**Requiem for Ricker: Unpacking MSY**

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**Abstract**

Much like the Cornucopia myth of the 19th and early 20th centuries, MSY as a management tool simply won't go away, regardless of evidence that managing for MSY has not been effective. Consequently, we investigate Ricker's definition of MSY, focusing on words such as *average catch*, *continuously taken*, and *existing environmental conditions*. To do this, we develop a model for the squid fishery in California; this is probably the last great open access fishery on the west coast of the US. By constructing the model in a step-wise fashion, one is able to illustrate particular points. Insight from the model leads to a deeper understanding of the definition of MSY, particularly that different methods of averaging and explicitly including risk to the stock in MSY may allow MSY to be used in the context of precautionary fishery management. Finally, we summarize results from the Third Mote Symposium that also shed light on this issue.

**Introduction**

In his classic book, Ricker (1975) defined MSY:

> MAXIMUM SUSTAINABLE YIELD (MSY OR YS): The largest *average* catch or yield that can *continuously* be taken from a stock under *existing environmental conditions*. (For species with fluctuating recruitment, the maximum might be obtained by taking fewer fish in some years than in others).

(Italics added and understanding the full implications of these words is the point of this paper). However, two years later, Peter Larkin (1977) proposed that we bury MSY:

"An epitaph for the concept of Maximum Sustained Yield"

M.S.Y.

1930s-1970s

Here lies the concept, MSY.
It advocated yields too high,
And didn't spell out how to slice the pie.
We bury it with best of wishes.
Especially on behalf of fishes.
We don't know yet what will take its
place.
But hope it's as good for the human race.

MSY, much like the 19th and early 20th century Cornucopia myth of the limitless bountiful ocean, seems to have a life of its own. Indeed, Kurlansky's (1997, pg 186) comments about the Cornucopia myth could just as easily apply to MSY

> Furthermore, the Kirby report [a Canadian government report ca. 1990 to assess the future of Atlantic fisheries] was still being influenced by Huxley's teaching about the resilience of indestructible nature. The idea itself to have more resilience than nature… As with the sixteenth-century belief in a westward passage to Asia, the theory cannot be killed by mere experience.

The usefulness (or lack thereof) of the concept of MSY hinges on how we understand the words that are marked in italics in Ricker's definition and that is what we explore in this paper. To do so, we will examine the meaning of MSY in the context of the squid fishery in central California (Pomeroy and Fitzsimmons 1998).

**The Squid Fishery in Central California**

The commercial fishery for California market squid (*Loligo opalescens*) dates from the 1860s in Monterey, when the Chinese used torches to attract squid and caught them using small purse seines (Dewees and Price 1983; Lydon 1985). In 1905 Monterey's Italian fishermen introduced lampara nets into the fishery. The fishery was centered in the Monterey Bay area until the 1960s, when the introduction of the power block, round haul gear and other innovations facilitated the development of the southern California fishery, primarily targeting spawning aggregations around the Channel Islands (Dewees and Price 1983). Through the 1960s and 1970s, the southern California fishery continued to grow, while the Monterey Bay fishery remained relatively constant. Although interest in California market squid as a potential focus of fishery development prompted attention to its biological and ecological aspects, and to the development of processing and marketing strategies, annual squid landings remained below about 25,000 mt through those years, due largely to limited demand (Pomeroy and Fitsimmons 1998). The fishery was sustainable at these low level of landings.

Following extremely low catches associated with the 1982-83 El Niño, southern California landings increased steadily, outgrowing those of the Monterey fishery, where landings held at around 10,000 mt per year. By 1995, squid ranked first in volume and second (to sea urchin) in value among California commercial fisheries; by 1996, it ranked first in both volume and value, with landings of more than 86,000 mt, worth over $32 million (Starr et al. 1997, Pomeroy and Fitzsimmons 1998). In late 1997 through early 1999, however, both southern California and Monterey landings plummeted during El Niño conditions (Figure 1). Statewide landings of squid dropped to just under 3,000 mt, and 17 tons were landed at Monterey area ports in 1998. The southern California fishery rebounded in 1999, with over 90,000 mt worth almost $32 million landed; squid have returned more slowly to Monterey. Since the early 1980s, catch per unit effort (CPUE), measured as tons per landing, appears to have increased, both in the Monterey Bay area and for the fishery as a whole (Figure 2). However, there have been important technological, capacity and regulatory changes that contribute to CPUE. The increase in CPUE may reflect these more than the availability of squid; alternatively the increase may reflect a nonlinear relationship between squid abundance and catch, due to schooling behavior of squid and non-random distribution of fishing effort.

These trends in landings and CPUE are the product both of the changing availability of squid and of changing economic and regulatory conditions within and outside the squid fishery. Domestic markets have grown as consumers have come to value the nutritional benefits of seafood in general, and have developed a taste for squid products marketed under the more appealing name of "calamari." Fluctuations in other squid fisheries (e.g., Falkland Islands) and the opening of new markets increased international demand from both traditional consumers (e.g., Greece, Italy) and new ones, most notably China in the mid 1990s. The scarcity of squid soon after the onset of El Niño conditions in late 1997, however, led to the loss of many of these markets especially as ex-vessel prices increased from about $300 to well over $500 per ton. This high-priced squid did not move as quickly, and receivers accumulated inventories of frozen, packed squid. When the squid returned to California waters in abundance in mid 1999, landings jumped, but vessels were placed on limits of half their capacity or less, while ex-vessel prices declined to $250 per ton or less.

Regulatory changes also played a role in the development of the squid fishery and the observed trends in landings and CPUE. Historically, squid fishing has been regulated by the state with legislative measures that restrict the use of lights to attract squid, limit on days or times when fishing is allowed, and for several years, prohibition on the use of purse seines in Monterey Bay (Dewees and Price 1983). The 1989 removal of the ban on purse seine gear in the Monterey Bay fishery led to its nearly universal adoption and to the subsequent increase in vessel size to accommodate the new gear. This enabled more of the Monterey fleet to venture south to participate in the winter fishery around the Channel Islands. In 1997, the California Legislature passed SB 364, instituting a $2500 permit requirement for fishing vessels and light boats to participate in the squid fishery, with the funds to be used to support a three-year program of research on the resource and the fishery toward the development of a conservation and management plan (CFG Code Sec. 8420-8429). With the prospect of limited entry coming to one of the last open access fisheries on the west coast of the US, 241 vessel owners purchased squid fishery permits for the temporary limited entry. Permittees include both historical and prospective participants, who now seek to establish landing records in the hope of qualifying for the anticipated permanent limited entry system. One consequence of this is that the capacity of the fleet, based on vessel net tonnage, has increased. CDFG estimated the fleet's maximum capacity in 1995 was 4,520 net tons, compared to 3,640 net tons in 1982. Based on net tonnage of vessels that had landings in 1997, it appears that overall fleet capacity had risen to over 6,000 net tons that year.

