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Finding the accelerator and brake in an individual quota fishery: linking ecology, economics, and fleet dynamics of US West Coast trawl fisheries

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In 2011, the Pacific Fisheries Management Council implemented an individual transferrable quota (ITQ) system for the US West Coast groundfish trawl fleet. Under the ITQ system, each vessel now receives transferrable annual allocations of quota for 29 groundfish species, including target and bycatch species. Here we develop an ecosystem and fleet dynamics model to identify which components of an ITQ system are likely to drive responses in effort, target species catch, bycatch, and overall profitability. In the absence of penalties for discarding over-quota fish, ITQs lead to large increases in fishing effort and bycatch. The penalties fishermen expect for exceeding quota have the largest effect on fleet behaviour, capping effort and total bycatch. Quota prices for target or bycatch species have lesser impacts on fishing dynamics, even up to bycatch quota prices of \$50 kg^{-1}. Ports that overlap less with bycatch species can increase effort under individual quotas, while other ports decrease effort. Relative to a prior management system, ITQs with penalties for exceeding quotas lead to increased target species landings and lower bycatch, but with strong variation among species. The model illustrates how alternative fishery management policies affect profitability, sustainability and the ecosystem.

Keywords: catch shares, ecosystem model, fleet dynamics, individual transferrable quotas, US West Coast.

Introduction

Fishery managers are increasingly adopting ecosystem-based approaches to management, focusing not just on harvested species but also on non-target and protected species, habitat, and the well-being of human communities (Pikitch *et al.*, 2004; McLeod and Leslie, 2009; Cochrane *et al.*, 2010). This difficult task is made more challenging on the US West Coast by the need to rebuild overfished stocks (Parker *et al.*, 2000), dramatic biological responses to climatic and oceanographic variability (Field and Francis, 2002), and international fisheries for migratory species like hake, *Merluccius productus* (Hamel and Stewart, 2009). In multispecies fisheries, such as those for US West Coast groundfish, individual transferrable quotas (ITQs or catch shares) are one tool that may offer fishermen incentives to limit bycatch of less productive species, while potentially increasing catch of target species up to allowable limits. ITQs allocate a fixed proportion of total quotas to individual vessels, which can then fish or trade their quota (Squires *et al.*, 1995; Grafton, 1996). Where they have been implemented, ITQs have generally improved profitability and have improved sustainability by constraining catches below the total allowable catch (TAC) (OECD, 1997; Shotton, 2001; Grafton *et al.*, 2006; Costello *et al.*, 2008). ITQ systems implemented in multispecies fisheries have a number of important design features that differ significantly across systems (Squires *et al.*, 1998). Catch-balancing mechanisms allow individual fishermen to balance discrepancies between their quota holdings and actual catch, and include mechanisms such as trading and leasing of quota, discarding or surrendering over-quota fish, or paying "deemed value" (a fine per pound) on over-quota fish. Catch-balancing mechanisms are a particularly critical part of multispecies ITQ systems and have substantial impacts on both economic and ecological performance (Sanchirico *et al.*, 2006). Identifying the appropriate catch-balancing mechanisms to include in a new ITQ system is a difficult and important problem that we address here.

Prior to 2011, the Pacific Fishery Management Council (PFMC) on the US West Coast used individual vessel bimonthly cumulative landings limits and spatial closures to constrain catches below total allowable catch (TAC). These measures were meant to control the race for fish and improve economic viability as well as constrain total catch, but they did not prevent overfishing of all stocks, nor did they achieve economic goals. One of the principal problems was the bycatch of depleted species such as long-lived, slow-growing rockfish (*Sebastes* spp.) in this multispecies trawl fishery targeting abundant stocks such as Dover sole (*Microstomus pacificus*) and sablefish (*Anoplopoma fimbria*). Fishery managers (PFMC, 2008) noted that there was little individual incentive for captains to avoid depleted species, since they could freely discard species for which they had exhausted their landings limit. Successive tightening of landings limits constrained the industry from fully harvesting target species and caused high regulatory discard rates.

In January 2011 an ITQ system was implemented for the limited-entry groundfish trawl fishery on the West Coast. The salient characteristics of the ITQ system include allocation of a portion of the total quota to each vessel based on recent catch history, the immediate ability to lease quota shares for the current year, sale of the semi-permanent shares themselves after an initial two-year delay, and full accounting for all catch of ITQ species against quota (including discards which are monitored by human observers on all vessels). The program also explicitly allows gear switching, for instance from trawl to pot or longline (PFMC and NMFS, 2010).

Species with quotas in short supply, which previously could simply have been discarded once a fisherman reached his cumulative limit, can now constrain the ability of fishermen to harvest quotas of other jointly caught species. The possibility of substantial penalties for exceeding individual quotas, including being forced to stop fishing, is likely to alter the incentives that determine fleet dynamics, increasing incentives to avoid catch of weak stocks with constraining TACs. In addition, the cost of obtaining quotas may alter fishery targeting and profitability, which could lead to regional shifts in fishing activity and changes in targeting practices. Branch *et al.* (2006) have demonstrated that, for the groundfish fishery in British Columbia, the incentives created by ITQs significantly changed fishing behaviour and the species mix of catch and greatly reduced discards.

The success or failure of these management strategies will be decided by the interaction of ecology with the behavioural responses of fishermen that determine the level and spatial distribution of catches. Here we develop a simulation tool that represents the ecosystem and fishery as a way to more fully explore the economic and conservation performance of management policy options (e.g. total allowable catches and spatial closures) under alternative management systems (ITQs vs. cumulative landings limits). We couple the Atlantis ecosystem model (Fulton, 2004; Fulton *et al.*, 2011) to fleet dynamics models of the groundfish trawl fleet that build on Holland (2000) and Holland and Herrera (2006). We model responses to quota lease prices for target species and for constraining rockfish species, as well as varying levels of penalties for exceeding quotas.

Success of any management program has different definitions for different stakeholders, and the strength of our ecosystem modelling approach is that it allows us to evaluate the impact of management policies in terms of multiple economic, single-species and multispecies metrics.

Methods

The California Current Atlantis model

The Atlantis ecosystem model projects population dynamics, ecology, oceanography and fisheries in a three-dimensional framework (Fulton, 2001, 2004). The simulation approach allows forecasting of system response to specific management actions and to physical variables. The model is intended primarily as a strategic tool to test and rank management options related to fisheries and other economic sectors (e.g. Smith *et al.*, 2011). Fulton *et al.* (2011) present 13 recent Atlantis models and insights from these applications. Detailed fleet dynamics and management strategies have been included in Atlantis models that capture the ecology and management of systems in Australia and the northeastern USA (Fulton *et al.*, 2007; Link *et al.*, 2010). In the case of southeastern Australia, these models of fleet dynamics included ITQs, spatial closures, gear switching, investment and disinvestment, and subsidies (Fulton *et al.*, 2007).

