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Defining Trade-Offs among Conservation, Profitability, and Food Security in the California Current Bottom-Trawl Fishery

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Abstract: *Although it is recognized that marine wild-capture fisheries are an important source of food for much of the world, the cost of sustainable capture fisheries to species diversity is uncertain, and it is often questioned whether industrial fisheries can be managed sustainably. We evaluated the trade-off among sustainable food production, profitability, and conservation objectives in the groundfish bottom-trawl fishery off the U.S. West Coast, where depletion (i.e., reduction in abundance) of six rockfish species (Sebastes) is of particular concern. Trade-offs are inherent in this multispecies fishery because there is limited capacity to target species individually. From population models and catch of 34 stocks of bottom fish, we calculated the relation between harvest rate, long-term yield (i.e., total weight of fish caught), profit, and depletion of each species. In our models, annual ecosystem-wide yield from all 34 stocks was maximized with an overall 5.4% harvest rate, but profit was maximized at a 2.8% harvest rate. When we reduced harvest rates to the level (2.2% harvest rate) at which no stocks collapsed (<10% of unfished levels), biomass harvested was 76% of the maximum sustainable yield and profit 89% of maximum. A harvest rate under which no stocks fell below the biomass that produced maximum sustainable yield (1% harvest rate), resulted in 45% of potential yield and 67% of potential profit. Major reductions in catch in the late 1990s led to increase in the biomass of the most depleted stocks, but this rebuilding resulted in the loss of >30% of total sustainable yield, whereas yield lost from stock depletion was 3% of total sustainable yield. There are clear conservation benefits to lower harvest rates, but avoiding overfishing of all stocks in a multispecies fishery carries a substantial cost in terms of lost yield and profit.*

Keywords: bioeconomic, fisheries management, overfishing, *Sebastes*

Definición de Compensaciones entre Conservación, Rentabilidad y Seguridad Alimentaria en la Pesquería de Arrastre de Fondo en la Corriente de California

Resumen: *Aunque se reconoce que las pesquerías marinas que capturan organismos silvestres son una fuente importante de alimento para mucha gente, el costo de las pesquerías sustentables para la diversidad de especies es incierto, y a menudo se cuestiona si las pesquerías industriales pueden ser manejadas sustentablemente. Evaluamos las compensaciones entre la producción sustentable de alimento, la rentabilidad y los objetivos de conservación de la pesquería de arrastre de fondo en la costa occidental de E. U. A., donde el agotamiento (i.e., reducción en la abundancia) de seis especies de pez roca (Sebastes) es de particular preocupación. Las compensaciones son inherentes a esta pesquería de múltiples especies porque hay una capacidad limitada para capturar especies individuales. A partir de modelos poblacionales y la captura de 34 reservas de peces de fondo, calculamos la relación entre la tasa de cosecha, la productividad a largo*

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plazo (i.e., peso total de peces capturados), ganancias y disminución de cada especie. En nuestros modelos, la productividad anual del ecosistema en las 34 reservas fue maximizada con una tasa de cosecha de 5.4%, pero la rentabilidad fue máxima cuando la tasa de cosecha fue 2.8%. Cuando redujimos las tasas de cosecha al nivel (2.2%) en que no colapsó ninguna reserva (<10% de niveles sin pesca), la biomasa cosechada fue 76% de la máxima producción sustentable y la rentabilidad fue 89% del máximo. Una tasa de cosecha debajo de la cual ninguna reserva quedó debajo de la biomasa que produjo la máxima producción sustentable (1% de la tasa de cosecha), resultó en un 45% de la producción potencial y 67% de la rentabilidad potencial. Las reducciones drásticas en la captura a fines de la década de 1990 llevaron a incrementos en la biomasa de las reservas más disminuidas, pero esta reconstrucción resultó en la pérdida de >30% de la producción total sustentable, mientras que la pérdida de producción por el decremento de las reservas fue 3% de la producción total sustentable. Existen claros beneficios de conservación al disminuir las tasas de cosecha, pero evitar la sobrepesca de todas las reservas en una pesquería de múltiples especies conlleva un costos sustancial en términos de la pérdida de producción y ganancias.

Palabras Clave: bioeconomía, manejo de pesquerías, *Sebastes*, sobrepesca

Introduction

Managers of marine ecosystems face the inevitable trade-off among sustainable yield of aquatic resources for the provision of food and the maintenance of species diversity and profitability of fisheries (Redford & Richter 1999; Brander 2010). When stocks are fished to very low abundance, species diversity, profitability, and food production all increase as harvest rates are reduced. However, once harvest rate is reduced to the level that produces maximum sustainable yield (MSY) of target species across an ecosystem, further reductions in harvest rate benefit conservation goals and profitability, but decrease food production. As much as 30% of both targeted and nontargeted marine fishes may collapse (<10% of unfished abundance) if harvest rates maximize sustainable yield at the ecosystem level (Worm et al. 2009). The collapse of some species results from the fact that groups of both target and nontarget (i.e., bycatch) species are caught simultaneously by a fishing gear, yet the ability to withstand harvest differs among species and populations of fishes. Negative effects of harvest on abundance of fished species may be reduced and profitability increased with little loss of yield if harvest rates are reduced well below the level that would produce MSY (Worm et al. 2009). Hilborn (2010) showed that fishing pressure equal to one-half of the level that would produce MSY results in only a 20% loss of yield, and Australia has adopted a target biomass 20% greater than the level that would produce MSY as an explicit economic objective (Department of Agriculture, Fisheries and Forestry 2007).

