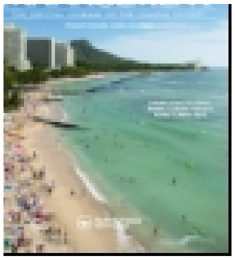

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Reference Points for Optimal Yield: A Framework for Assessing Economic, Conservation, and Sociocultural Tradeoffs in Ecosystem-Based Fishery Management

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ABSTRACT
We propose a conceptual framework for evaluating fishery management performance using conservation, economic, and sociocultural metrics. We develop a value function that weights outcomes for each measure based on their relative importance to decision makers and show how it can be derived from fundamental economic principles (the latter initially in collaboration with Mark Plummer). This approach allows one to explore how Optimal Yield, as mandated by the Magnuson-Stevens Act, varies with biological, economic, and sociocultural weightings.

KEYWORDS
conservation goal; economic goal; sociocultural goal; triple bottom line

Introduction

The Magnuson-Stevens Fishery Conservation and Management Act (1996) mandates that:

1. "Conservation and management measures shall prevent overfishing while achieving, on a continuing basis, the optimum yield from each fishery for the United States fishing industry" (National Standard 1).
2. "Conservation and management measures shall, consistent with…conservation requirements…(including the prevention of overfishing and rebuilding of overfished stocks), take into account the importance of fishery resources to fishing communities by utilizing economic and social data in order to:
   a) provide for the sustained participation of such communities; and
   b) to the extent practicable, minimize adverse economic impacts on such communities" (National Standard 8).

These are great ideas, but the problem is that nobody has yet made this operational, even for data-rich fisheries.

As Ecosystem-Based Fishery Management (EBFM) becomes more common, decision makers and managers increasingly face tradeoffs among conservation, economic, and sociocultural goals (the triple bottom line, TBL). However, arbitrary increases in catch often become a proxy for socioeconomic considerations. This happened, for example, at the

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meeting of the International Pacific Halibut Commission (IPHC) in January 2015 when, in response to a letter of January 20, 2015 from Eileen Sobeck (Assistant Administrator for Fisheries, NOAA Fisheries), the Commissioners increased directed catch limits in IPHC Area 4CDE (Bering Sea) by 800,000 lbs. Conservation goals are intended to protect species dependent upon those targeted or the targeted species itself, but often become an arbitrary decrease of catch limits. However, a 20% reduction in breeding success in 1 year due to fishery-induced prey-depletion is very different for a short-lived species than for a long-lived species.

It is not that the above are bad decisions or rules of thumb, but that they are arbitrary—in part because the tradeoffs involve values that are difficult to be directly compared. Understanding the tradeoffs, however, is essential for a holistic view of the ecosystem. For instance, evaluating tradeoffs between the revenue from a pound of herring, the survival and reproduction of seabirds or mammals eating those herring, and the social capital derived by indigenous people gifting the roe of herring is challenging because their values are non-commensurate. Overcoming this problem is central to operationalizing EBFM in socioecological systems.

Charles (1992) argued that conservation biologists see the purpose of fishery science as conserving fish populations, fisheries sociologists as maintaining fishing communities and their traditions, and fisheries economists as determining wealth generation and distribution associated with harvesting (Figure 1). Poe, Norman, and Levin (2014) use slightly different wording ("ecological integrity," "viable economics," and "sociocultural wellbeing") but emphasize the same vertices as in Figure 1.

A focus on one of the vertices in Figure 1 is a single bottom line (e.g., sustainability of the stock, economic returns, or maintenance of the fishing community). Tradeoffs between two of these involve moving along the line between the vertices (Lee 2010; Levi et al. 2012;