The California Current Atlantis ecosystem model (Brand *et al.*, 2007) was built to address the impacts of climate, oceanography, nutrient dynamics, and spatially explicit fishing effort on a dynamic food web. The model extends from the US/Canada border to Point Conception, California, and out to the 1200 m isobath. The trophic dynamics represent 55 functional groups in the food web, using nitrogen as a common currency between groups. Functional groups are typically comprised of pools of 1–10 species with similar ecological roles. General classes of functional groups include habitat-forming species like kelp, corals and sponges, as well as vertebrate consumers, benthic invertebrates, zooplankton, phytoplankton and detritus. Phytoplankton and invertebrates are modelled as simple biomass pools, while vertebrates are modelled with age structure and growth that varies, dependent on consumption. The model includes Beverton–Holt stock recruitment relationships for fish and fixed offspring per adult for mammals and birds. Movement of vertebrates is density-dependent and based on prey availability. Plankton and nutrients are advected by currents, and species such as whales migrate into and out of the model domain. The model domain is divided into 62 spatial zones, each with up to seven depth layers. This allows us to explicitly test hypotheses regarding fleet dynamics and spatial management. The model is forced with daily hydrodynamic flows, salinity, and temperature outputs from a high-resolution Regional Ocean Modelling System (ROMS, implemented by Hermann *et al.*, 2009). Separate sub-modules simulate management rules and effort dynamics of fishing fleets, detailed below. This version of the model has been used to test ecological indicators (Kaplan *et al.*, 2009) and potential effects of ocean acidification (Kaplan *et al.*, 2010); a related model with finer spatial resolution has been used in Central California to screen alternative fishery management strategies and their economic effects (Kaplan *et al.*, 2012; Kaplan and Leonard, 2012).

Here we augmented the California Current Atlantis model (Brand *et al.*, 2007) so that it could be used to evaluate management strategies for the West Coast groundfish bottom trawl fishery and to illustrate impacts of these strategies on the ecosystem. In addition to developing algorithms and parameterizations related to fishery harvest and fleet dynamics, we also improved the species resolution of rockfish (*Sebastes*). To most clearly illustrate how quotas for these species constrain fleet dynamics, we modelled six rockfish species separately, rather than in aggregated functional groups: yelloweye (*Sebastes ruberrimus*), canary (*S. pinniger*), Pacific Ocean perch

(*S. alutus*), widow (*S. entomelas*), bocaccio (*S. paucispinis*), and darkblotched (*S. crameri*). Yelloweye, canary, and Pacific Ocean perch are currently listed as overfished, with abundances at 21, 23 and 19% of unfished abundance (Taylor and Wetzel, 2011; Wallace and Cope, 2011; Hamel and Ono, 2011). Bocaccio, widow, and darkblotched rockfish are not currently categorized as overfished, but in the last decade these stocks fell as low as 13, 30 and 11% of unfished abundance, respectively (Field *et al.*, 2009; He *et al.*, 2011; Stephens *et al.*, 2011). As described in Brand *et al.* (2007), the distribution of groundfish species including rockfish was initialized based primarily on NMFS trawl survey data (Bradburn *et al.*, 2011) but is dynamic through the course of the simulation. As an example, Figure 1 illustrates the initial spatial distribution of two rockfish, ports associated with the 12 fleets, and the model domain. Figures A.1–A.2 (supplementary data) illustrate the spatial distribution of four other rockfish species.

As described below, the Atlantis model code explicitly simulates fleet dynamics and management rules for the groundfish trawl fishery under cumulative landings limits, a competitive TAC, and different options for an ITQ system. Fleet dynamics include choices about the amount of fishing effort and the spatial location of that effort. Management rules include schemes for leasing quota, penalties for going over quota limits, and areas closed to fishing.

Management and fleet dynamics under cumulative landings limits

Prior to 2011, the groundfish trawl fishery was managed with individual bimonthly cumulative landings limits on certain species, and with closed Rockfish Conservation Areas (RCAs). These measures were designed to spread fishing over the year as well as limit bycatch. We calibrated the model under the cumulative landings limit system to match observed effort, spatial distribution, and catch composition for 2004. That year represents a relatively stable management period prior to public consideration of ITQs. The groundfish trawl fishery we model includes 95 vessels grouped into 12 distinct fleets operating from major ports or port groups from California to Washington (Figure 1). We do not model the midwater trawl fleet that targets hake, nor do we model non-groundfish fisheries in the region (e.g. squid, sardine, Dungeness crab). Effort is modelled at the fleet (port group) level rather than modelling individual vessels, with fleets varying in size from 2–25 vessels.

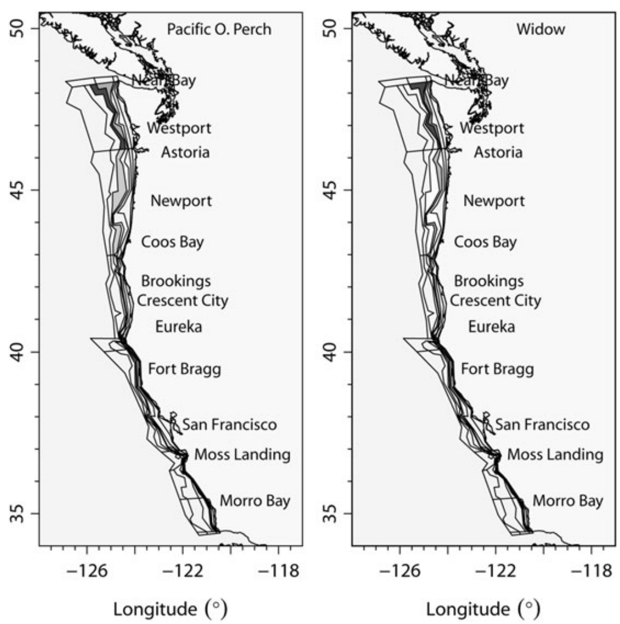

Figure 1. The Atlantis model domain with initial relative abundance of Pacific Ocean perch and widow rockfish (*Sebastes spp.*). Abundance proportional to shading of boxes (white to black). Atlantis model cells are delineated by the black lines. See Figure A.1–2 for maps of spatial abundance of bocaccio, darkblotched, yelloweye, and canary rockfish.