In addition to the change from lampara to purse seine gear, other technological innovations have increased the efficiency and scope of squid fishing operations. These include the fish pump, depth sounders and sonar, and the use of light boats - small vessels that scout for fishable aggregations, and using halogen lamps to attract and hold the squid for a seiner to catch. These have facilitated the spread of the central California fishery from the inner waters of Monterey Bay to outer bay waters, while the southern California fishery has expanded its coverage of Channel Islands fishing sites.

As the size of the take of market squid increased, concerns about the sustainability of the fishery also increased. As of this writing (November 2000) the Statistical Committee of the Pacific Fisheries Management council is planning a stock assessment review committee in spring 20001. Simultaneously, the California Department of Fish and Game (CDFG) plans to propose draft Fishery Management Plan recommendations by late December 2000. CDFG is considering the use of two real-time management options instead of an MSY. Their first is an escapement-based procedure, involving developing an index relating the weight of a mantle section and the degree to which a female has spawned. The second is a DeLury model, similar to the ones used in the Falkland Islands (Beddington et al. 1990, Rosenberg et al 1990); however estimates of effort, which are needed for removal methods, are still difficult to obtain.

**Krill and Squid in the California Current System**

Euphausiids, or krill, have the highest biomasses of all zooplankton grazers in the central California upwelling system (Barham 1957, Benson et al. in press, Marinovic et al. in press). Krill form a key trophic link in coastal upwelling systems between primary production and higher trophic level consumers (Loeb et al. 1997). Squid feed almost exclusively on krill (Karpov & Caillet, 1972). Thus, squid form the apex of a relatively simple, directly linked trophic system consisting of upwelling-induced nutrient enrichment, phytoplankton, krill, and squid. The productivity of this linked system is strongly affected by interannual events such as El Niño (Hayward 1996, McGowan et al. 1998).Largescale declines in zooplankton (and especially krill) abundance occured in the central California upwelling system during the 1997/98 El Niño

(Marinovic et al, in press), and similar observations were made off southern Calfironia during both the 1982/83 and 1997/98 El Niño events (McGowan et al, 1998.) As described above, market squid landings in California declined drammatically following both these events. The abundance and spatial distribution of kril is also connected to environmental conditions within a year (Figure 3b). The upweling index ($m^3$/second-100m of coastline) in this figure is calculated on the theoretical relationship between wind (resolved to a N-S vector) and Ekman transport resulting from Coriolis deflection. The wind data are obtained from the Navy in the form of $3^o$ surface pressure fields and then the resulting upwelling is calculated. (A detailed description of how the upwelling index is calculated can be found at http://www.pfeg.noaa.gov/products/PFEL/modeled/indices/upwelling/NA/how_computed.html)

The simplicity of the connection between physical and biological components and the relatively simple food web thus allows us to understand much about the system with simple models.

**A Model Allowing Us to Unpack MSY**

We now develop a conceptual model of the krill-squid fishery in California. We focus on yearly population dynamics, although it is known that squid can have flexible growth and reproductive strategies (Boyle et al 1995, Brodziak and Macy 1996, Maxwell and Hanlon 2000). Also, for simplicity, we use catch numbers rather than biomass and thus ignore growth and environmental determinants of maturation (Odor 1983), and yearly levels of effort rather than within season management (e.g. Beddington et al. 1990, Rosenberg et al 1990). The next step in the unpacking of MSY would be to add these features, because we know already that there are marked within-season differences in fishing mortality and squid migration patterns (Brodziak and Rosenberg 1993) and that in some squid fisheries at least there may be multiple cohorts that recruit to the fishery (Agnew et al. 1998) However, for purposes of beginning to unpack MSY, the simpler model suffices.

Characterizing the Dynamic States

The model has terms that represent environmental forcing in the California Current system, krill abundance, and density-dependent availability of recruited squid biomass. The symbols characterizing these are

$E(t)$ = environmental state

$K(t|E(t))$ = krill abundance, depending upon the environmental state

$S(t)$ = squid abundance (measured in recruited biomass),

depending upon krill abundance

(1)

For simplicity, we assume that the environment exists in one of two states, denoted by $E(t)=1$ or $E(t)=2$ with transitions between them given by a Markov process (see MacCall 2001 for an example and additional references)

$$\Pr\{E(t+1) = j \mid E(t) = i\} = p_{ij} \tag{2}$$

Thus $p_{i1} + p_{i2} = 1$, for i=1 or 2. We refer to $p_{ii}$ as the "repeatability" of the environment, since it measures the likelihood that next year's environment (but not krill abundance, see below) will be the same as this year's environment. On average, the probability that the environment is in state 1 is given by

$$\bar{p} = \frac{p_{21}}{1 - p_{11} + p_{21}} \tag{3}$$

For simplification we set $p_{11}=p_{22}$.

The environment itself is not observed; instead an upwelling index $U(t)$ is observed, related to the environmental state according to

$$U(t) = E(t) + \sigma_{env} Z(t) \qquad (4)$$

In this equation $\sigma_{env}$ is the standard deviation of the observation uncertainty (Hilborn and Mangel 1997) and Z(t) is a normally distributed random variable with mean 0 and standard deviation 1.

Given that the environmental state is i, we assume that krill abundance follows a gamma density with mean $\bar{k}(i) = \frac{\nu}{\alpha(i)}$ and shape parameter ν, which is assumed to be the same for both environmental states. Thus, the frequency distribution for K(t) = k is

$$f(k|E(t) = i) = c_n(i) \exp(-\alpha(i)k)\, k^{\nu - 1} \qquad (5)$$

where $c_n(i)$ is a normalization constant (Figure 4).

Squid dynamics are characterized for a semelparous annual species by

$$S(t+1) = \frac{K(t|E(t))S(t)}{1 + \left(\frac{S(t)}{S_c}\right)^b} \exp(-M) \qquad (6)$$

where $S_c$ is critical value of squid abundance at which density dependent effects become important, b is a shape parameter for squid recruitment, and M is natural mortality.

<u>The Case of Constant Environments</u>

To begin, one can iterate Eqn 6 for the case in which krill abundance is fixed at the average value for the environment. That is, K(t|E(t)) is replaced by $\bar{k}(i)$, for i=1 or 2. Doing this shows that, on the assumption of a constant environment and constant krill recruitment, environment type 1 leads to squid steady state population about 480; environment type 2 to squid steady state about 1510.