The objective of maximizing long-term average yield (i.e., MSY) is engrained in legislation such as the U.S. Magnuson–Stevens Fisheries Management and Conservation Act and the International Law of the Sea (Hilborn & Stokes 2010). Overfishing is defined traditionally as harvesting at a higher rate than would produce long-term maximum yield. Maximizing long-term yield became the goal of most fishery management in the 1950s, fell out of favor in the 1970s (Larkin 1977), and again became the goal stated in 1980s legislation (Punt & Smith 2001). In recent years, there has been growing emphasis on ecosystem and economic objectives as considerations in determining fishing policies. It is well established that long-term profitability is maximized at harvest rates lower than would produce MSY (Grafton et al. 2007). In general, low harvest rates minimize negative environmental effects. Higher harvest rates maximize biological yield and employment in the harvest sector (Hilborn 2010).

Reducing overall harvest rate is a simple solution to overfishing, but concerns over lost jobs, income, and yield have often prevented its implementation. The result has been a focus by the conservation community on alternative strategies, such as marine reserves (NRC 2001; Halpern 2003) and bycatch-reduction technology (Glass 2000; Chuenpagdee et al. 2003), that can reduce mortality of species with low population growth rates without a reduction in total fishing effort. Although gear modifications have often been accepted, or even developed, by fishermen (Campbell & Cornwell 2008), other strategies, especially marine reserves, are a source of controversy (Suman et al. 1999; Hilborn et al. 2004*b*; Osmond et al. 2010). In addition, the basic premise that reduced harvest rate results in substantial loss of yield has not been examined empirically at the multispecies level except by Hilborn et al. (2004*a*).

The groundfish trawl fishery off the U.S. West Coast is of particular interest to the conservation community because the abundance of many rockfish species (*Sebastes* spp.) is low (Levin et al. 2006) and because fisheries in the area have served as tests of efforts to rebuild stocks. The Pacific Fisheries Management Council has been a leader in classifying stocks as overfished and taking actions to rebuild them. Worm et al. (2009) identified the U.S. West Coast as having the lowest overall harvest rates out of 10 ecosystems for which harvest-rate data were available.

Field and Francis (2006) describe the history of fisheries of the U.S. West Coast. Western commercial fisheries of marine mammals began in the 18th and 19th centuries. Sea otters (*Enhydra lutris*), sea lions (*Zalophus*

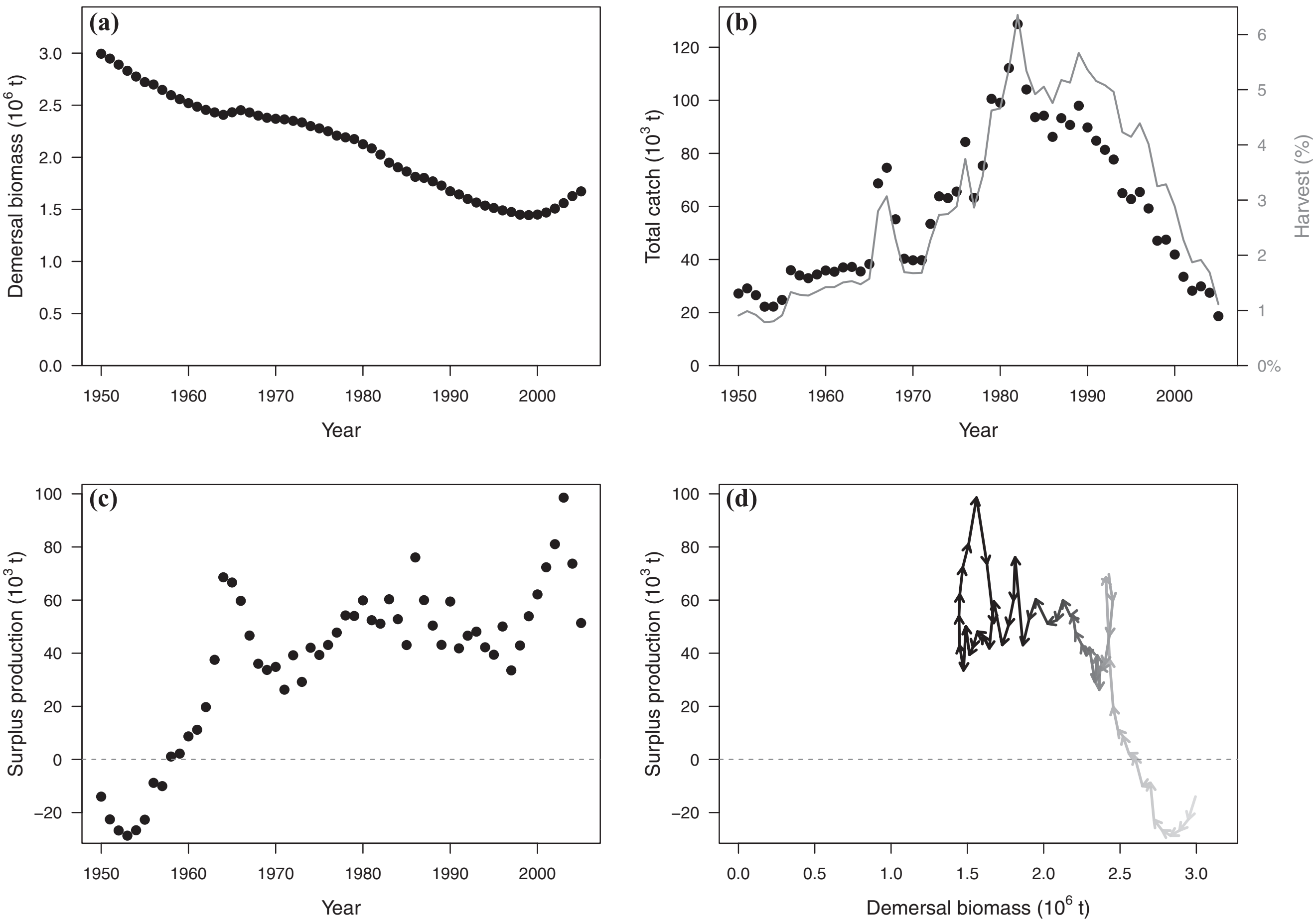

Figure 1. (a) Total biomass, (b) total catch (circles) and total harvest (line, catch divided by total biomass), (c) total surplus production from 1950 to 2005, and (d) total surplus production relative to total biomass of the 34 assessed stocks of groundfish of the California Current ecosystem. Arrows indicate direction and time moves from lightest (1950) to darkest (2005) (gray to black lines, respectively).