Fleets are constrained by landings limits and the RCAs. We calculate each fleet's total landings limits by multiplying the number of vessels per fleet by a per-vessel quota for each species; this approximates the cumulative-catch-limit system prior to ITQs. Total annual quota per species is based on the 2005 commercial harvest guidelines for limited entry trawl (Federal Register Vol. 69, No. 246); this includes both target and non-target groundfish. In the model, quotas are fixed and do not vary with stock size. Where necessary, we aggregated species into Atlantis functional groups, though several key target and bycatch species are modelled separately. We approximated the RCAs by preventing trawl effort between 75–200 fm in cells or portions of cells north of 40°10', and between 100–150 fm south of 40°10' (137–366 m and 182–274 m, respectively; see NOAA NW Regional Office, 2010).

During each simulated trip, each fleet's effort is distributed across a number of fishing areas in proportion to relative utility scores for different areas. The utility score for each potential fishing location for a given fleet is determined by the expected (i.e. potential) revenue from that area relative to other areas, taking into account available towing time, which subtracts steaming (travel) time from an assumed three-day trip. Expected revenue *Rev* for fleet *i* in area *j*, catching species groups *m* is:

$$Rev_{i/j} = \sum_{m=1}^{M} (CPUE^{i,j,m} * \mathrm{AT}_{\mathrm{i,j}} * \mathrm{P}_{\mathrm{i,j,m}}), \qquad \text{Equation 1}$$

where $CPUE_{j,m}$ is expected landings per unit effort of species group *m* for fleet *i* in area *j*, $AT_{i,j}$ is available tow time for a vessel from fleet *i* that chooses to fish in area *j*, *P* is price of species group *m* for fleet *i* in area *j*. Expected landings per unit effort ($CPUE_{j,m}$) is the product of the abundance of that target species in that area, and a scalar $q_{i,m}$ (catchability).

Prices for each species group are assumed constant over time, but vary by area to account for differences in average species composition of the catch for each species group in each area. Prices are based on average prices in 2004–2005 (PacFIN, 2006). Under the cumulative landings limit system, once a fleet reaches its cumulative limit for a particular species group during a bimonthly period, the fleet can continue fishing in areas where it is caught, but the price for that species group for that fleet goes to zero on the assumption that it must be discarded.

Normalized expected revenue, $N_{i,j}$ for each fleet and area is calculated by dividing area-specific expected revenue by the maximum expected revenue across all areas for that fleet. We then calculate a utility score for each area by taking the exponent of the normalized expected revenue multiplied by a scalar, β.

The utility score *PR* for fleet *i* and area *j* is:

$$PR_{ij} = \frac{\exp(N_{ij} * \beta)}{\sum_{j=1}^{62} \exp(N_{ij} * \beta)} \qquad \text{Equation 2}$$

Equation 2 yields a vector of j positive probabilities of choices for each area which sum to one. Note that as β is increased, the model concentrates fishing effort more heavily in the areas with the highest revenue. These probabilities are used to distribute the effort of each fleet across the 62 fishing areas. However, to avoid spreading effort too widely and sending effort to areas with very low probabilities and potentially negative net returns, we set any probabilities below a minimum threshold to zero and eliminate choices where expected revenue for the trip do not exceed variable costs. We also set probabilities to zero for areas that are closed. We then rescale the other probabilities so that they sum to one and use the rescaled probabilities to distribute the effort of each fleet across areas.

Models of fleet dynamics under a competitive TAC and ITQs

We evaluate competitive TACs and several ITQ-based alternatives that include a range of penalties for exceeding quota, and alternatives for formation of quota prices (Table 1).

The competitive TAC case is a benchmark against which to measure the impacts of penalties and quota prices; this case is identical to the ITQ alternatives below, but with all penalties and quota costs set to 0. Under the competitive TAC, we assume that all fleets can continue to fish in any area and land each species until the coastwide TAC of that species is taken. Under the competitive TAC system, once the TAC of each species is met, vessels can continue to fish in areas where it is caught but must discard the over-quota species, which then generate no revenue. This is a less restrictive scenario than the cumulative landings scenario, which limits bimonthly landings of species at the fleet level, based on initial allocation per fleet. The competitive TAC scenario would not be legally viable under current US law but it provides a benchmark to compare how alternative features of an ITQ system affect economic and ecological outcomes.

The ITQ alternatives all use the same total quotas and closed areas as the cumulative landings scenario and the competitive TAC scenario. The ITQ approach is based closely on the model described above in equations 1 and 2, but expected revenue across location alternatives is based on alternative combinations of three system design features that affect the net prices used to calculate expected revenue: (i) "over quota" penalties for catching species groups for which all quota is exhausted, applied to each species once the TAC for that species is reached, (ii) a quota lease price based on Newell *et al.* (2005) that is applied to all harvested species, and (iii) a "scarce quota" lease price that allows quota prices to rise well above ex-vessel price, and that is applied only to the overfished rockfish species. While none of these mechanisms accurately reflect the functioning of the quota market and penalty system in the West Coast groundfish fishery, they serve to demonstrate how plausible alternative policies and market outcomes would affect incentives that drive fishing choices and, in consequence, overall outcomes. The ITQ alternatives here differ from the competitive TAC only in terms of these penalties and lease prices, and thus comparing ITQs to competitive TACs illustrates the effects of these additional incentives.

Table 1. List of management scenarios, including cumulative landings limits, competitive total allowable catches (TACs), and individual transferable quotas (ITQs).

Scenario	Penalty for exceeding quota \$ kg^{-1}	Quota lease cost \$ kg^{-1}	Max cost for scarce quota \$ kg^{-1}
Cumulative landings limits	–	Not applicable	–
Competitive TAC	–	0	–
ITQ	5	0	–
ITQ	0	Newell model	–
ITQ	0	0	50
ITQ	5	Newell model	50
ITQ	10	Newell model	50

Over-quota penalties

The over-quota penalties apply to all species including target species, for the amount of catch above the quota. This is similar to the "deemed value" system in New Zealand, though we consider penalties of \$5–10 kg^{-1}, which are higher than most deemed values in New Zealand. The six rockfish species are a special case. For these, the over-quota penalty is the maximum of three quantities: the general over-quota penalty (\$5–10 kg^{-1}), and the two types of quota lease prices described below.