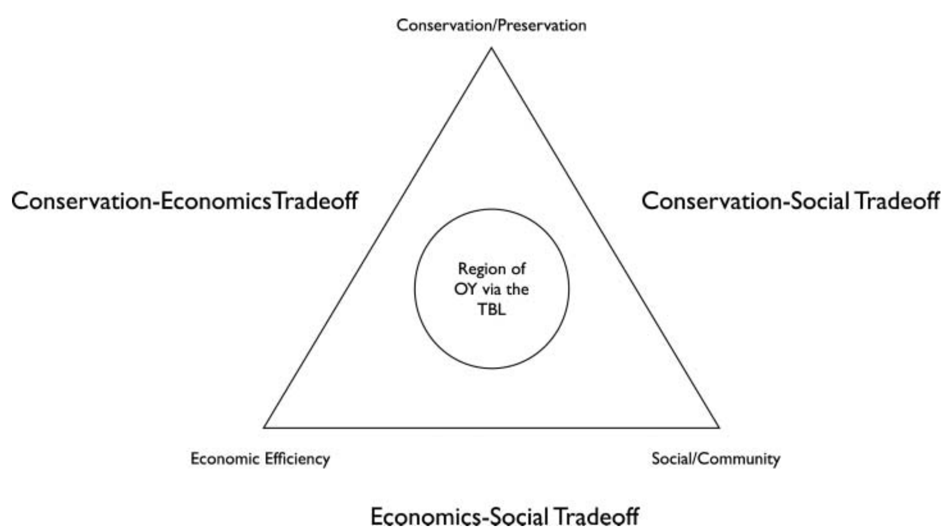

Figure 1. Charles's (1992) representation of fishery science. The vertices correspond to the single bottom lines of a focus on conservation metrics, economic metrics, and social metrics; the double bottom line involves tradeoffs along one of the edges. To consider the triple bottom line, we need to move into the interior of the triangle.

Richerson, Levin, and Mangel 2010). However, optimal yield requires that we deal with all three simultaneously—moving into the interior of the triangle and focusing on the TBL that deals with all three concerns simultaneously (Dichmont et al. 2013; Pascoe et al. 2009, 2013). The problem is even more complex since there are likely to be several social objectives that may not be compatible with each other, let alone the economic and biological ones. However, "[P]roblems are not solved by avoiding them" (Feller 1971, p. 12).

To move from these vertices or edges into the interior requires that we

1. Derive mathematical expressions that relate ecological conditions and management strategies (monitoring, stock assessment and harvest control/decision rules; Butterworth and Punt 2003; Sainsbury, Punt, and Smith 2000) to economic, conservation, and sociocultural metrics.
2. Determine a way to compare these metrics, given that their different units prohibit direct comparison (Mardle and Pascoe 2002; Mardle, Pascoe, and Tamiz 2000).

From the double to the triple bottom line

Previously, Richerson et al. (2010) and Levi et al. (2012) developed a method for addressing the tradeoffs between conservation and economic metrics. Both metrics are mediated by the biomass of the target stock. For example, the economic revenue to the fishery and the production of chicks or total size of a seabird population are generally functions of the biomass of the targeted stock. By developing relationships between percentage changes in conservation and economic metrics as a function of management choices, we create a simple, transparent means for comparing fishery and conservation goals.

When considering conservation and economic tradeoffs only, we proceed as follows: Yield (either biological or economic), $Y(F)$, when the rate of fishing mortality is F, increases from 0 when there is no fishing to a maximum value at F_{MSY} (the rate of fishing mortality giving maximum sustainable yield (MSY)) or F_{MEY} (that giving maximum economic yield). To be specific, we focus on biological yield; over the range $0 \leq F \leq F_{MSY}$, the ratio $\frac{Y(F)}{Y(F_{MSY})}$ increases from 0 to 1. At the same time, biomass of the targeted stock $B(F)$ is decreasing, as is chick production $c(B(F))$ by dependent species [for the case studied by Richerson et al. (2010), kittiwakes and terns]. Hence, the ratio $\frac{c(B(F))}{c(B(0))}$ declines from 1 as the rate of fishing mortality increases.

Richerson et al. (2010) proposed combining these two ratios into a single value function, determined by weighing each. That is, if $0 \leq \omega_c \leq 1$ denotes the weight given to conservation, the value function is

$$V(F \mid \omega_c) = \omega_c \bullet \frac{c(B(F))}{c(B(0))} + (1 - \omega_c) \bullet \frac{Y(F)}{Y(F_{MSY})} \tag{1}$$

Richerson et al. (2010) showed that this value function is relatively flat for a range of values of fishing mortality, and that the loss of revenue when decreasing F below F_{MSY} is more than compensated in a relative sense by the increase in chick production. Using this approach, Levi et al. (2012) analyzed tradeoffs between grizzly bear survival and salmon harvest in Alaska and British Columbia.