californianus), elephant seals (*Mirounga angustirostris*), and whales were sequentially depleted. Industrial salmon (*Oncorhynchus* spp.) fishing began late in the 19th century and was soon dwarfed by the sardine (*Sardinops sagax*) fishery (1930–1950) until its collapse in the early 1950s. Fisheries for invertebrates (primarily shrimp and crab) and groundfish were also developed by 1950, but expanded considerably after 1960. From the 1970s to present, the Pacific hake (*Merluccius productus*) and market squid (*Loligo opalescens*) fisheries were added. Currently Pacific hake, invertebrates (mainly market squid, Dungeness crab [*Cancer magister*], and pink shrimp [*Pandalus jordani*]), and a resurgent sardine stock comprise 94% of the catch. The catch of groundfish species, particularly the most depleted long-lived rockfish, peaked in the 1980s at 122,000 t (Fig. 1b) and then declined to 27,000 t in 2003. To some, this dramatic decline is an indication of collapsing stocks, whereas to others it is a sign that the efforts of fisheries managers are working.

Levin et al. (2006) documented changes in abundance and size distribution of groundfish species in the California Current. They showed that the trends in abundance were related to life-history characteristics and habitat and that, in general, long-lived species living on hard-bottom substrates, such as rockfish, had declined more than short-lived species living on soft-bottom substrates during 1977–2001. Rockfish catch limits and fishing-gear restrictions in the late 1990s and early 2000s led to reduced fishing effort in areas of prime rockfish habitat through area closures and reduced allowable catches (Hannah 2003; Bellman et al. 2005). The management goal up to the mid-1990s was to fish at harvest rates that would maximize sustainable yield. These harvest rates had been so greatly overestimated for several rockfish species that abundances of those species declined to levels much lower than would maximize yield (Ralston 2002).

The groundfish species are of particular interest because a wide range of species are caught in the trawl gear;

the group contains all the stocks in the region that are classified as overfished by the National Marine Fisheries Service; and the Pacific Fisheries Management Council has taken strong actions to reduce harvest rates and rebuild stock abundance. Since 2000, the Pacific Fisheries Management Council has addressed overfished species, and groundfish species have been the focus of 74 stock assessments, nine assessment updates, and all 27 stock-rebuilding analyses.

We explored the trade-offs among conservation of species diversity and food security and profitability in these groundfish species. We determined the extent to which conservation actions have affected the abundance of groundfish species and the effect of fisheries management actions on the most depleted species. This required reconstructing the history of the abundance and productivity of the groundfish species. We also explored the costs of overfishing in terms of lost yield, reduction in species diversity, and economic loss.

Methods

Our primary data source was stock assessments published by the Pacific Fisheries Management Council, which include catch data and estimates of spawning stock biomass, total abundance, recruitment, and fishing mortality rate (mortality rate attributable to fishing). Information on the source of data for each stock, unfished stock size (i.e., estimated average biomass given natural variability in mortality and productivity but without fishing mortality), estimated MSY, current biomass relative to the unfished biomass, and recent rate of increase in biomass are available in Supporting Information.

Total biomass of species, not the female-only spawning biomass on which most fisheries management actions are based, provides more information on the effects of fishing on ecosystems. This is because the dominant roles of fish in marine ecosystems are predation and competition, which are tightly linked to total biomass. We therefore focused on total surplus production (net population growth plus catch), which is calculated from total biomass. Surplus production in a given year is the maximum biomass of fish that could be caught in that year without reducing the population biomass. Estimates of total biomass and total catch (including discards) are available from the stock assessments, so we were able to calculate directly the fraction of total biomass removed through harvesting.

From catch and total biomass data, we calculated the observed surplus production for each stock as in Hilborn (2001) and Walters et al. (2008)

$$S_{s,t} = B_{s,t+1} - B_{s,t} + C_{s,t}, \tag{1}$$

where $S_{s,t}$ is the surplus production of the stock s from year t to $t+1$, $B_{s,t}$ is the total biomass of the stock s in year t, and $C_{s,t}$ is total removal of stock s in year t including estimated discards.

To evaluate the effect of different intensities of fishing, we fitted the Fox model (Eq. 2 in Fox [1970]) to the surplus production data

$$S_{s,t} = r_s B_{s,t}\left(1 - \frac{\ln\left(B_{s,t}\right)}{\ln\left(K_s\right)}\right), \tag{2}$$

where r_s is a parameter associated with the intrinsic rate of increase and K_s is the unfished stock size (carrying capacity). Other researchers analyzing the same set of data (Worm et al. 2009; Hutchings et al. 2010; Ricard et al. 2012) used the Schaefer model, which assumes a symmetric relation between biomass and surplus production. The Fox model is more appropriate because it more accurately reflects the productivity versus biomass relation in the age-structured populations used in assessments of these stocks (Hilborn 2010). The default assumption for the ratio of B_{MSY} to unfished stock size is 0.40 for these stocks. In the Fox model, the ratio is 0.37, and in the Schaefer model it is 0.50. The stock assessments generally provide an estimate of this ratio. Across all stocks considered, it averages 0.35, which is much closer to the Fox model than the Schaefer. In fitting the Fox model, we assumed the unfished stock size (K_s) was fixed at the value of total unfished biomass estimated in the stock assessments. Thus, we needed to estimate only the rate of increase (r_s) (everything to the right of r_s in Eq. 2 was known). Because r_s was a linear function of known values ($S_{s,t}$, $B_{s,t}$, and K_s), we used a simple regression constrained to go through the origin to estimate r_s. Regression statistics, data, and regression-model estimates are in Supporting Information. We made no specific assumption about the biomass at the beginning of the data series because the stock assessments often incorporated the catch history before our start periods and many stocks were already depleted to some extent at the beginning of the time-series used in our analyses.