Quota lease price

It will likely be several years before quota markets for the West Coast groundfish fishery mature and stabilize and sufficient information is available to model them empirically. Thus to model quota lease prices we adapt an empirical estimation for quota price formation in the New Zealand ITQ from Newell *et al.* (2005), who modelled quota lease price, QP, per ton of species group i as:

$$\begin{aligned}\ln(QP_{i,m}) = {} & B_1 \ln p_{imy} + B_2(\ln p_{imy})^2 + B_3 \ln c_{my} \\ & + B_4 \frac{H_{iy-1}}{Q_{iy-1}} + B_5\left(\frac{H_{iy-1}}{Q_{iy-1}}\right)^2 + \ldots \\ & \ldots + B_6\left(\frac{\sum_{n=1}^{m-1} h_{imy}}{Q_{iy}} - \frac{\sum_{n=1}^{m-1} h_{imy-1}}{Q_{iy-1}}\right) \\ & + B_7\left(\frac{\sum_{n=1}^{m-1} h_{imy}}{Q_{iy}} - \frac{\sum_{n=1}^{m-1} h_{imy-1}}{Q_{iy-1}}\right)^2 + B_8 \ln p_{imy}\left(\frac{H_{iy-1}}{Q_{iy-1}}\right) \\ & + \ldots \\ & \ldots + B_9 \ln s_{my} + B_{10} g_{my} + B_{11} R_i t_y + a_0,\end{aligned}$$

Equation 3

where QP is quota lease price, i indexes species, m indexes month or season, B_{1-11} are coefficients, y indexes year, p is landed value of the fish, c is fishing costs, H is actual annual catch, Q is the annual TAC, h is the actual catch to date for one year, s is a value of a climate index (southern oscillation index), g is gross domestic product (GDP) growth rate, R is the ratio of past to current quota (always 1.0 in our case), t is time, and a_0 is a constant term. Note that quota price is dynamic, varying over months (m) and years (y). When simulating quota prices, we set the climate index and GDP variables to mean values from Newell (2005) and set the constant, a_0, to a value of 0.1. Our modelled quota lease prices range from 5–22% of landed value, varying primarily based on the proportion of the prior year's quota that was caught. Since we assume 100% observer coverage, we do not include potential effects of noncompliance

(Hatcher, 2005) on quota price. For comparison, we also test cases where quota lease price is zero.

"Scarce quota" lease price

The Newell model may provide a good approximation of quota price formation for target species on the West Coast, but it probably does a poor job of modelling quota prices for scarce bycatch species that represent only a small part of catch but have the potential to constrain catch of other target species. In such cases we might expect quota price to rise to well above ex-vessel price reflecting the fact that a small amount of additional quota for that species can allow a much greater quantity of catch of the associated target species. Thus for the overfished rockfish species, which have low quotas relative to the target species, we model a "scarce quota" price that captures the very high prices that were observed in 2011 on the US West Coast for some leases of rockfish quota. In relevant simulations (Table 1), this quota price applies only to the six rockfish species listed above. We tested quota prices for these rockfish that rise at an increasing rate to an arbitrary maximum as the proportion of the previous year's quota harvested reaches 1.0 (supplementary Figure A.3). We considered maxima of \$10 kg^{-1} and \$50 kg^{-1}. For the six rockfish species, quota lease price is the maximum of the price derived from the scarce quota price and the Newell model price; in practice this means the scarce quota price applies.

Expected revenue and effort distribution under ITQs

Expected revenue for each fleet and area is modelled as in equation 1 above, except that the price used is the ex-vessel price minus the quota lease price, determined either from the Newell model or (for rockfish) from the scarce quota price in scenarios where it is applied. Note that net prices for rockfish can be highly negative in the scarce quota scenarios. The quota prices affect relative profitability of areas with different species mixes and thus location choice decisions. When all quota of a particular species group is exhausted the landed price is set to zero and quota price is set at the over-quota penalty (depending on simulation this ranges from \$0–10 kg^{-1}, and up to \$50 kg^{-1} for the six rockfish species, see Table 1). These penalties drive down the profitability of any area where that fish is caught. If the over-quota penalty is set at a sufficiently high level it eliminates any fishing in areas where that species group is caught. However, the model can continue to distribute some effort to areas that have produced catch of species for which no quota is available, allowing catches to exceed TACs provided the penalties do not negate expected revenue. Overall, if the sum of variable cost, quota cost, and penalties exceed gross revenue (landings × price) in all model spatial cells, effort is set to zero for the current three-day trip. Note that the model does not optimize the timing of effort over the year in such a way as to maximize annual net revenues; fleets here are assumed to be responding only to current catch availability and net price signals rather than "thinking ahead" regarding how price and fish abundance might evolve later in the year.

Annual net revenue calculation

In addition to catch and landings, we also calculated annual net revenue (gross revenues less fixed and variable costs). Costs are based on detailed cost-earnings data obtained from 58 in-person interviews conducted during 2003–2004 in Oregon (Lian, 2010). Fixed costs include insurance, docking, and maintenance fees but not capital costs (e.g. interest on loans), while variable costs include fuel, food and ice (but not labour). Thus net revenues include returns to capital and labour and thus differ from accounting profits. Since many vessels participate in multiple fisheries, we apportioned fixed costs proportional to the fraction of total revenue derived from West Coast groundfish trawling. Both variable and fixed costs differ between fleets, and depend upon average vessel length and horsepower. Fishing location does not influence variable costs, because each trip is of the same duration, and costs are not expected to be substantially impacted by the percentage of time spent transiting versus fishing. Variable costs per three-day trip range from \$2267–7204 per vessel, depending on the fleet. Fixed costs attributable to groundfish range from \$17 000–89 000 per year per vessel. Note that annual net revenue calculations do not deduct quota costs, as quota lease payments are simply transfers between vessels. We do not deduct over-quota penalties, which are deterrents to fishing in particular areas but are not true costs (i.e. they are a transfer between the vessel and government and thus do not reduce the overall net benefits generated by the fishery).

Results

Cumulative landings limit scenario

We calibrated fisheries catchability and the effort "clumping" parameter β (equation 2) so that the scenario with cumulative landings limits qualitatively matched observations from 2004. This involved comparing the spatial distributions and catch composition of each simulated fleet to logbook data (PacFIN, 2006). This comparison for the cumulative landings limit simulation is presented in the supplementary material; other simulations were based on this calibration.

Northern fleets have relatively high catches of darkblotched rockfish and Pacific Ocean perch (Table 2); northern fleets have a high degree of spatial overlap with rockfish species (supplementary Table B2), and catch of these rockfish can reach 2–3% of total catch for these fleets (supplementary Table B3). Bocaccio was primarily caught by southern fleets (Table 2), and the four southernmost fleets had higher spatial overlap with bocaccio than with any of the other rockfish species. Morro Bay, the southernmost fleet, had minimal catches (<100 kg) of all constraining species. Small and large flatfish and sablefish dominate the catches of target species.

To estimate the immediate effects of the management system, and to separate these effects from long-term trends in abundance (see below), we calculated average catches over the first five years of the simulation. Under cumulative landings limits, five-year average catches of most major target species were below total quotas (Table 3). Catches of the six rockfish species were 22% above quotas (averaged over five years), with only bocaccio and yelloweye rockfish below quota and other species above the quota.