To generalize Equation (1) and thus create value function for the TBL, imagine that as a function of management strategy M (e.g., fishing mortality or allowable catch, with $M = 0$ corresponding to no take), we have characterized a conservation metric $C(M)$ (e.g., population size of the target stock itself or production of dependent predators), economic metric $E(M)$ (e.g., net revenue), and social metric $S(M)$. As mentioned previously, we can generally assume that $C(M)$ is a decreasing function of the management strategy, $E(0) = 0$, and $E(M)$ rises to a maximum at M_E^* (e.g., corresponding to maximum sustained yield or maximum economic yield for example). We will assume that there is also a management strategy M_S^* that maximizes the social metric. The generalization of Equation (1) is then to assume that we assign weight $0 \leq \omega_C \leq 1$ to the scaled conservation metric, weight $0 \leq \omega_E \leq 1 - \omega_C$ to the scaled economic metric, and $1 - \omega_C - \omega_E$ to the scaled social metric leading to a value function

$$V(M \mid \omega_C, \omega_E) = \omega_C \bullet \frac{C(M)}{C(0)} + \omega_E \bullet \frac{E(M)}{E(M_E^*)} + (1 - \omega_C - \omega_E) \bullet \frac{S(M)}{S(M_S^*)} \quad (2)$$

Equation (2) provides a way for evaluating all the components of the TBL and for determining optimal yield. The conservation and economic components of the right-hand side are well studied, and the social components less so (although there has been considerable recent activity, Table 1). Our paper has two goals. First, we show how Equation (1) or (2) can be derived from more standard economic arguments. Second, we describe some historical and recent work that allows characterization of social metrics as a function of management strategy.

Unpacking the value function

Following the publication of Richerson et al. (2010), Mangel and Plummer had an exchange concerning the derivation of the value function for the tradeoff between conservation and economic metrics in Equation (1). Mangel and Plummer did not publish that work, we do so here; it generalizes readily to include social factors and thus the TBL, but for simplicity we just consider conservation and economic aspects.

To begin, imagine we conduct a survey and ask people about the "value placed on yield," w_F, and the "value placed on seabirds,"w_B. People can think about value in terms of population sizes because they can relate population size to bird watching or other sources of final value.

If the value function is linear and separable in each of the arguments, the value function of fish yield Y_{Fish} when the bird population is N_{Birds} is then

$$W(Y_{Fish}, N_{Birds}) = w_F Y_{Fish} + w_B N_{Birds} \quad (3)$$

$W(Y_{Fish}, N_{Birds})$ is thus a function that ranks alternative combinations of (Y_{Fish}, N_{Birds}). We assume that $W(Y_{Fish}, N_{Birds})$ has "social-value-utils" as its units. We could use dollars instead of "social-value-utils," because expressing tradeoffs in terms of dollars is easier if one is gathering actual data on preferences; the argument that follows still holds. Because the arguments of $W(Y_{Fish}, N_{Birds})$ are in terms of pounds and numbers, they are not yet commensurate in physical terms. They can be added together because the weights, w_F and w_B, scale to a common unit. They express the social value per unit (pounds and numbers, respectively) of absolute fishery yield and absolute bird population size, so that w_F and w_B have the units of social-value-utils/pound and social-value-utils/bird, respectively. It is also easy to consider that in terms of \$/lb and \$/bird, if one wants to express value in terms of willingness to pay for increases in either.

To derive the value function used in Richerson et al. (2010), we scale yield by its value at MSY and bird population size by its value when there is no fishing, as follows:

$$W(Y_{Fish}, N_{Birds}) = w_F Y_{F=F_{MSY}} \left(\frac{Y_{Fish}}{Y_{F=F_{MSY}}} \right) + w_B N_{F=0} \left(\frac{N_{Birds}}{N_{F=0}} \right) \tag{4}$$