Still maintaining the assumption of constant environment and constant abundance of krill, it is now possible to include fishing and consider MSY. The squid population dynamics are now

$$S(t+1) = \frac{K(t|E(t))S(t)}{1 + \left(\frac{S(t)}{S_c}\right)^b} \exp(-M-F) \tag{7}$$

where F is fishing mortality. Catch in year t, C(t), is (Quinn and Deriso 1999)

$$C(t) = S(t)(1-\exp(-M-F))\frac{F}{F+M} \tag{8}$$

and the average cumulative catch between year t=1 and t=T is

$$C_T = \frac{1}{T}\sum_{t=1}^{T} C(t) \tag{9}$$

Note that this is an arithmetic average.

Each level of fishing effort generates a value for maximum sustainable yield (MSY), an optimal level of fishing mortality ($F_{MSY}$) and a steady state squid biomass ($B_{MSY}$). In environment 1, these are about MSY=31, $F_{MSY}(1)$=0.14, and $B_{MSY}$ =268; in environment 2, they are MSY =370, $F_{MSY}(2)$=0.62, and $B_{MSY}$ = 869; see Figure 5.

## Mis-matches Between the Environment and Fishing Effort

Environments are not constant and krill abundance fluctuates. This means that there is the possibility of a mis-match between fishing mortality and the environment. Continuing to keep krill recruitment constant, one may ask what happens if the mismatch occurs and the environment is constant, but the “wrong” one for the fishing mortality. This is not a question for rocket science: if the fishing effort for environment type 1 is applied in a constant environment type 2, the squid steady state is higher (1363 vs 869) and the cumulative catch is lower; on the other hand if the fishing effort for environment type 2 is applied in a constant environment type 1, the squid will be driven towards biological extinction (although economic extinction is likely to occur beforehand), but the total catch taken from the environment is greater.

The Case of Fluctuating Environments

To take account of fluctuating environments, according to the Markov process described previously and to allow for fluctuating krill recruitment, one must develop the stock dynamics with a Monte Carlo simulation, rather than numerically solve the stock equations. We begin by determining the state of the environment, according to the two state Markov process described above, and from this krill availability. Then by cycling over a fixed level of fishing mortality (see below for "adaptive" approaches to fishing mortality) and applying Eqns 7 and 8, we determine the squid stock dynamics and the catch in each year.

The cumulative average catch described by Eqn 9 is an arithmetic average. However, it is also possible to compute average catches by either a geometric or harmonic average; these are

$$C_{GM} = \left[\prod_{t=1}^{T} C(t)\right]^{1/T} \qquad (10)$$

for which

$$\log(C_{GM}) = \frac{1}{T}\sum_{t=1}^{T} \log(C(t)) \qquad (11)$$

and

$$C_H = T\left[\frac{1}{\sum_{t=1}^{T}\frac{1}{C(t)}}\right] \qquad (12)$$

Which of these averages (arithmetic, geometric or harmonic) Ricker meant in his definition is uncertain, but as will be seen below the choice matters. Once the averaging method is picked, it is possible to determine the economically optimal level of fishing mortality, where optimal is understood to mean maximizing the catch over 100 years per simulation and 500 simulations. The optimal level of fishing mortality, for the parameters used here, was relatively insensitive to the value of $p_{ii}$ over the range from 0.55 to 0.8. However, it was sensitive to the averaging method used. For the arithmetic average, the optimal value of fishing mortality was about 0.3, whereas for the geometric average it was slightly higher than 0.2 and for the harmonic average it was slightly lower than 0.2. These should be compared with the constant environment values of 0.14 and 0.62; note that even the arithmetic average is not simply an average of the two optimal values for constant environments.  The lower levels of fishing mortality for geometric and harmonic averages translate into lower yearly and cumulative catch and higher stock abundance.

When the environment fluctuates there is always a chance of depleting the stock and putting it at risk (Musick 1999).  “Depletion” is relative term and one must thus be careful about its definition.  For the results shown here, we assumed that a depletion event occurred if the squid stock in a particular year was less than 30% of $B_{MSY}$ in constant environment 1.  This translates to a depletion level of about 80.  In this model, squid can be depleted for two reasons. First, krill recruitment may be poor, leading to poor squid recruitment. Second, fishing effort may be too high for the given level of squid. Of course, the two are not mutually exclusive and can interact with each other. The risk to the squid stock increases as $p_{ii}$ increases (Figure 6), because one is more likely to be “stuck” in the poor environment, and it depends upon the averaging method used.  However, by using a risk-averse averaging method (in this figure, a geometric average) one may reduce the risk to the stock.

Using Environmental Cues.

We have assumed that the environment and krill stocks are not directly observable. However, it may be that an environmental cue, such as upwelling (Eqn 4) is available. If this environmental cue provides some information about the availability of krill, then one may be able to do a better job of managing both catch and risk by using the cue.

For example, one might adopt the rule that if the upwelling index is below a threshold, then the environment is likely to be type 1 and a lower level of fishing effort is applied; otherwise a higher level of fishing effort is applied. There are, of course, an infinite number of ways of achieving this rule, but a simple one is a bang-bang control

$$F(t) = \begin{cases} F_{MSY}(1) \text{ if } \; U(t) \quad U_{thr} \\ F_{MSY}(2) \text{ if } U(t) > U_{thr} \end{cases} \qquad (13)$$

where $U_{thr}$ is an adjustable parameter.

In Figure 7, we show the (arithmetic) average catch and risk as a function of the upwelling threshold for the case in which $p_{ii}$=0.65. For comparison, when fishing effort is fixed, the average catch is only 3% higher (100.8 vs. 97.8), but the risk is nearly 20% higher (0.37 vs 0.31). Thus, using this simple rule leads to equivalent catches but less risk to the stock. More complicated rules could be developed, of course, but the point of this illustration would not change. Thus, an environmentally based feedback rule may have much the same effect as a risk-averse averaging method of reducing the risk to the stock without having a severe negative impact on catch.

One of the problems with a rule such as Eqn 13 is the question of what happens to excess effort in years in which fishing mortality is intended to be lower. This requires that one model the behavior of the fishing fleet, given a circumscribed set of opportunities; we are currently doing this.

**Implications of the Mote Symposium for Unpacking MSY**

To be sure, all kinds of information are needed for the successful management of human intervention in ecosystems (Mangel et al. 1996, Pomeroy and Fitzimmons 1998). Ricker's definition says nothing about the risk to the stock, which somehow must be included as one considers management action and biological reference points. The power of computing that exists today, which did not when Ricker published in 1975, allows us to evaluate management action in a prospective manner (Overholtz 1999). Ricker's definition hinges on three notions: average, continuously and existing environment. The model here suggests that, given uncertainties and fluctuations in the world, one may want to choose a averaging method that is, of itself, risk averse. Both harmonic and geometric averages have that feature. Furthermore, catch can be taken continuously only if there are no interruptions, showing that maximum biological production must be modulated by the risk of stock collapse if one aims to determine MSY according to Ricker's definition. Finally, by existing environment, one must have a broad understanding of the temporal pattern of the environment; local understanding is insufficient.