Competitive TAC and ITQ scenarios

Fleet dynamics and catch

The competitive TAC scenario provides a benchmark case as the least restrictive management scenario. This hypothetical case allows all vessels to access a coast-wide pool of allowable quota, and illustrates differences between systems with transferable quotas and the previous bimonthly cumulative landings limits. The competitive TAC system results in an overall doubling of fishing effort relative to the cumulative landings limit scenario, driven primarily by seven of 12 fleets (Figure 2, supplementary Table B4). These seven fleets had the lowest amounts of fishing effort under the cumulative landings scenario, and thus have the largest scope for increases in effort. Three other fleets show comparable levels of effort with and without ITQs. Under cumulative trip

Table 2. Catches (metric tons) for Year 1 of the cumulative landings limit simulation, by fleet and functional group.

	SOUTH											NORTH	
	Morro Bay	**Moss Landing**	**San Francisco**	**Fort Bragg**	**Eureka**	**Crescent City**	**Brookings**	**Coos Bay**	**Newport**	**Astoria**	**Westport**	**Neah Bay**	**Sum**
Number of vessels	3	3	4	8	9	3	5	13	12	25	2	8	95
Darkblotched rockfish	0.0	0.5	1.7	20.2	20.9	5.1	2.1	72.4	51.7	149.3	0.3	9.2	333.5
Pacific ocean perch	0.0	0.0	0.0	0.0	0.0	0.0	0.3	5.8	28.6	124.5	0.0	0.0	159.1
Canary rockfish	0.0	0.2	0.2	0.0	0.9	0.1	0.0	0.7	0.3	3.9	0.1	2.9	9.2
Bocaccio	0.0	1.2	2.0	0.2	0.2	0.0	0.0	0.0	0.0	0.0	0.0	0.0	3.7
Widow rockfish	0.0	0.1	0.1	0.0	0.0	0.0	0.0	0.0	0.4	2.6	0.0	0.0	3.1
Yelloweye rockfish	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.3	0.0	0.2	0.5
Small flatfish	282.7	279.5	278.7	1 355.0	1 338.4	536.5	705.5	1 945.1	739.7	5 432.0	276.2	920.2	14 089.4
Large flatfish	54.9	134.6	106.2	39.1	414.5	124.6	51.5	607.2	587.2	3 776.7	126.1	3 027.4	9 050.0
Sablefish	89.2	88.6	93.5	424.2	369.5	138.4	209.0	587.3	473.1	1 154.3	38.1	333.2	3 998.3
Hake	0.0	0.0	0.0	0.0	2.5	0.0	0.0	72.5	10.8	893.4	52.9	1 017.3	2 049.3
English sole	0.0	29.3	13.9	10.6	175.0	71.4	9.2	177.3	83.1	517.9	31.0	413.3	1 531.7
Deep small rockfish	142.7	64.1	73.0	430.8	239.5	39.5	40.5	165.1	44.8	163.1	3.4	33.1	1 439.6
Skates and rays	0.0	14.4	5.9	6.5	80.6	25.1	10.4	310.8	395.6	366.8	9.8	193.1	1 419.0
Deep large rockfish	74.9	48.6	25.6	151.7	116.2	17.7	31.2	136.6	118.2	223.1	2.9	32.0	978.6
Midwater rockfish	16.7	56.5	16.4	51.5	35.9	0.7	0.0	3.8	5.2	65.4	6.7	46.8	305.7
Deep misc. fish	0.0	38.1	1.2	19.1	72.8	0.6	4.9	38.9	3.1	1.2	0.0	0.0	179.9
Sm. dem. sharks	0.0	9.3	1.0	0.0	0.0	0.0	0.0	0.0	0.3	3.9	0.0	115.4	130.0
Lg. dem. predators	0.0	4.3	2.9	3.3	6.1	3.4	0.9	8.3	6.9	44.5	6.0	18.0	104.5
Chilipepper rockfish	0.0	13.2	2.6	19.6	11.6	0.0	0.0	3.1	0.0	0.0	0.0	0.0	50.0
Shallow sm. rockfish	0.0	0.2	0.1	0.2	1.1	0.0	0.0	1.8	0.3	6.4	0.1	3.7	13.8
Cephalopods	0.0	0.0	0.0	0.2	0.0	0.0	0.0	6.4	0.2	0.8	0.0	1.2	8.8
Shallow lg. rockfish	0.0	0.6	1.4	0.0	0.4	0.0	0.0	0.3	0.0	2.1	0.0	0.0	4.9
Misc. pelagic sharks	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0

The first six rows are the rockfish groups that have low quotas. The next nine rows are target species. Catches less than 0.1 mt (100 kg) shown as 0.0.

Table 3. Catch of each species or functional group (average over first five years of simulation) relative to total quota.

Quota system	**CLL**	**Comp. TAC**	**ITQ**	**ITQ**	**ITQ**	**ITQ**	**ITQ**
Over-quota penalty, $ kg^{-1}	–	0	5	0	0	5	10
Quota lease price	–	0	0	Newell	0	Newell	Newell
"Scarce quota" lease price (max $ kg^{-1})	–	0	0	0	50	50	50
Species or functional group							
Darkblotched rockfish	1.10	5.94	1.89	5.95	5.94	1.87	1.42
Pacific ocean perch	1.42	5.01	0.76	5.00	5.01	0.94	0.53
Canary rockfish	1.63	6.51	2.44	6.52	6.51	1.76	1.77
Bocaccio rockfish	0.38	2.13	0.67	2.13	2.13	0.66	0.56
Widow rockfish	3.89	5.23	2.56	5.23	5.23	2.55	2.51
Yelloweye rockfish	0.82	8.12	0.80	8.11	8.12	0.74	0.78
Sum of six rockfish	1.22	5.50	1.45	5.51	5.50	1.50	1.08
Small flatfish	0.89	5.77	5.18	5.79	5.77	11.13	2.32
Large flatfish	0.93	2.29	1.61	2.30	2.29	2.06	1.09
Sablefish	0.69	3.69	1.19	3.69	3.69	1.23	0.92
English sole	0.42	1.97	1.05	1.98	1.97	1.10	0.71
Deep small rockfish	0.43	11.36	1.45	11.33	11.36	1.36	1.17
Skates and rays	0.15	0.90	0.64	0.90	0.90	0.67	0.32
Deep large rockfish	0.47	4.25	0.98	4.25	4.25	1.00	0.63
Midwater rockfish	1.14	7.29	6.17	7.33	7.29	14.80	2.64
Deep miscellaneous fish	0.02	0.44	0.15	0.44	0.44	0.16	0.10
Small demersal sharks	0.02	0.06	0.02	0.06	0.06	0.02	0.02
Large demersal predators	0.47	3.47	0.67	3.47	3.47	0.64	0.57
Chilipepper rockfish	0.07	0.85	0.33	0.85	0.85	0.56	0.20
Shallow small rockfish	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Shallow large rockfish	0.00	0.01	0.01	0.01	0.01	0.01	0.00

The first six rows are the rockfish groups that have low quotas. The next eight rows are target species. CLL = cumulative landings limits, comp. TAC = competitive TAC.