The MSY is given by Eq. 2 evaluated at $B_t = B_{\mathrm{MSY}}$. The model parameters for each stock (Supporting Information) are all in units of total biomass, whereas the Pacific Fisheries Management Council reference points are in spawning-stock biomass.

A given level of fishing effort (e.g., one day of fishing by one boat) can result in a different harvest rate for different species because of inherent differences in species' vulnerability to the fishing gear, methods, and locations. We used the following procedure to estimate and account for differences in vulnerability. For any year (t) the harvest rate (u_{st}) for any species (s) at time t is

$$u_{s,t} = \frac{C_{s,t}}{B_{s,t}}, \tag{3}$$

and the aggregate harvest rate across total assessed species (u_t) is

$$u_t = \frac{\sum_s C_{s,t}}{\sum_s B_{s,t}}. \tag{4}$$

The relative vulnerability for any stock (v_s) when averaged from year t_1 to t_2 is

$$v_{s,t_1 \to t_2} = \frac{\sum_{t=t_1}^{t=t_2} u_{s,t}}{\sum_{t=t_1}^{t=t_2} u_t}. \tag{5}$$

The relative vulnerability is a product of the choice of the operators of fishing vessels in when, where, and how to fish together with the effect of closed areas. The equilibrium biomass B_s^* and equilibrium catch C_s^* for species s at any long-term aggregate harvest rate (u) is

$$B_s^* = \exp\left[\left(1 - \frac{uv_s}{r_s}\right)\ln(K_s)\right]$$
$$C_s^* = B_s^* u v_s. \tag{6}$$

To determine the lost yield ($L_{s,t}$) for any stock in any year, we compared theoretical surplus production ($\hat{S}_{s,t}$) at the stock size in that year to the MSY for the stock

$$L_{s,t} = \text{MSY}_s - \hat{S}_{s,t} \tag{7}$$

and

$$\hat{S}_{s,t} = r_s B_{st}\left(1 - \frac{\ln(B_{st})}{\ln(K_s)}\right). \tag{8}$$

Long-term yield is maximized by maintaining all stocks at the biomass that produces MSY and harvest at the rate that produces MSY. Given the multispecies nature of this fishery it would be impossible to achieve this ideal state of long-term yield for all species simultaneously, so the lost-yield calculation of Eq. 7 is a theoretical maximum loss in yield. Calculating the true lost yield would require evaluating a range of alternative harvesting policies and their time trajectories.

We calculated revenue from the 2005 price per ton for each species (NOAA 2010). We used data from Lian et al. (2010) to consider three scenarios of the cost of groundfish harvesting (each increment 1% of total biomass): US$3, $5, and $7 million. The assumption of constant costs proportional to harvest rate is simplistic, but it provides a basis for evaluating the economic consequences of different levels of fishing mortality. At such low harvest rates it seems unnecessary to consider declining marginal increase in harvest rate as fishing effort increases.

We calculated total profitability at equilibrium harvest rate u (P_u) as

$$P_u = \sum_s \left(C_s^* p_s\right) - e_u, \tag{9}$$

where p_s is the price of species s and e_u is the cost of harvesting at rate u (calculated in units of millions of dollars per percent total stock harvested). The simplest possible assumption is that cost is proportional to harvest rate. A more complex economic analysis could include the distinction between fixed and variable costs, the possibility of density-dependent catchability and changes in target species as stocks change in abundance.

To calculate the long-term trade-off among sustainable yield, biomass of fished species, and profitability, we simulated (Eq. 6), the yield of each species at equilibrium, for different levels of fishing mortality. We assumed the relative vulnerability of each stock was the average vulnerability from 2001 to 2004 and we calculated the equilibrium yield as a function of the aggregate harvest rate (total catch divided by total biomass), and equilibrium profit as a function of harvest rate. We used the number of stocks that would collapse, be overfished, or be below B_{MSY} at any harvest rate as measures of the effect of fishing on species diversity. We considered a stock collapsed if the biomass was <10% of the unfished biomass (Worm et al. 2009).

We analyzed overfished stocks separately from those not classified as overfished because the former were the specific target of rebuilding plans. Under National Marine Fisheries Service guidelines, stocks must be classified as overfished if their spawning stock biomass is <50% of B_{MSY}. Below this level the long-term yield is substantially reduced. For most West Coast species, this translates into an overfishing threshold of 20% of unfished levels. However, the Pacific Fisheries Management Council selected a more precautionary threshold of 25% for its groundfish management plan. Stocks are classified as "subject to overfishing" if the fishing mortality rate (i.e., the instantaneous form of the harvest rate) is greater than the fishing mortality rate that results in MSY (F_{MSY}).

Results

There were assessments for 34 stocks, which constitutes nearly 99% of the landed catch from groundfish species from 1981 to 2005. Estimates of abundance for all stocks did not extend to 1950, but abundance estimates were available for stocks representing 98% of the catch from 1970 onward. Total biomass declined to about 50% of its 1950 value and then increased, whereas catch and annual harvest rate (groundfish catch divided by the groundfish biomass) increased and then declined dramatically (Fig. 1). Aggregate biomass in 2005 was 56% of the biomass in 1950. The catch rose rapidly up to the early 1980s and then declined, primarily as a result of regulatory restrictions on catch and effort, but also as a result of decline in biomass. Before 1970 the total harvest rate (total catch divided by total biomass) was 1%/year.