The papers at the Third Mote Symposium, included in this volume, shed light on different aspects of average, continuous and existing environment. We now review those contributions.

## Biological Considerations

We must recognize from the outset that setting fishing mortality on the basis of current abundance relative to unfished stock size $B_0$ is based on a theoretical construct (unfished stock size) which surely depends on existing environmental conditions (Hilborn 2001, Walters and Martell 2001).

Biological reference points such as MSY may be meaningless for specie) of limited mobility, species with complex life histories, mixed stock fisheries or stocks with long-term changes in productivity (Parma, pers. Comm., MacCall 2001).

Classic bioeconomic analysis (Clark 1985, Clark and Munro 2001) leads to the prediction that the bionomic population size (at which the fishery in aggregate makes no money) is $N_b = c/pq$ where c is the cost of unit effort, p the price of a unit of fish biomass and q the catchability coefficient. Note that the bionomic population size has no "bio" in it; this may indeed be the source of many of our management problems: the bioeconomic approach treats all biology as identical.

Regardless of what the economists say, there is importance in knowing the organism one studies (Mangel 1993) and of doing biology on the harvested species (Bolker et al. 2001, Hilborn 2001). Furthermore, we should seek to integrate diverse information at the population, behavioral and physiological level (Essington and Kitchell 2001) and exploit both fishery and fishery-independent data (Harris 2001) in our attempts for better management. MacCall (2001) shows that rebuilding a slow-growing stock in a multispecies fishery may require exceptionally long periods of time because of the combination of environmental regime shifts and competitive and predator-prey interactions.

Fishing pressure is a form of artificial selection (Mangel et al. 1993) and we should expect that evolution (e.g. towards smaller size or younger age at reproduction) will occur (Heino and Godø 2001)

Technical Issues

We must be prepared to work with models that have parameter, process, observation, structural and implementation uncertainty (Charles 2001, McAllister and Kirchner 2001, Nowliss and Bollerman 2001, Siddeek 2001). Doing this will provide great benefits. For example Kinas (2001) showed how Bayesian analysis of population dynamics and data on anthropogenic (incidental take) mortality allow one to separate the current size of a stock from its trajectory. The technical problems are considerable but not insurmountable. For example, de Valpine (2001) shows how an approach based on paths in state space (Schulman 1981, Freidlin and Wentzell 1984) can allow one to fit models with both process and observational uncertainty.

No analysis of a fishery should proceed without multiple hypotheses (Hilborn and Mangel 1997) that compete with data as the arbitrator. Imagine, for example, if Canadian scientists charged with thinking about the cod fishery had observed an increase in the catch of Age-3 cod and considered multiple hypotheses:

- The catch of Age-3 cod increased because spawning biomass increased.
- The catch of Age-3 cod increased because of evolution of age at maturity.
- The catch of Age-3 cod because fishermen targeted them.

For what they actually did, see Hutchings and Myers (1994) or Hutchings (1996).

We must have models that incorporate fisherman behavior (Cox and Beard 2001, Clark and Mangel 2000, Wilen et al. 2001). Doing this is more than optional: it is an essential task if we are to avoid unpleasant surprises (Wilen et al. 2001). In that context, we might actually ask if fishermen ever try to optimize (vs. satisfice) their catch and consider replacing the notion of Maximum Sustainable Yield by the concept of Pretty Good Yield.

To some extent, Congress already did that with the Sustainable Fisheries Act (1996) and its emphasis on sustainability rather than maximum or optimal yield.

<u>Importance of Prospective evaluation of Management Procedures</u>

Prospective evaluation of the management procedures, which includes fishing controls, monitoring, and decision rules for altering fishing controls or monitoring, to determine those which satisfy the performance criteria (de la Mare, 1998; Cooke 1999; Sainsbury *et al.* 2000) are essential. They involve

- Data
- Decision Rules
- Advance agreement on how data is used in decision rules
- Testing (by simulation)

Indeed, it is often the lack of any management framework that causes problems, rather than a particular management framework (Polacheck 2001).

The evaluation of management procedures prior to their implementation provides the opportunity to eliminate management options that would fail to meet the objectives, thereby potentially avoiding a trial and error approach that has led to stock collapses (e.g. whales – Holt 1998; finfish - Ludwig *et al.* 1993). Methods for the development of new fisheries and for managing existing fisheries while introducing a precautionary approach that accounts for uncertainty have been developed by the Scientific Committee of the Commission for the Conservation of Antarctic Marine Living Resources (Constable *et al.* 2000) and the FAO (FAO 1995). The elements to consider in a management procedure and its evaluation are well described (de la Mare 1998; Sainsbury *et al.* 2000; Smith *et al.* 1999). Such evaluation allows the implementation of a management procedure that is most likely to achieve the objectives despite uncertainties in the various parts of the system, including the limitations of a monitoring program, such as incomplete data and low power in assessments. It can also be used to ensure that the costs of management are commensurate with the value of the fishery.

Such forward projection is essential if we are to be able to evaluate short-term costs and long-term benefits (Peterman 2001).

Furthermore, prospective management allows us to explore the consequences of possible management procedures -- and to understand the range of dynamics of the stock-- as well as allowing us to deal with discarding, incidental take, habitat damage and food web effects (Essington and Kitchell 2001).

Connection between science and policy

Perhaps the most important conclusion that we can draw concerning the connection between science and policy is that the ultimate technical result is that the problem is not a technical one (Ludwig 2001).

Management must be transparent with clear and multiple metrics (Brodziak and Link 2001). Data-based rules, rather than assessment-based rules, may be a step forward (Hilborn 2001); Martell and Walters (2001) provide an example showing how monitoring effort and catchability coefficients via tagging may be more cost-effective and risk averse than standard methods.

The connection between science and policy also hinges on understanding the human behavioral response to property rights and incentives. Without doing this, well-intentioned plans may have exactly the opposite effect from the one desired (e.g. Clark and Munro 2001, Cox and Beard 2001). Similarly, understanding consumer behavior, for example in relation to eco-certification of product may provide an incentive for dealing effectively with uncertainty and risk (Peterman 2001)

We should manage so that precise reference points are not needed and if they are desired, we should use meta-analysis to construct them (R. Myers, pers. comm). Management (Brodziak and Link 2001) must be accountable(explicit about decision criteria), legitimate (explicit about policy strategies), and flexible (explicit about uncertainty) and must also carefully deal with issues concerning burden of proof (Charles 2001).