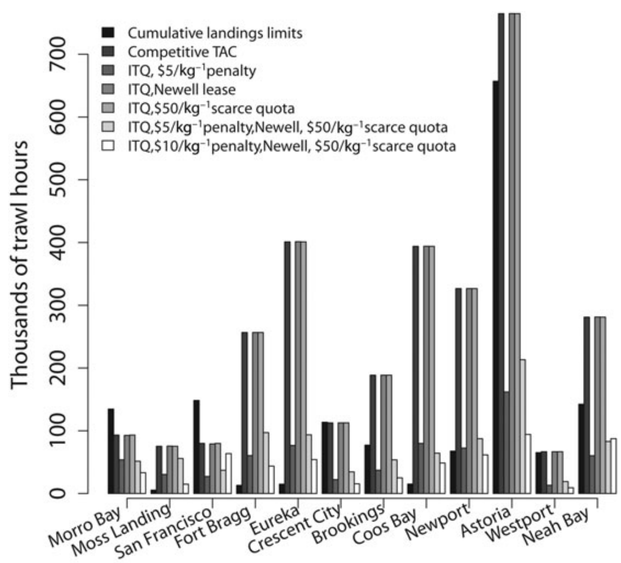

Figure 2. Effort per fleet and scenario, summed over five years.

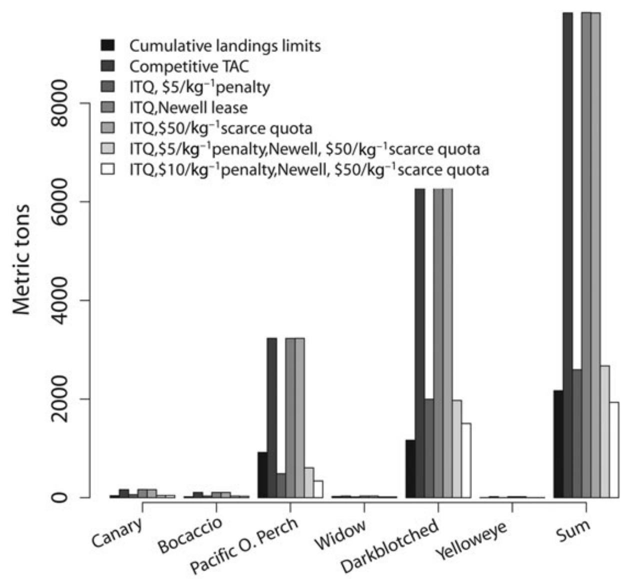

Figure 3. Catch of six rockfish species summed over the first five years of the simulation, by fleet and scenario.

limits, fleets are constrained by their original allocation of quota; under the competitive TAC scenario these quotas can effectively be transferred between fleets during the course of each year, allowing increased opportunities for higher catch and positive net revenue. Note also that under the cumulative landings limit system, fleets in the real world spent only 25–70 days per year at sea targeting groundfish, spread between bimonthly periods. Similarly, in the Atlantis simulations, most fleets fill their quota in the first three weeks of each bimonthly cumulative trip limit, and remain idle for the remainder of that two-month period (supplementary Figure B3). Under the competitive TAC scenario, effort increases and continues through the year, cycling with seasonal movement of the fish stocks and annual quota availability. Catch of all six rockfish species increased (Figure 3) concurrent with this increase in fishing effort. Total catch of these species over five years was four times the catch under landings limits and 5.5 times quotas.

Catches of most target species exceed total quotas by several fold (Table 3).

The penalty for exceeding quota (of all species) was the primary determinant of total fishing effort and bycatch of rockfish species (Figures 2 and 3). Penalties of \$2 kg^{-1} had little effect—fishing effort and rockfish bycatch were similar to those with no penalties. Penalties of \$5 kg^{-1} led to a halving of summed fishing effort relative to effort under cumulative landings limits (supplementary Table B4). However four fleets—Moss Landing, Fort Bragg, Eureka, and Coos Bay—were able to increase effort and remain profitable despite the penalties. With the exception of Coos Bay, these are southern ports with low overlap and bycatch of most rockfish except for bocaccio (supplementary Tables B2–B3). For these four fleets, and also the northern fleets of Brookings, Newport, and Neah Bay, effort that had been forced into odd months (January, March, May etc.) by the bimonthly landings limits was instead concentrated into fewer, larger peaks of effort within the year (e.g. Figure B3). Summed rockfish catch for all fleets over five years was 45% above quotas (Table 3), similar to rockfish catch under the landings limits system, but varied by species and fleet. Catches of target species typically exceeded quotas, but this was variable across species (catch/quota $= 2.3 \pm 3.4$ s.d.).

Quota lease prices based on the Newell (2005) model did not substantially alter effort or bycatch of rockfish. For instance, assuming the Newell model for quota prices, with no other penalties or quota costs, leads to fleet behaviour similar to that under competitive TACs (Figures 2 and 3, Table 3, Table B4). As parameterized, the model allows quota price to range from 5–22% of landed value, depending on quota scarcity by the end of the previous year. Several target species were not caught at the full quota, and for these species quota prices remained low, typically 10% of landed value. Prices for rockfish quota under this quota price model were not high enough to alter total fishing effort or bycatch rates. Though in the model it is possible for quota price—an additional cost—to reduce expected revenue and cause vessels to reduce effort (i.e. skip a three-day trip), in our simulations this lower revenue threshold is not reached.

Implementing very high prices for scarce rockfish quota caused only minor changes to fleet effort and bycatch. Scarce quota prices up to \$50 kg^{-1}, without other penalties, led to effort comparable to the benchmark competitive TAC scenario (Figure 2, Table B4). Darkblotched and Pacific Ocean perch catch increased along with this increase in effort, despite the high cost of quota for these species (Figure 3). Scarce quota prices of \$10 kg^{-1} (not shown) did not lead to qualitatively different behaviour than \$50 kg^{-1}.