Table 1. Status and changes in vulnerability of stocks classified as overfished.*

Common and scientific name	*Year classified as overfished*	*Year of recovery*	*Status in 2009 (spawning stock relative to unexploited,%)*	*Relative vulnerability 1994–1998*	*Relative vulnerability 2001–2004*
Bocaccio, *Sebastes paucispinis*	1999	not recovered	28	1.20	0.26
Canary rockfish, *Sebastes pinniger*	2000	not recovered	24	1.63	0.20
Cowcod, *Sebastes levis*	2000	not recovered	5	2.01	0.18
Darkblotched rockfish, *Sebastes crameri*	2001	not recovered	28	1.60	0.75
Pacific ocean perch, *Sebastes alutus*	2001	not recovered	29	0.62	0.27
Widow rockfish, *Sebastes entomelas*	2001	not recovered	39	0.93	0.26
Yelloweye rockfish, *Sebastes ruberrimus*	2002	not recovered	20	1.16	0.35
Lingcod, *Ophiodon elongatus*, northern stock	2001	2005	62	1.87	0.64
Lingcod, *Ophiodon elongatus*, southern stock	2001	2005	74	1.87	1.07
Petrale sole, *Eopsetta jordani*	2009	not recovered	12	3.74	6.74

**Vulnerabilities calculated from Eq. 5 and they represent the harvest rate on each stock compared with the aggregate harvest rate of all stocks combined.*

Harvest rate peaked at 6%/year in 1984 and declined rapidly through the mid-1990s to mid-2000s as a result of management actions, including reductions in total allowable catches and fleet size, and closure of some areas to fishing.

Results of basic population-dynamic models, such as the Fox model used here, suggest that surplus production should be maximized at an intermediate biomass between the unfished state and low biomass. Total surplus production summed overall stocks rose rapidly in the 1950s, as harvest rates increased, and has remained reasonably stable around 50,000 t/year since 1970 (Fig. 1c). The relation between surplus production and biomass (Fig. 1d) suggests that surplus production increased continually as biomass was reduced from the unfished level, with no sign of a peak. The pulse in surplus production that began in the late 1990s (Fig. 1c) was caused by a number of years with unusually high reproductive success in the late 1990s, and this pulse in recruitment, combined with a lower harvest rate, caused the biomass of the stocks in aggregate to increase.

The history of the overfished stocks (Table 1) is generally similar to the rest of the groundfish species except that the abundance was reduced to a lower proportion of the initial biomass, the peak harvest rates were higher, and catches and harvest rates declined more rapidly after the late 1990s because of stock rebuilding measures (Fig. 2). Surplus production of the overfished stocks as a whole did not decline as biomass declined (Fig. 2d), but the variability in surplus production increased. The years with the lowest one-third total biomass had an average surplus production of 10.3 kt, the middle one-third an average of 9.8 kt, and the highest one-third had an average of 11.4 kt. The biomass of the overfished stocks from 1990 to 2008 was one-half of the biomass from 1975 to 1989. The total surplus production for the overfished stocks was 10.4 kt in this earlier period of high abundance and 10.2 kt in the recent period of low abundance. Surplus production for cowcod (*Sebastes levis*) and bocaccio (*Sebastes paucispinis*) declined almost 70%, and for canary rockfish (*Sebastes pinniger*) declined about 30% during the low abundance period. Over the same period, for the two lingcod (*Ophiodon elongatus*) stocks, darkblotched rockfish (*Sebastes crameri*), widow rockfish (*Sebastes entomelas*), Pacific ocean perch (*Sebastes alutus*), and yelloweye rockfish (*Sebastes ruberrimus*) surplus production increased. The increase in surplus production of some species compensated for the large decline in surplus production of cowcod and bocaccio so that in aggregate there was no decline. The biomass and surplus production of the overfished stocks also increased in response to the large recruitment events (high reproductive success) of the late 1990s.

During the period of maximum depletion in the mid-1990s, when biomass of 13 of 34 stocks was less than B_{MSY}, overfishing resulted in only a 3% loss of yield (Fig. 3) because there was little loss of sustainable yield just below B_{MSY} because of the flatness of the yield curve. In addition, the most severely overfished stocks (cowcod, bocaccio, and canary rockfish) constituted only 4% of the potential sustainable yield. The lost yield from underfishing (stocks that were at biomasses $> B_{MSY}$) was very high when the fishery began and declined to only 15% when harvest rates were high in the late 1990s. Lost yield increased dramatically as harvest rates were curtailed and were 33% of potential yield in 2005, the last year for which we had complete assessments for the less-harvested species (Fig. 3). We based these calculations solely on biomass relative to B_{MSY} and assumed sustainable catches that would maintain biomass at that same reference level as the MSY catch (Eq. 7). In reality, these stocks were largely caught together and simultaneously holding each stock at its individual B_{MSY} was not possible.