Regardless of the technical or scientific considerations, management is an “incredibly tortuous negotiation process” (A. Rosenberg, pers comm) so we must be pragmatic:

> Being pragmatic does not mean the rejection of rules or principles in favor of ad hoc decision making or raw intuition. Rather, it means a rejection of the view that rules, in and of themselves, dictate outcomes. ...Hard policy decisions can't be programmed into a spreadsheet... But we also need an analytic framework to help structure the process of making environmental decisions... Rather than rigid rules or mechanical techniques, we need a framework that leaves us open to the unique attributes of each case, without losing track of our more general normative commitments.

(Farber 1994).

**Conclusion: Wisdom from John Gulland**

We began the paper quoting Bill Ricker and Peter Larkin, giants of fishery management in the 20th century. It seems only appropriate to end by quoting John Gulland:

MSY

A quantity that biologists say does not exist. That economists say would be irrelevant if it did exist. It is, in short, the most important concept in fisheries management.

(R. Hilborn, personal communication).

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**Table 1 Parameters and Their Values**

| Parameter | Interpretation | Value | |
|---|---|---|---|
| $p_{ij}$ | Probability of transition from environment state i to environment state j | Varies | |
| $\bar{k}$ | Mean of the gamma density characterizing abundance of krill | | 1.5 or 4.0 |
| $\nu$ | Shape parameter of the gamma density characterizing abundance of krill | | 3 |
| $S_c$ | Squid abundance level at which density dependence begins to be important | | 1000 |
| b | Shape parameter in squid recruitment distribution | | 2 |

| | | |
|---|---|---|
| M | Squid natural mortality | 0.2 |
| $\sigma_{env}$ | Observational uncertainty of the upwelling signal | 0.2 |
| $U_{thr}$ | Threshold value of the upwelling index when fishing with cues | Varies |

Captions for figures

Figure 1. Statewide (panel a) and Monterey Bay (panel b) landings of squid, 1981-1999.

Figure 2 Mean tons of squid per landing (a measure of catch per unit effort) and, in the standard Schaefer model, a proxy for population size

Figure 3 Relationship between acoustic backscatter from krill and an upwelling index in Monterey Bay showing that krill abundance correlates with the index of upwelling.

Figure 4. Frequency distribution of krill abundance generated by Eqn 5 under the two different assumptions about the environment.

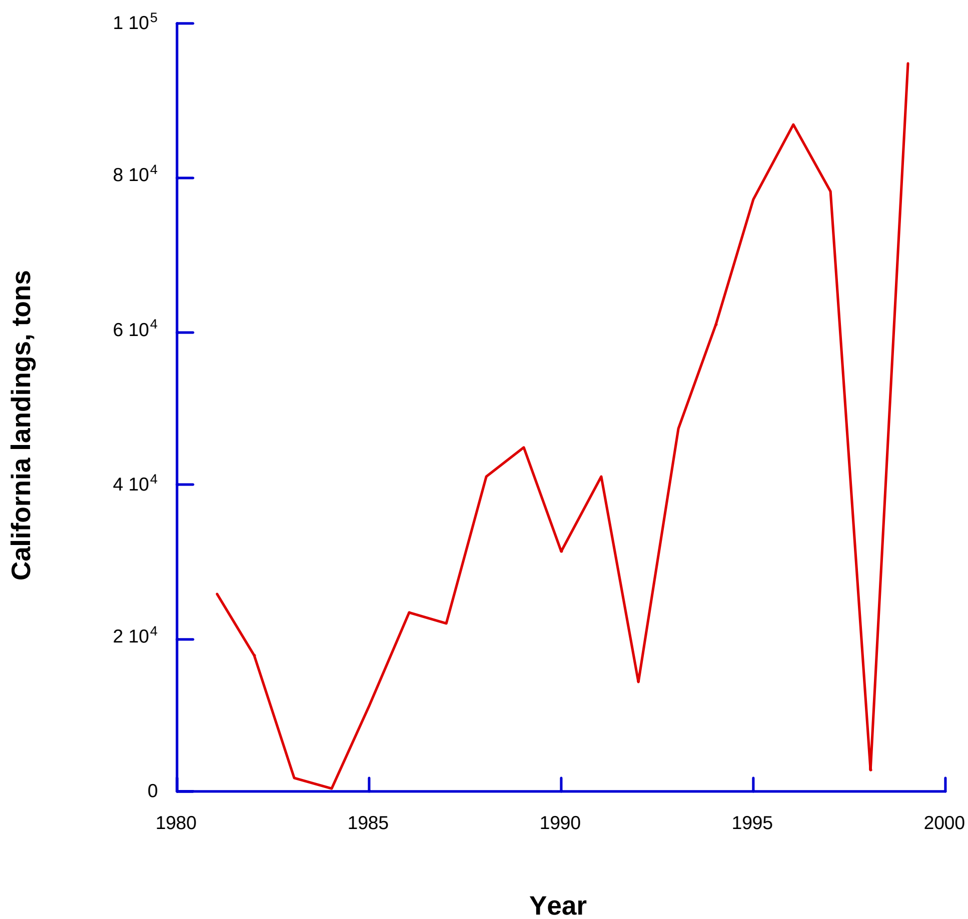
Figure 5 Squid abundance and cumulative catch on the assumption of constant environment and constant krill recruitment. a) E=1, with lower krill recruitment. b) E=2, with higher krill recruitment

Figure 6 Risk to the squid stock (falling below 30% of the steady state value for constant krill in constant environment 1) as a function of environmental repeatability and the averaging method used to determine fishing mortality. The result for the harmonic average is similar to that for the geometric average and thus not shown.

