fish without leaving fish in the water to lower costs (Squires and Vestergaard 2013ab).

The Golden Rule with investment and with and without changes in technology or technical efficiency can be compared to highlight their impact. The Golden Rule for a fishery static in technology and prices, allowing for investment in physical capital, and only dynamic scale efficiency can be written (Clark, Clarke, and Munro 1979):

$$\frac{\partial F}{\partial S_t} + \frac{\left(c_v B + c_f(\gamma+\delta)\right) F(S_t)}{(PqAS_t - (c_v B + c_f(\gamma+\delta)))S_t} = \delta,$$

where the left-hand side is the marginal productivity of the resource stock, the middle term is the marginal stock effect, γ is the discount rate, c_v is all costs other than investment (capital costs are rental prices), and c_f is the fixed cost of investment.

[10] Ratios of marginal products to corresponding ratios of input economic – not necessarily market -- prices are equal.

[11] Ratios of marginal rates of product transformation equal corresponding ratios of economic – not necessarily market – prices.

The Golden Rule allowing for changes in technology that is not embodied in the physical capital stock, investment in physical capital that embodies new technology, and full economic efficiency can be written (Squires and Vestergaard 2013b):

$$\frac{\partial F}{\partial S_t} + \frac{\left(c_v B + c_f(\gamma + \delta)\right) F(S_t)}{(PqAS_t e^{(\lambda + M_2\psi)t - \mu(t,Z)} - (c_v B + c_f(\gamma + \delta)))S_t} + \frac{\left(c_v B + c_f(\gamma + \delta)\right)(\lambda + M_2\psi - \partial\mu(t,Z)/\partial t)}{PqAS_t e^{(\lambda + M_2\psi)t - \mu(t,Z)} - (c_v B + c_f(\gamma + \delta))} = \delta$$

The second term is the modified marginal stock effect and the new term is the marginal technology effect. Technical progress now lowers the costs of search and harvest for fish, so that fewer fish need to be left in the water to lower costs. Prices and costs can also change over time (Clark and Munro 1975).

No-growth steady-state equilibrium MEY estimated from a non-autonomous bioeconomic model and Golden Rule provides an economic target that does not exist – unless the fishery is not subject to the forces of technological change, and also creates a widening gap over time between the autonomous and non-autonomous MEY and foregone net economic benefits due to erroneous management when not accounting for technological change.

5. Consumer surplus and external benefits from biodiversity and ecosystem services

Now consider consumer surplus measured through a general equilibrium inverse derived demand curve and allowing for potential market distortions. Fish price is an economic (shadow) price (denoted P_t^*) that can change over time, and cost is an economic cost (denoted c* and kept constant for simplicity), where * denotes economic values measured by economic (shadow) prices when there are market distortions, and U* denotes consumer surplus measured by economic prices under a general equilibrium inverse derived demand curve for fish. Writing this demand function by $P_t^* = D(Y_t)$, $\partial P_t^* / \partial D(Y_t) < 0$, gives the gross willingness to pay associated with the fish Y_t as $U^*(Y_t) = \int_0^\infty D(Y_t)\, dY$, where as a general equilibrium function all sources of consumer and producer welfare from benefits (other than public good externalities) are captured throughout the value chain (Just, Hueth, and Schmitz 2004). The objective function in the optimization problem now becomes:

$$PV(U^*, \pi^*) = \int_0^\infty \big[U^*(Y_t) - C^*[Y_t, B_t, t, -\mu(t, Z)]\big] e^{-\delta t} dt \ ,$$

where $C^*[Y_t, B_t, r^*, t, -\mu(t, Z)]$ is the economic cost of harvesting (measured in economic prices for inputs, r^*). This economic measure of producer benefits captures benefits from economic rent and employment, can allow for distributional impacts if individuals or households are differentially weighted by some criteria, accounts for market distortions such as overvalued exchange rates, informal labour and capital markets in developing countries or depressed regions, persistent excess capacity throughout the value chain, the common resource stock externality, and all consumer and producer welfare throughout the value chain. The measure of consumer benefits captures benefits from consuming fish.