To evaluate the effectiveness of the specific regulations implemented to reduce harvest rates on the overfished stocks (reductions in total allowable catch and closed areas in prime rockfish habitat), we calculated their

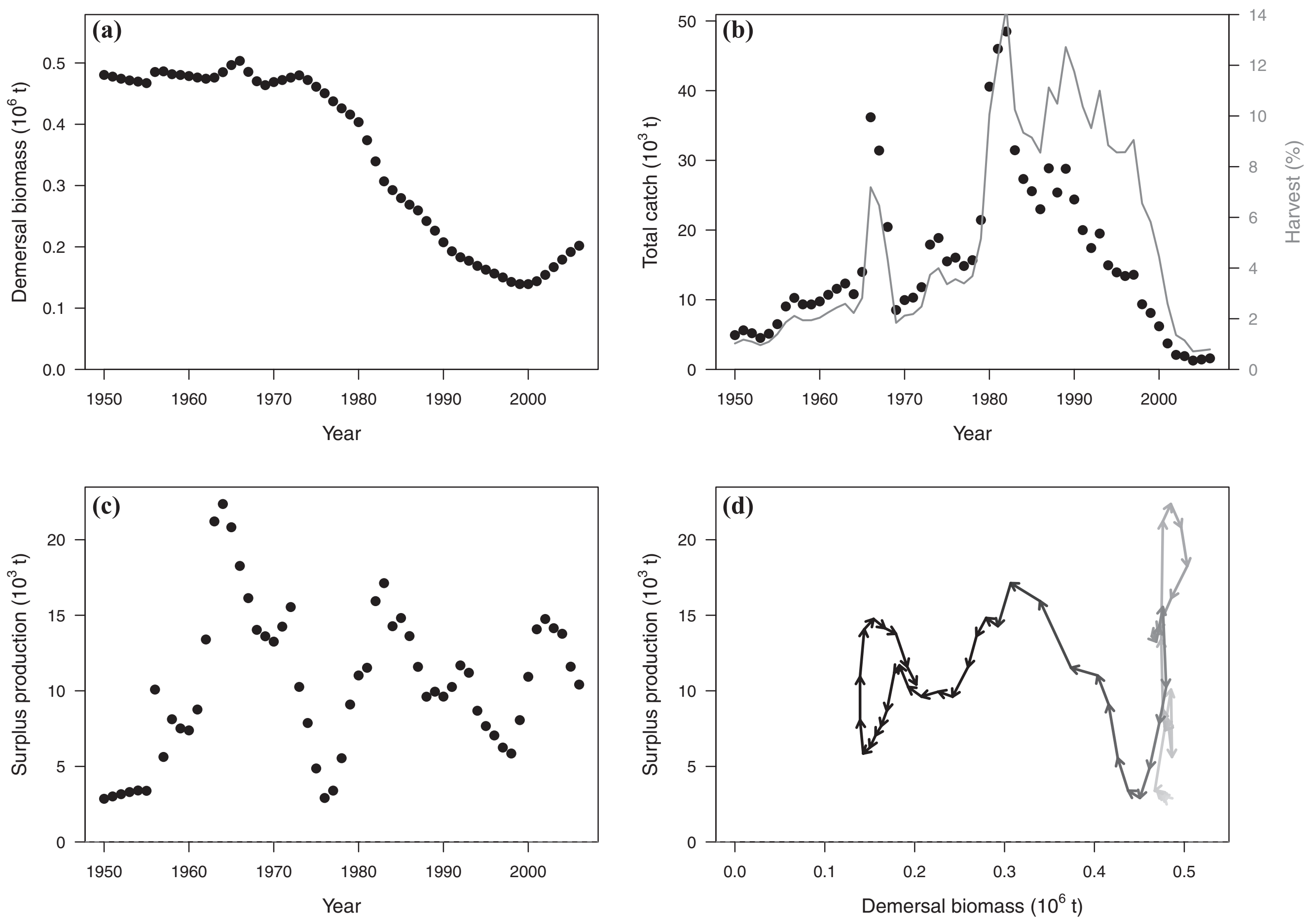

Figure 2. (a) Total biomass, (b) catch (circles) and harvest (solid line), (c) total surplus production from 1950 to 2005, and (d) total surplus production relative to biomass of the groundfish stocks of the California Current ecosystem that have been classified as overfished by the Pacific Fisheries Management Council and are subject to stock rebuilding plans (petrale sole excluded because it was not classified as overfished until 2009). Arrows indicate direction and time moves from lightest (1950) to darkest (2005) (gray to black lines, respectively).

vulnerability (relative to the average of all species, see Eq. 5) before stock rebuilding (1994–1998) and after implementation of most rebuilding plans (2001–2004; Table 1). In addition to the 6-fold reduction in harvest rate across all stocks (from 6% to 1%), the average vulnerability of the overfished rockfish dropped from 1.4 in 1994–1998 to 0.44 in 2001–2004 (an average reduction of 69%), and excluding lingcod (which recovered quickly), the reduction was 75%. Thus, the harvest rate of overfished rockfish declined 19-fold. For some species, particularly the near-shore species (e.g., black rockfish [*Sebastes melanops*], blue rockfish [*Sebastes mystinus*], and cabezon [*Scorpaenichthys marmoratus*]) and those found primarily in rocky habitat (yelloweye and cowcod), the majority of historical catch came from separate fisheries, such as hook and line. However, all stocks had a common harvest history and contributed to ecosystem productivity. Shifts in relative vulnerability before and after stock rebuilding reflected not only management of the trawl quota, but also designation of closed areas and changes in allocation of the total allowable catch, including the closing of some targeted fisheries.

Given the relation between surplus production and harvest rate (Fig. 4a), equilibrium yield would be maximized at a harvest rate of 5.4%, six stocks would be collapsed, 13 stocks would be classified as overfished or collapsed, and 18 stocks would be classified as collapsed, overfished, or below B_{MSY} (Fig. 4c). Although 18 of 34 stocks were below B_{MSY}, many of these were only slightly below B_{MSY}, where there is little loss of sustainable yield. With our intermediate estimate of costs ($5 million/1% harvest rate), profit was maximized with a harvest rate of 2.8% (Fig. 4b) and two stocks collapsed, six were overfished or collapsed, and six were overfished, collapsed, or less than B_{MSY} (Fig. 4d). The effect of fishing on each individual stock depended on its intrinsic rate of increase and the relative vulnerability of the stock to fishing effort. Stocks with low rates of increase or