We combined prices of up to \$50 kg^{-1} for scarce rockfish quota with the over-quota penalty of \$5 kg^{-1} and quota lease prices based on Newell (2005). This led to total catches and effort comparable to those when only the \$5 kg^{-1} over-quota penalty was in place (Figures 2 and 3, Table 3, Table B4). Relative to the case with only the over-quota penalty, in this combined simulation total rockfish catch was within 3%, though catches of five rockfish declined slightly. Despite the potential costs of buying scarce quota, five of the seven southernmost ports had > 30% increases in fishing effort in the combined scenario relative to one with only the \$5 kg^{-1} over-quota penalty (Table B4). In test scenarios (not shown here), very high scarce quota costs of \$1000 kg^{-1} led to 50% reductions in effort, a 93% reduction in the catch of Pacific Ocean perch, and 50% reductions in catch of the other five rockfish species. However, such prices were not observed in reality in the 2011 ITQ on the West Coast, and fishermen have strong incentives to avoid such extremely high quota prices (Holland, 2010), for instance through the formation of risk pools (Holland and Jannot, 2012).

Considering higher penalties of \$10 kg^{-1} in this combined simulation led to declines in effort for ten fleets. Catch of four of six rockfish species declined at this level of penalty—though canary, widow, and darkblotched rockfish catches were still above quotas—and over five years, summed catches of rockfish were within 8% of quotas. Catches of target species declined and approached quotas (catch/quota $= 1.23 \pm 0.82$ s.d.); catches of some species such as small flatfish still substantially exceeded the quota (Table 3).

Fishery revenue

Over thirty years under cumulative trip limits, annual gross revenue ranged from \$36–46 million, beginning at \$44 million and ending at \$41 million (Figure 4). This gross revenue is dockside value of landed fish, up to the tonnage of the annual quotas. As populations of target species increased through time, less effort was required later in the simulation for this harvest, with the result that net revenue (after fixed costs and non-labour variable costs) increased after the first five years of the simulation (Figure 4).

Under the competitive TAC scenario, high initial gross revenue declined as target species were overfished over the course of 30 years (Figure 4). By Year 30, declining catches combined with high variable costs associated with the large amount of fishing effort led to economic losses (negative net revenue, Figure 4). Similarly, ITQ scenarios that lacked over-quota penalties had high variable costs and negative net revenue by Year 30. Adding over-quota penalties (for all species) of $\geq$ \$5 kg^{-1} led to more moderate levels of effort, prevented overfishing of target stocks, and had net and gross revenues comparable to or greater than under cumulative trip limits. ITQ scenarios with over-quota penalties had annual net revenues of \$35–40 million versus \$29 million under cumulative landings limits.

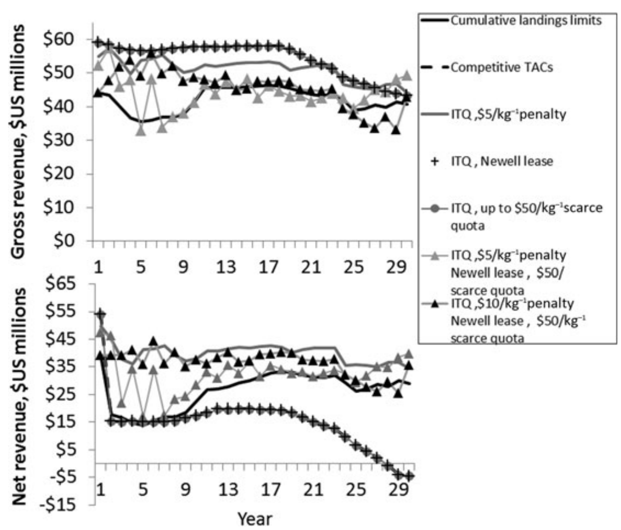

Figure 4. Top: Gross (ex-vessel) revenue for all fleets over 30 years. Catches that exceed annual quotas do not contribute to revenue. Note the overlap of the three ITQ scenarios (including competitive TAC) that lack the penalty for exceeding quota (\$5 kg^{-1} or \$10 kg^{-1}). **Bottom:** Net revenue for all fleets over 30 years. This simple metric of net revenue is gross revenue minus fixed costs (excluding capital costs) and variable costs (fuel, ice and food, but not labour or quota costs). Note same overlap as in top panel.

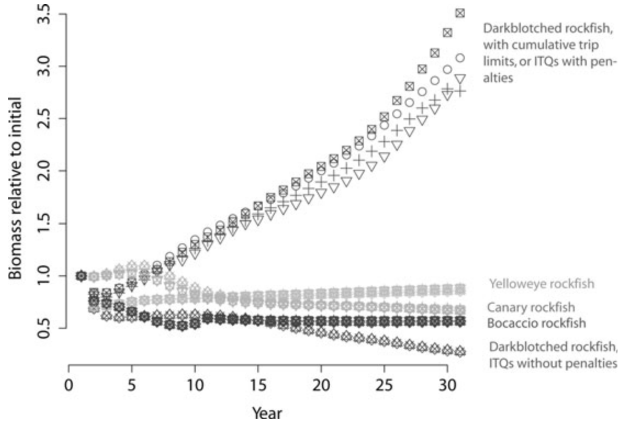

Figure 5. Coast-wide biomass time-series for four rockfish species. The seven scenarios ordered as in Table 2 are represented by circles, triangles, plus signs, crosses, diamonds, inverted triangles, and crossed boxes. For darkblotched rockfish, final biomass is highest for scenarios with highest penalty and lease costs. Their abundance increases in the simulation with cumulative trip limits, or with ITQs accompanied by penalties for exceeding quota. For each of the other species, biomass time-series overlap between scenarios.

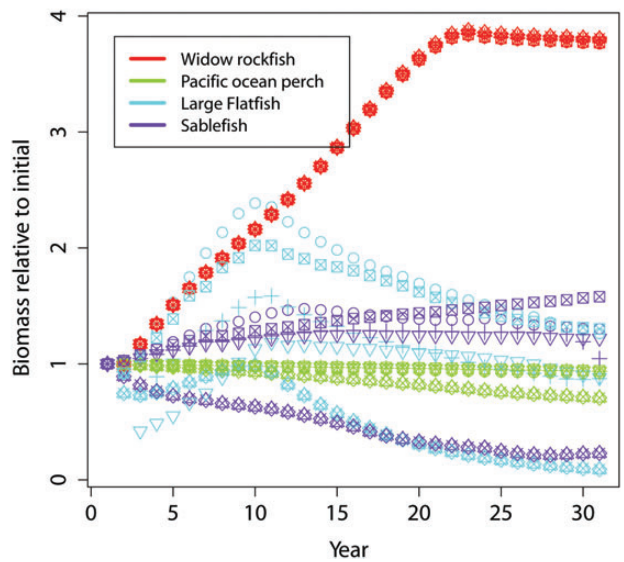

Figure 6. Coast-wide biomass time-series for two rockfish species, and two fishery target groups: large flatfish and sablefish. The seven scenarios ordered as in Table 2 are represented by circles, triangles, plus signs, crosses, diamonds, inverted triangles, and crossed boxes. For sablefish, large flatfish, and Pacific Ocean Perch, final biomass is highest for scenarios with highest penalty and lease costs.