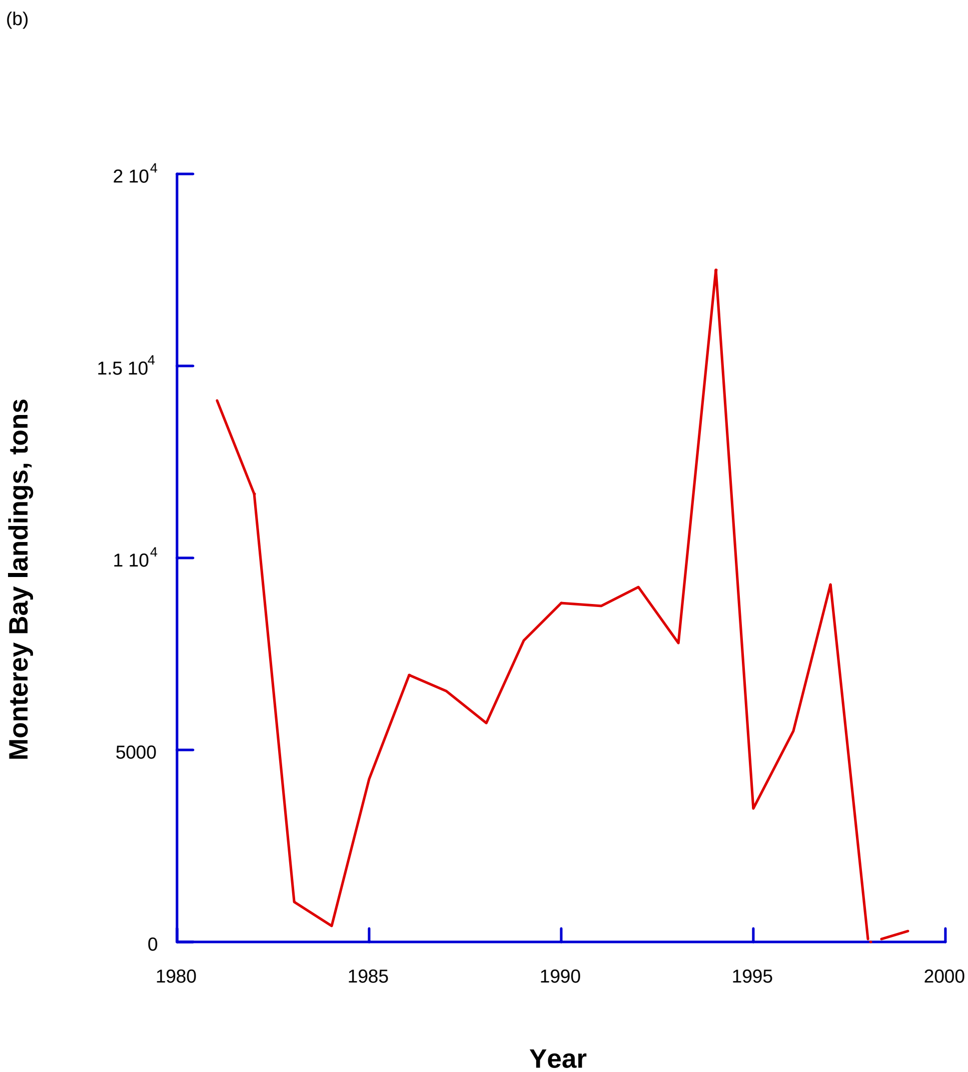
Figure 7 Average catch (over the 100 year period of 500 simulations) and risk as a function of the upwelling threshold (Eqn 13).

Mangel et al Figure 1a

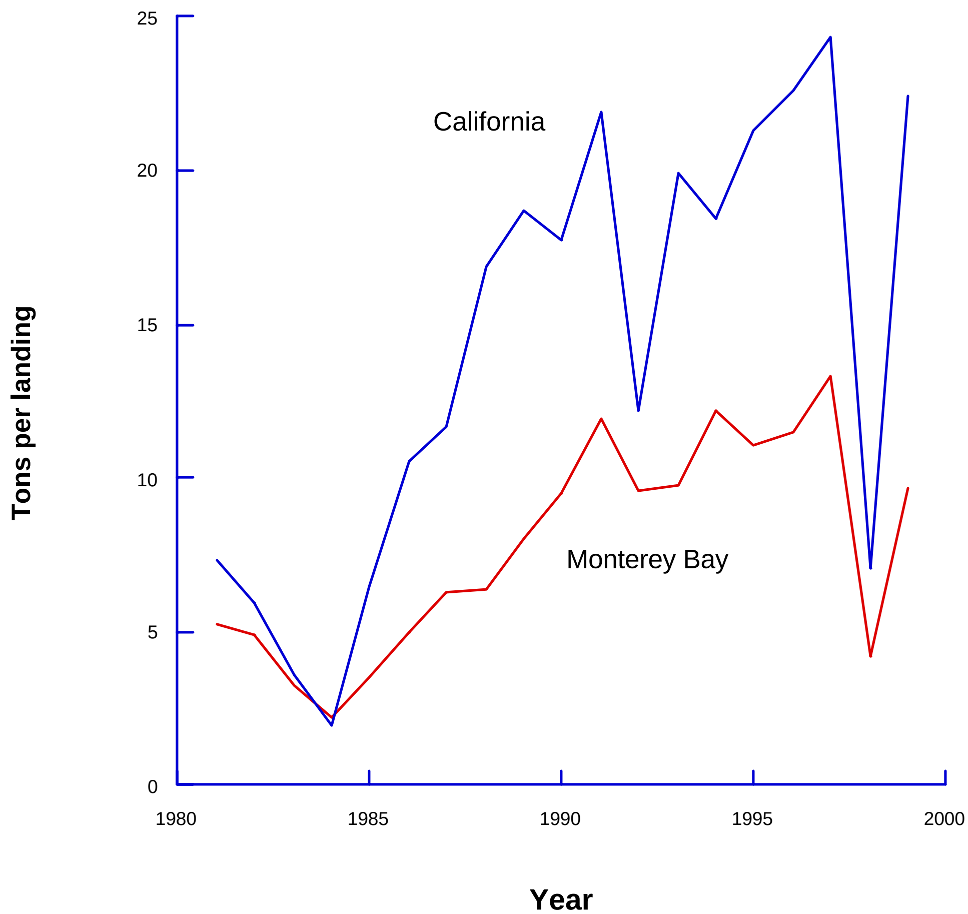
(a)