Now, let $W^*(B_t)$ denote willingness to pay (or accept, depending upon who owns the property right and has standing) for separable consumer utility from external benefits due to the public goods of biodiversity and ecosystem services (Bulte et al. 1998). The total willingness to pay measured in economic prices is then $U^*(Y_t) + W^*(B_t) = \int_0^\infty D(Y_t)\, dY + W(B_t)$. The optimization problem leading to MEY is now written:

$$PV(U^*, W^*, \pi^*) = \int_0^\infty \big[U^*(Y_t) + W^*(B_t) - C^*[Y_t, B_t, t, -\mu(t, Z)]\big] e^{-\delta t} dt \ .$$

This comprehensive measure of consumer and producer benefits provides a comprehensive measure of MEY consistent with microeconomic theory and welfare economics – thereby accounting for market distortions, disembodied and embodied technological change, a more comprehensive dynamic Debreu-Farrell economic efficiency rather than dynamic scale efficiency, and bioeconomic theory.

The corresponding Golden Rule of optimal renewable resource management now allows for both consumer welfare from consumption of fish (direct use values) and consumer welfare from non-market economic values such as indirect use value and existence value due to the public good external benefits of biodiversity and ecosystem services along with accounting for market distortions and changes in technology and economic efficiency. When including the non-market values, $W(B_t)$, the Golden Rule is expanded by a new term called the marginal public effect, accounts for the non-market public benefits from the resource stock, and modifies the term of van Kooten and Bulte (2000) to account for the effects of changes in technology and technical efficiency:

$$\frac{\partial W / \partial B_t}{P - \frac{c}{qB_t e^{(\lambda + M\psi)t - \mu(t,Z)}}}$$

Adding this term will lead to a higher economic optimal stock level of B_{MEY}.

6. Taking stock: MEY vs. MSY

Where does the above discussion leave us in the relationships between MEY and MSY and B_{MEY} and B_{MSY} when accounting for the full economic benefits and costs and market distortions through the use of economic (shadow) prices that accounts common resource and public good externalities and using general equilibrium inverse derived demand functions for fish at the ex-vessel level? A strong case has been made for $B_{MEY} > B_{MSY}$ in many instances (Grafton et al. 2012). Christensen (2009) contends that MSY = MEY when accounting for the full benefits in the value chain. Sumaila and Hannesson (2010) state that MEY differs from MSY, even when the net benefits from the full value chain are included. Throughout our discussion we have implicitly assumed that the fishery regulation is designed so that MEY is a meaningful concept in the first place. Schwindt, Vining and Gloverman (2000) studied Canadian Pacific Salmon Fishery, which in practice was open-access, and concluded that the economic welfare was negative. In such cases MEY is zero. The reason for this result is that they included management cost, and in general these has to be included in cost-benefit analysis and in the assessment of MEY.

Our first key point is that MEY is not the full economic MEY until all market distortions are accounted for through the judicious use of economic (shadow) prices. Accounting for market distortions through economic rather than market prices allows accounting for “social” benefits such as employment and persistent excess capacity as well as market distortions such as taxes, subsidies, controlled prices, official exchange rates, informal capital and labor markets, and the like. We have emphasized that zero shadow prizing of labour when unemployed is, in general, not correct, and that instead there is a positive shadow wage rate.

Second, accounting for changes in technology and dynamic scale, allocative, and technical efficiency but not market distortions other than the common resource externality means that, in many instances, eventually $B_{MEY} < B_{MSY}$, even when properly measuring and accounting for all economic costs and benefits throughout the supply chain. Third, non-autonomous bioeconomic models are ideally required, and if not estimated then constant updating of autonomous bioeconomic models. Fourth, MEY as discussed in the literature ignores the full range of costs and benefits of concern to society, notably those nonmarket external benefits from the (impure or pure) public goods of biodiversity and ecosystem services (a market distortion we single out, and the most important one for fisheries going forward). The discussion on MEY has instead largely (but not exclusively) contented itself with accounting for the common resource’s stock externality. When the public external benefits from leaving fish in the water (biodiversity, ecosystem services) are explicitly incorporated into the dynamic model (Bulte et al. 1998), B_{MEY} increases relative to B_{MSY}, although the relationship is unknown and likely varies over time according to the fishery (Squires and Vestergaard 2013ab).

In sum, until all market distortions and changes in technology and economic efficiency are accounted for, and most notably, the full external benefits derived from biodiversity conservation and ecosystem based fisheries management are understood, measured, and accounted for, whether B_{MEY} is even the full B_{MEY} plus whether or not B_{MEY} exceeds, equals, or falls short of B_{MSY} remain open questions and will undoubtedly vary by fishery. This relationship between B_{MEY} and B_{MSY} is also likely to change and fluctuate over time due to changes in technology, technical efficiency, prices, market distortions, recruitment, the environment, society's preferences and income that increasingly value biodiversity and ecosystem services, and other factors. Some form of adaptive management is undoubtedly required.

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