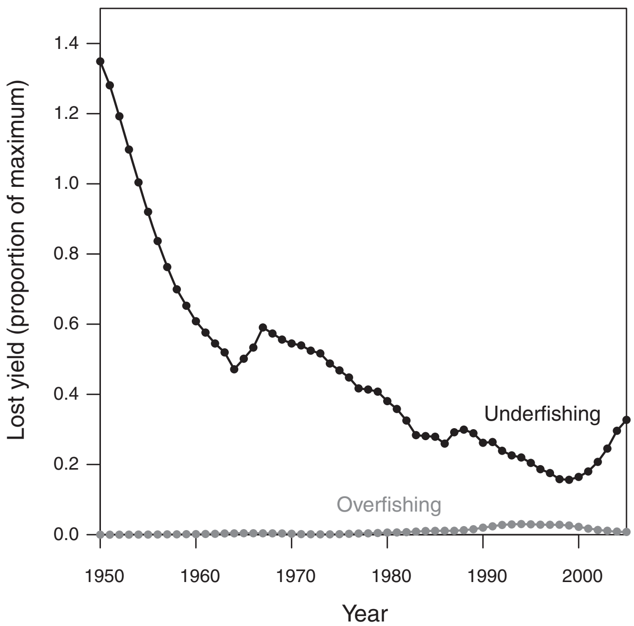

Figure 3. The fisheries yield lost because of overfishing and underfishing of the groundfish stocks in the California Current ecosystem.

high relative vulnerability were the first to decline to the states of overfished and collapsed as aggregate harvest rate increased. Using the vulnerability values from 2001 to 2004, the order of collapse of stocks would be kelp greenling (*Hexagrammos decagrammus)*, gopher rockfish (*Sebastes carnatus*), petrale sole (*Eopsetta jordani*), cabezon (southern stock), longspine thornyheads (*Sebastolobus altivelis*), and sablefish (*Anoplopoma fimbria*). Thus, with a harvest rate of 2.8%/year, two stocks collapsed: kelp greenling and gopher rockfish. The relative vulnerability of the most overfished stocks, cowcod, canary rockfish, and bocaccio was reduced enough that they were not among the stocks most likely to be overfished and collapse. Kelp greenling and gopher rockfish are inshore species not commonly caught in the bottom-trawl fishery, and the habitat of petrale sole is different from the habitat of the overfished rockfishes. So, these species did not benefit from the reduction in harvest rate on rockfish in general.

At a harvest rate of 2.2%/year, no stocks collapsed. To have no overfished stocks, the harvest rate would need to be 1.4%, and to have no stocks below B_{MSY} the harvest rate would need to be 1%—close to current harvest rates. With no collapsed stocks, the result would be 76% of maximum total yield and 89% of maximum total profit. With no overfished stocks, the result would be 57% of potential yield and 67% of potential profit. With no stocks below B_{MSY}, the results would be 45% of potential yield and 52% of potential profit.

Discussion

In each of the 34 assessments, we used as inputs, there was uncertainty about trends in biomass and thus in surplus production. Catch is assumed in the assessments to be known without error, although there is often uncertainty about catches from years before 1970 and discarded catch. The uncertainty in the assessments could possibly be carried over into our analysis, but given that there is no common method of calculating uncertainty in the original assessments it would be difficult to do. Hilborn (2001) explored the sensitivity of estimates of surplus production to different trends in biomass and found surplus production is more stable than biomass. We focused on aggregate patterns across the entire groundfish assemblage and are reasonably confident our conclusions regarding the trade-off between conservation of stock abundance and sustainable yield are robust to uncertainties that have been identified. We explicitly considered uncertainty in the overall cost functions, but not in uncertainty of price.

Trade-Offs Among Conservation and Food Security and Profitability

There are trade-offs among food security and profitability and conservation of species diversity in a multispecies fishery, and in the fisheries we examined, we found that to have no stocks overfished the harvest rate needs to be low enough that the average yield is 76% of maximum and profit is 89% of maximum. If profitability were maximized, then only two stocks would collapse. The marginal increase in yield achievable by harvesting at higher rates is more than offset by the increased cost.

At no point in the history of the fisheries we examined has the aggregate biomass across all stocks been reduced enough for surplus production to decline. If the definition of *overfished* is having a biomass that produces less than MSY, the groundfish species were never, in aggregate, overfished. Certainly biomass of individual stocks has been low enough to result in decreased surplus production, but the reduced surplus production in these stocks appeared to have been offset by increase in surplus production of other stocks. Even among the overfished stocks as a group, there was no decline in overall surplus production. The failure of surplus production in aggregate to decline at low abundance was because of a number of species having large year classes in the late 1990s. We cannot say whether the large year classes were because of pure coincidence, environmental drivers, interspecies interaction, or the lack of a relation between stock abundance and recruitment. The higher variability in surplus production in the overfished stocks was because of the smaller number of stocks involved and the stronger influence of individual year classes.