Now, factor $w_F Y_{F=F_{MSY}} + w_B N_{F=0}$ from the right hand side of Equation (4) which allows us to write it as

$$\begin{aligned} W(Y_{Fish}, N_{Birds}) = (w_F Y_{F=F_{MSY}} + w_B N_{F=0}) \left[\frac{w_F Y_{F=F_{MSY}}}{w_F Y_{F=F_{MSY}} + w_B N_{F=0}} \left(\frac{Y_{Fish}}{Y_{F=F_{MSY}}} \right) \right] \\ + (w_F Y_{F=F_{MSY}} + w_B N_{F=0}) \left[\frac{w_B N_{F=0}}{w_F Y_{F=F_{MSY}} + w_B N_{F=0}} \left(\frac{N_{Birds}}{N_{F=0}} \right) \right] \end{aligned} \tag{5}$$

We now define the weight given to the conservation metric by

$$\omega_c = \frac{w_B N_{F=0}}{w_F Y_{F=F_{MSY}} + w_B N_{F=0}} \tag{6}$$

and if we set $\theta = w_F Y_{F=F_{MSY}} + w_B N_{F=0}$, then

$$W(Y_{Fish}, N_{Birds}) = \theta \left[(1 - \omega_c) \left(\frac{Y_{Fish}}{Y_{F=F_{MSY}}} \right) + \omega_c \left(\frac{N_{Birds}}{N_{F=0}} \right) \right] = \theta \bullet V(F, \omega_c) \tag{7}$$

where $V(F \mid \omega_c)$ is the value function in Equation (1), evaluated when the rate of fishing mortality is F and the weighting of the conservation metric is ω_c.

Since θ is a constant once, we specify the values placed on yield and birds, $W(Y_{Fish}, N_{Birds})$, and $V(F, \omega_c)$ will have the same shape as a function of fishing mortality but will scale differently. The mechanics of optimizing $W(Y_{Fish}, N_{Birds})$ with respect to fishing mortality, and optimizing $V(F \mid \omega_c)$ with respect to fishing mortality, are therefore identical (see Richerson et al. (2010), Levi et al. (2012)).

Laying out this transformation illustrates what lies inside the weights of the value function. That is, the transformations from non-commensurate to commensurate values have implications for the composition of these weights. They are positively related to the underlying per-unit values of fishery yields, bird populations, and the social metric, but they are also related to the maximum values of these metrics. This also makes the data requirements for estimating the value function greater than those for estimating $W(Y_{Fish}, N_{Birds})$. That is, if w_F and w_B and other parameter values must be known to choose the appropriate value of ω_c, then using $W(Y_{Fish}, N_{Birds})$ in Equation (7) may be a simpler route to commensurability than scaling and weighting alone[1]. This is because $W(Y_{Fish}, N_{Birds})$ directly transforms yield and bird populations into commensurate *value* units without the intermediate steps of, first, transforming them into commensurate *physical* units, and second, choosing the correct value weights, since the weights emerge from this transformation.

The application of Equation (2) requires quantifying social metrics, so we turn to that.

Characterizing social metrics: A function of management strategy

Early social metrics applied to fisheries are the Lorenz curve and Gini coefficient measure of inequality (Adelaja, Menzo, and McCary 1998; Smith 1990) (Figure 2); they continue to be used (Kitts et al. 2011; Voss et al. 2014). Smith (1990) found, for example, that the Gini coefficient of gillnetters on the Columbia River was 0.31, but that of Oregon salmon fishermen was 0.74. He also showed that the Gini coefficient of gillnetters increased between 1899 and 1971 as the resource decreased. Voss et al. (2014) used the Gini coefficient as a metric of social equity in their modeling of the TBL for cod, herring, and sprat fisheries in the Baltic Sea.

More recent work focuses on the structure of social capital (Easley and Kleinberg 2010; Poe et al. 2014; Portes 1998; Pretty 2003; Putnam 1993, 2000), in which social networks and the associated norms of reciprocity have value. Social capital is simultaneously a private and a public good. Reciprocity through a social network generates healthy communities. Putnam (1993, 2000) showed that social capital is a good indicator of education and children's welfare, safe and productive neighborhoods, health (e.g., age-adjusted mortality rate), and effective government.