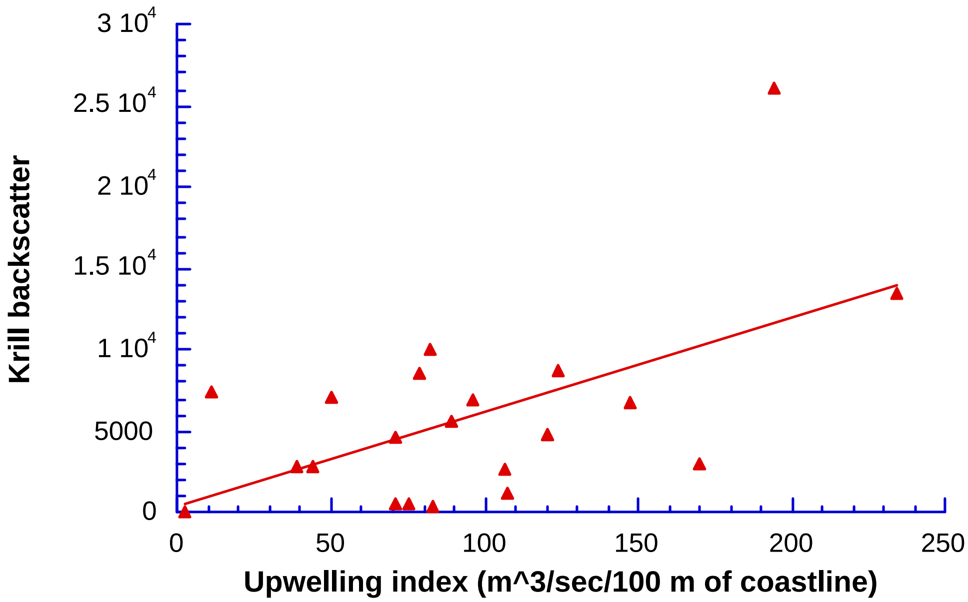
Mangel et al Figure 1b



Mangel et al figure 2



Mangel et al, figure 3



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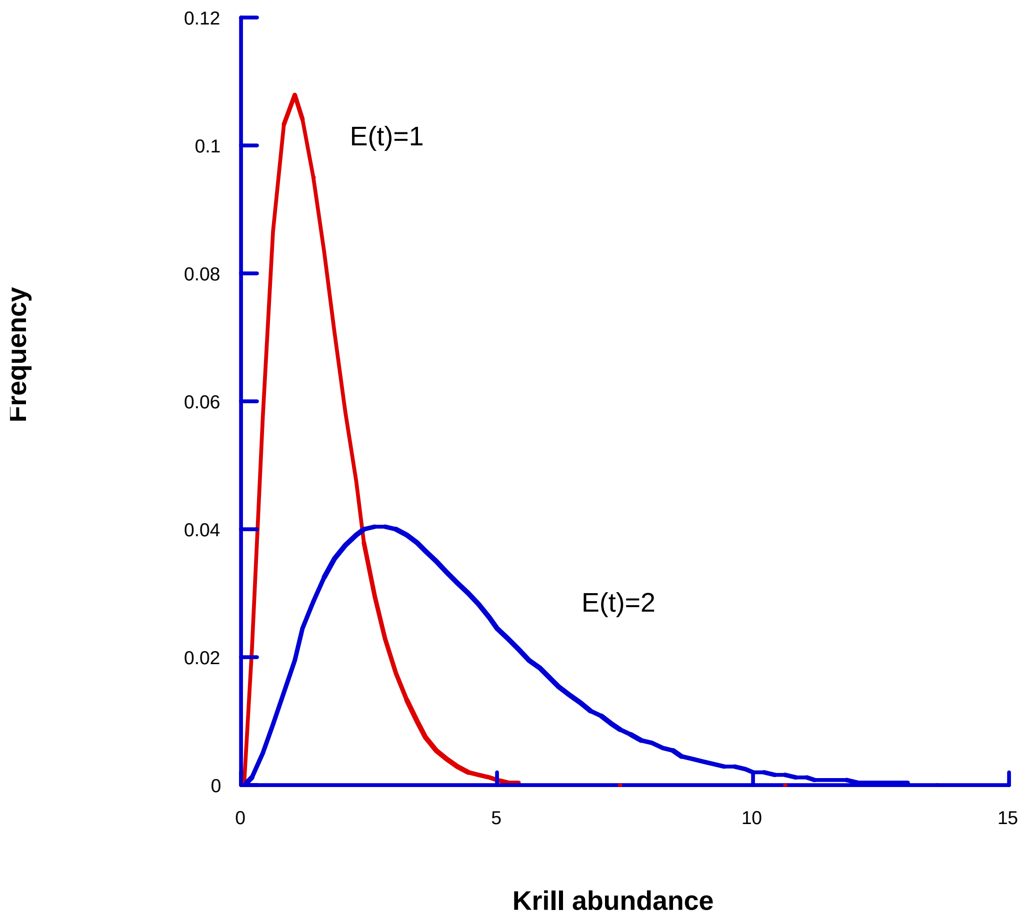
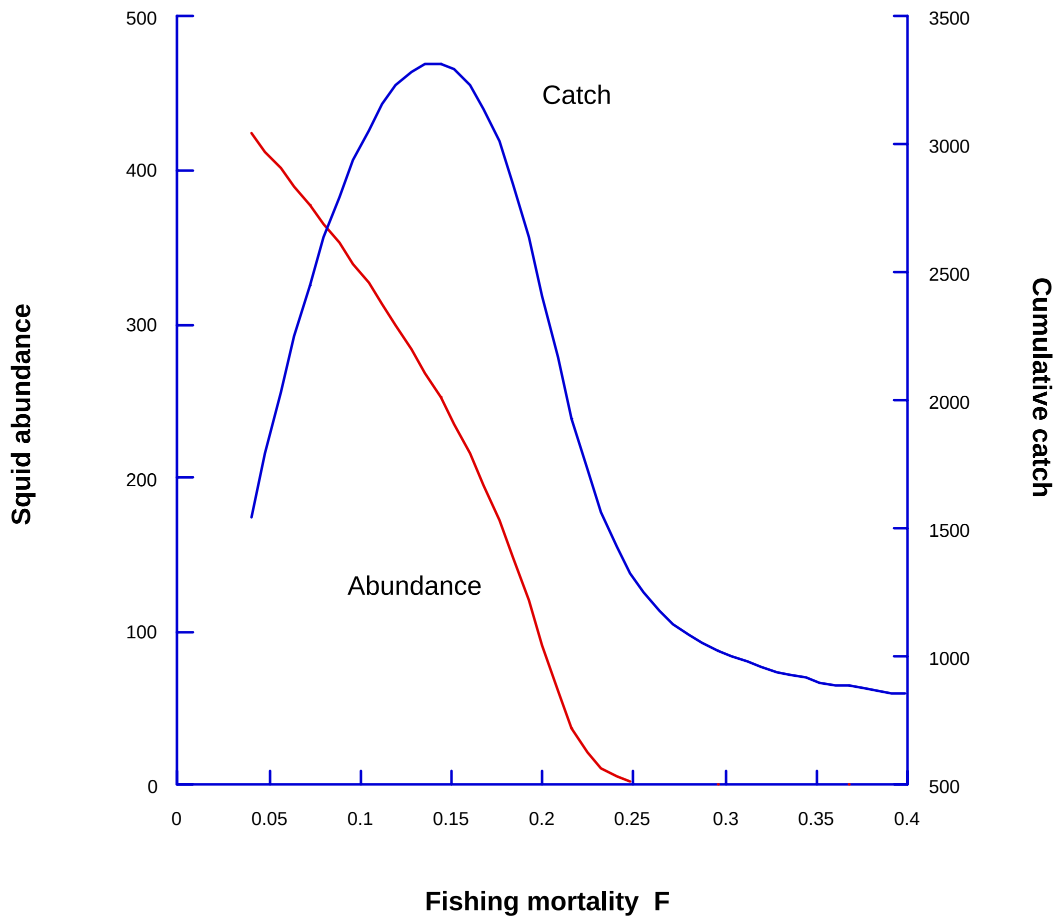