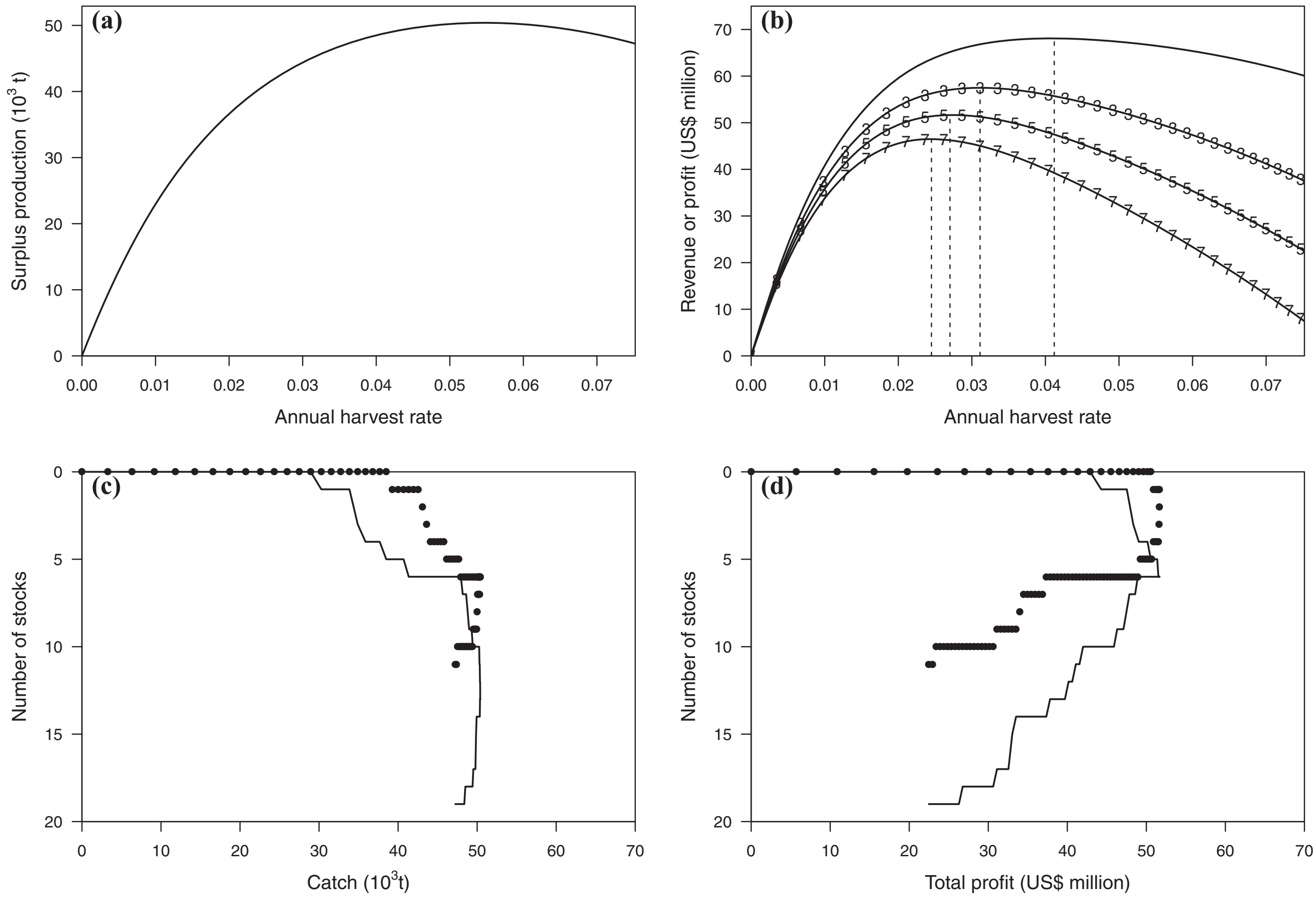

Figure 4. Relations between (a) annual harvest rate and sustainable yield, (b) annual harvest rate and landed value (black lines) and total profit for three different values of cost (US$ 3 million, 5, and 7 million), (c) sustainable yield and number of collapsed stocks (circles) and overfished stocks (line), and (d) total profit and number of collapsed stocks (circles) and overfished stocks (thin line).

There are other trade-offs beyond food security, profitability, and stock biomass. Maintaining stocks at higher biomasses would likely provide a buffer against climate change, ocean acidification, and establishment of nonnative species and would likely benefit marine birds and mammals.

Our results show that management actions were taken to rebuild the overfished stocks. The harvest rates on all stocks classified as overfished were reduced markedly, and the abundance of all overfished stocks is increasing (Supporting Information). This rebuilding has come at a considerable short-term cost in yield from stocks that are not overfished. In 2005, 33% of the potential sustainable yield was being foregone to rebuild overfished stocks (Fig. 3).

Costs of Overfishing

We found that lost yield because of overfishing was low. Overfishing never seriously compromised food production from this fishery. At the lowest point of abundance and highest fishing mortality, only 3% of the potential yield was lost because of overfishing. Effects of overfishing on species' abundances were much higher; several stocks were harvested to low levels of abundance. The economic costs of overfishing were also relatively high. Harvest rate in the late 1980s and early 1990s roughly doubled the level of harvest that would produce maximum profitability.

The lost food production from low harvest rate has always been considerably greater than the lost food production from overfishing, although the foregone yield before the 1990s can be ignored because this was a period of fishery development, when stocks had not yet been depleted to the biomass that maximizes sustainable yield. As of the late 2000s, the ratio between the two forms of lost yield was the most extreme and was primarily the result of annual catch limits designed to allow rebuilding of stocks classified as overfished. This trade-off is largely unacknowledged in any discussion of U.S. fishing policy.

We quantified the trade-offs among food production, conservation of species diversity, and profitability and showed that fisheries management agencies can rebuild overfished stocks and profit can be maximized with little loss in sustainable yield. We also found that although there was a cost in sustainable harvest of the stringent measures used to rebuild overfished stocks and that biomasses of many species were heavily depleted, there is little evidence that the stocks were overfished (or surplus production diminished) for any length of time in aggregate. Although there does not seem to be a strong trade-off between yield and single-species conservation goals, there is a clear trade-off among rapid rebuilding of stocks at low abundance, lost food production, and economic cost to fishing-dependent communities.

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Supporting Information

Detailed information about individual stocks used in this analysis (Appendix S1), the regression statistics (Appendix S2), and plots of the surplus production data and best-fitting models (Appendix S3) are available online. The authors are solely responsible for the content and functionality of these materials. Queries (other than absence of the material) should be directed to the corresponding author.

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