Management strategies can create or destroy social capital. Allison and Horemans (2006) called this the "Sustainable Livelihoods Approach." Degnbol and McCay (2007) noted that

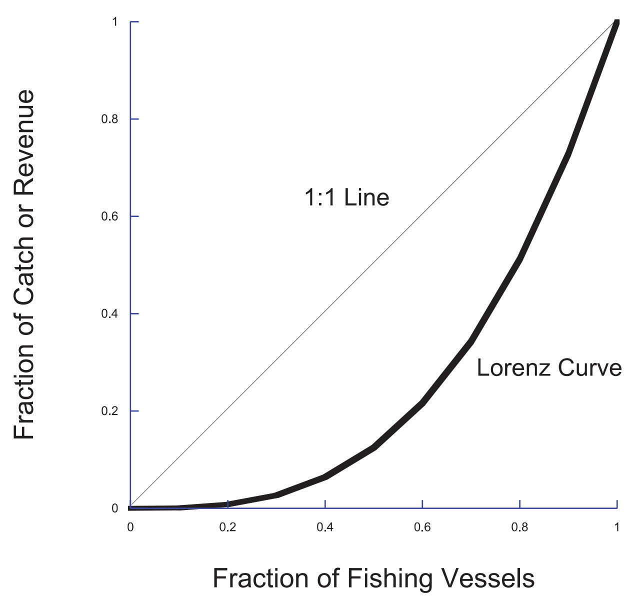

Figure 2. Inequality can be measured by the Gini coefficient. To do this, we first plot the Lorenz curve of the cumulative fraction of fishing vessels on the *x*-axis and the cumulative percentage of dollars earned, fish caught, or some other resource allocation on the *y*-axis. The diagonal line running from the origin to the point (1,1) represents perfect equality. Inequalities are captured in skewed Lorenz curves. The Gini coefficient is twice the area between the 1:1 line and the Lorenz curve; it ranges between 0 (perfect equality) and 1 (perfect inequality).

Table 1. Examples of social metrics for fisheries that have been quantified.

Region and fishery	Social metrics	Additional	Reference
Australia-Papua New Guinea rock lobster fishery	Full-time vs. part-time employment Potential for new entrants Maintenance of traditional customs Community coherence Inequity (both access to fish and unequal distribution of fish) Management complexity Sense of self control		Plaganyi et al. (2013)
Hawaiian longline fleet	Network-based social capital		Barnes-Mauthe et al. (2013, 2015a, 2015b)
Red drum stock enh ancement in Florida	Angler satisfaction per trip		Camp et al. (2014)
U.S. Northeast Region: Catch share programs and harvest cooperatives	Distributional outcomes	If coupled with resource responses to catch shares (Essington et al. 2012) then all three components of the triple bottom line are in place.	Clay, Kitts, and Pinto da Silva (2014)
	Stewardship Well-being		
New England harvest cooperatives	Bonding		Holland et al. (2013)
	Bridging Linking (the connection between the network of fishers and fishery managers) Social capital Information sharing		
Red snapper in the Gulf of Mexico	Social vulnerability indices (including personal disruption, population composition, the level of poverty, the demography of the labor force, and characteristics of housing)	Factors that can shape an individual or community's ability to adapt to change (these exist within all communities regardless of the importance of fishing).	Anonymous (2013); Jepson and Colburn (2013)
	Gentrification pressure indices [including housing disruption, retiree migration, urban sprawl, and natural amenities (or lack thereof)]	Factors that, over time, may indicate a threat to the viability of a commercial or recreational working waterfront, including infrastructure.	
	Fishing engagement and reliance indices (including recreational and commercial fishing engagement and recreational and commercial fishing reliance)	Factors that portray the importance or level of dependence of commercial or recreational fishing to coastal communities.	
West Coast groundfish fisheries	Factors that drive local (vs. regional) fishing activity, such as changes in abundance that the fleets target in common and changes in regulations		Speir, Pomeroy, and Sutinen (2014)
Lake Michigan salmon fisheries	Information sharing		Mueller et al. (2008)
U.K. lobster fishers	Information sharing		Turner, Polunin, and Stead (2014)
Jamaica	Network-based social capital		Alexander, Armitage, and Charles (2015)

when social objectives are not incorporated into management strategies, it becomes difficult to reconcile them with rebuilding a stock.