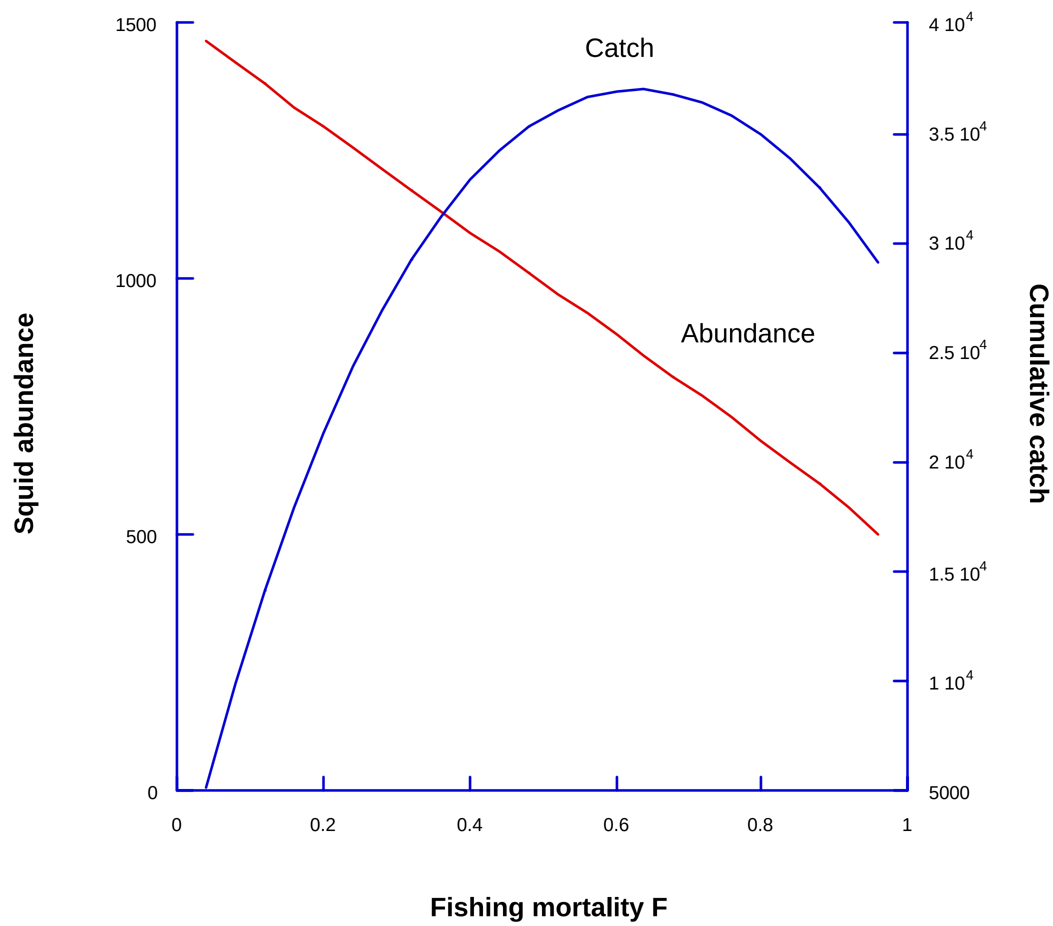
Mangel et al, figure 5a

(a)

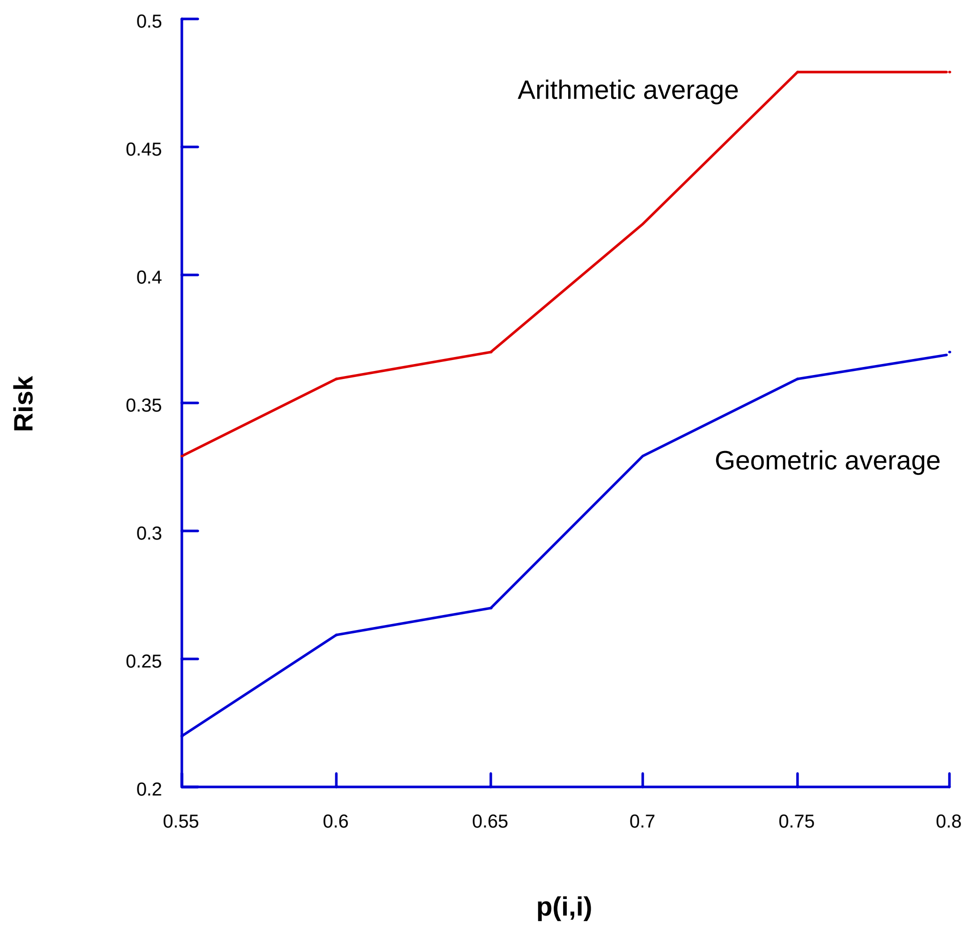


Mangel et al, figure 5b

(b)



Mangel et al, figure 6



Mangel et al, figure 7