For fisheries, metrics of social capital can include social cohesion (strength of ties, positions in networks, opportunities for connection), bequest of culture, protection of shoreline, trust, community involvement, the distribution of fish, management complexity, and sense of self-control (Table 1, also see http://www.st.nmfs.noaa.gov/humandimensions/social-indicators/ind-categories, Brinson and Thunberg 2013; Jepson and Colburn 2013; Pascoe et al. 2009, 2013, 2014). Catch share programs (Essington et al. 2012) and Territorial User Rights Fisheries (TURFS; Arbuto et al. 2013), which allow individual fishermen, fishing cooperatives, and fishing communities to take a certain amount of fish implicitly, have social capital as a motivation. Less than a month before the symposium in memory of Mark Plummer, Anderson et al. (2015) published a comprehensive study in which they evaluated nearly 70 individual metrics—ranging from ecological to social-cultural—and used expert assessment to assess the TBL in 61 case studies. However, this approach cannot answer the question of how the TBL tradeoffs vary with management strategy.

Discussion and conclusion

The distinction between economic and sociocultural dimensions will always blur, and several kinds of sociocultural dimensions are routinely analyzed by economists (e.g., social networks, distributional impacts of policy). For example, if a fishing community consists—as it almost always does—of vessels with different operating characteristics and costs, then a simple social metric is the fraction of the fishing vessels participating in the fishery. However, unless the fishery is subsidized, this has a strong economic component.

Conservation and economic metrics are more commonly quantified than sociocultural ones. This need not be the case, although applying these ideas will be challenging. It is relatively straightforward to define a single metric for conservation goals (e.g., probability threshold for meeting the biomass generating MSY if the focus is on the targeted species or the probability that a dependent predator stays above a threshold if the focus is on the predator) and a single metric for economic goals (e.g., exceeding some net revenue threshold), but there may be many metrics for the sociocultural dimension. To account for multiple sub-metrics, we can further modify Equation (2) to write the conservation, economic, and social metrics themselves as sums of sub-metrics.

Richerson et al. (2010) and Levi et al. (2012) found that the value function in Equation (1) for a double bottom line was relatively flat as a function of the weighting of the conservation and economic goals, suggesting that it is important to weigh the two tradeoffs, but that precise weights may not be crucial for approximately optimal results. We generalized this result by developing a simple bioeconomic model (*sensu*Clark 2010) with multiple classes of fishing vessels having different costs of operation and catchabilities; the social metric was the fraction of those vessels able to participate in the fishery. We discovered that the value function from Equation (2) was relatively flat over a range of weights of the three components. The generality of this result is not clear, so we hesitate to make a firm statement, but our investigation shows encouraging results given their consistency with the previous work.

Achieving optimum yield requires that we explicitly model the behavioral dynamics of fishers and investigate the implications of management (Salas and Gaertner 2004). That is, traditional fishery management models treat the mortality due to fishing as an aggregate value, but what is required here is the development of explicit models of the behavior of fishing vessels so that one can calculate Lorenz curves or network properties. Work is being done in this direction already (Dowling, Wilcox, and Mangel 2015; Dowling et al. 2012; Mangel and Clark 1983; Mangel, Dowling, and Lopez Arriaza 2015; Mangel and Plant 1985; Mueller et al. 2008; Palmeter 1991; Ramirez-Sanchez and Pinkerton 2009; van Putten et al. 2012), so it is reasonable to envision fish population dynamic models embedded in social networks of fishing vessels.

Our proposed method is targeted at managers, fishery management councils, scientists, and stakeholders with the intention of increasing their ability to consider a richer range of tradeoffs than currently possible. This will allow more thorough policy analysis of the costs and benefits associated with management strategies. Our approach will provide a quantitative method firmly based in biological, economic, and sociological principles for setting target reference points for fisheries that account for the needs of other species as well as human communities.

Many challenges remain, of course. Multi-sector fisheries are most directly confronted with the TBL; yet their data quantity and quality are often mixed; reference points and performance indicators vary between them; and environmental, economic, and social information for both sectors is often limited. The TBL has yet to be operationalized within a harvest strategy context. A harvest strategy framework specifies predetermined management actions in a fishery to achieve management objectives via monitoring, assessment, and harvest control rules. As opposed to a broader management strategy or procedure, harvest strategies focus on controlling exploitation rates for relevant species. We have recently started applying the ideas developed in this paper to multi-sector fisheries in Queensland, Australia, with the goal of characterizing the TBL for those fisheries and thereby giving an example of how the ideas can be applied and generalized.

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Note

1. This was Mark Plummer's insight after reading Richerson et al. (2010).

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