Biological response

Limiting bycatch of overfished species and promoting recovery of these species is a primary motivation for a shift to ITQs. Of the six constraining species in the simulation, darkblotched rockfish and Pacific Ocean perch were the species with the highest catches in the 2004 data and in the cumulative landings limit scenario, and these species have the largest absolute drop in bycatch when over-quota penalties are applied (Figure 3). The 30-year ecosystem simulation predicts increasing abundance of darkblotched rockfish except under competitive TACs or ITQs with no over-quota penalty (Figure 5). In the absence of this over-quota penalty, adding high quota price for scarce rockfish quota did not reduce bycatch or increase abundance. Similarly, Pacific Ocean perch stocks were stable under all scenarios except those with competitive TACs or ITQs with no over-quota penalty (Figure 6); adding high quota prices for scarce rockfish did not alter this. Other rockfish species (bocaccio, yelloweye, canary, and widow rockfish) demonstrate little stock-wide variation in abundance across scenarios; in absolute terms, catches of these species vary little between scenarios (Figures 5 and 6, supplementary Table B5).

Under competitive TACs or with ITQs and no over-quota penalties, target species such as sablefish and large flatfish are overfished and decline (Figure 6, Table B5). Overall, both the more realistic ITQ scenarios (with over-quota penalty) and the cumulative landings limits led to stable or increasing abundances of these species, suggesting that adherence to limits on total catch is most important, regardless of whether this is implemented in terms of cumulative landings limits or ITQs.

Indirect trophic effects predicted by the ecosystem model are most evident under the benchmark case of competitive TACs, or the similar ITQ simulations that lacked penalties for exceeding quotas (Table B5). Competitive TACs led to increased fishing effort, subsequent decreases in piscivores, and a release of forage groups (small planktivores, deep vertically migrating fish, cephalopods, and nearshore fish); 30–60% increases in these forage groups led to 10–50% increases in bird and pinniped abundance under these scenarios, since birds and mammals also consume forage species such as sardines and squid. Two highly productive invertebrate groups, shrimp and meiobenthos (flagellates, ciliates and nematodes), also respond indirectly to these benchmark ITQ cases. These benchmark high fishing mortality rates were required for the ecosystem model to predict strong indirect (trophic) effects on the food web.

Discussion

Global data suggest that ITQs can reduce the likelihood of fishery collapse (Costello *et al.*, 2008), decrease discarding (Branch *et al.*, 2006), or decrease variability in landings, discard rates, or the ratios of catch/quota (Essington, 2009; Melnychuk *et al.*, 2011). For the US West Coast, preliminary data from 2011, the first year of ITQs for the groundfish trawl fleet, suggest that rockfish catch has declined and that catches of key deep-water target species such as sablefish were harvested near their quotas, matching the intent of fishery managers (PFMC, 2008). However, the ITQ system is a complex package of regulations; our simulations here suggest that for the US West Coast some aspects of the ITQ package are potential accelerators of fishing pressure, others are brakes, and others appear as brakes but may ultimately have less effect than expected.

In hypothetical cases with a competitive TAC and similar cases with ITQ systems lacking penalties for exceeding quota, the ability to transfer quota between vessels drove increases in fishing effort. This quickly led to declines in the resource and fish populations. These scenarios allowed legal discarding once aggregate quotas were exhausted. Under current US law they would not be allowed, but might be considered in other countries if full monitoring of discards was infeasible. This hypothetical case is a reminder that trading quota can ease restrictions on fishing, allowing vessels to fish and lease quota until all available quota coast-wide is exhausted, rather than having vessels or fleets bound by their own quota allocations.

We found that the penalties fishers expect for exceeding quota once the TAC is reached and leased quota is unavailable is the major factor that caps bycatch, quota overruns of target species, and overall fishing effort. These penalties are crucial, as they apply to all harvested species including the high-volume target species. Note that it is the penalties paid for overharvesting high volume target species (not rockfish) that constrain effort and bycatch. These over-quota penalties reflect fishers' sense of the severity of fines and the probability of detection and conviction (Sutinen and Andersen, 1985). (In the model, expected penalties and actual ones are the same since catch is not uncertain and there is 100% observer coverage.) The penalties of \$5 or \$10 kg^{-1} modelled here act as brakes on fishing effort and bycatch, but are a somewhat crude tool: in general they reduce overruns of target and bycatch species catch, but catches of three species (widow, canary, and darkblotched rockfish) exceeded quotas under all scenarios tested here. This illustrates the challenges of "weak stock" management (Hilborn *et al.*, 2004), which pits economic goals of multispecies fishery management against conservation interests focused on single species.

Our analysis suggests that costs associated with leasing quota in the US West Coast ITQ system may have limited impact on fleet behaviour and management performance, at least if quota price dynamics are similar to what has been observed in the New Zealand ITQ. Also, higher prices for scarce quota for bycatch species do not have large effects on fleet behaviour, effort or catch. Though we simulated quota prices that could reach \$50 kg^{-1} for six rockfish species, they are applied to small volumes of catch and can be offset by revenues from large volumes of target species catch.

Population dynamics predicted by the full ecosystem model suggest that the depleted stocks and target stocks recover or remain stable as long as harvests are near TACs, regardless of the details of the quota system. When overfishing occurred in simulations with large increases in fishing effort, trophic effects led to increases in lower trophic level species (e.g. small planktivores and squid), birds and mammals. However, in actuality fishery managers would be required by law (Magnuson-Stevens Fishery Conservation and Management Reauthorization Act, 2006) to prevent such depletion of managed populations.

In scenarios that avoided such overfishing, the food web interactions in the Atlantis model are less important, but instead the model serves as a spatially explicit simulator that begins to represent the true complexity of this multispecies fishery. In comparison, Toft *et al.* (2011) present a fleet dynamics model of this fishery with ITQs versus cumulative landings limits, but include only one target species and one bycatch species. Under ITQs, Toft and colleagues' model predicted nearly perfect quota attainment of the one target species and ~30% reductions in bycatch of the single rockfish species, but these authors suggest extending such models in a multispecies context. The Atlantis model captures the complexities of the multispecies fishery, demonstrating trends in target and bycatch species similar to those predicted by Toft *et al.* but with deviations due to the spatial overlap of fleets and species, bycatch of each rockfish group, and quota allocation across the suite of species.

This work should be viewed as an effort to understand the implications of the anatomy of an ITQ system, in particular how incentives from quota lease prices and penalties for exceeding quotas affect outcomes. The fishery is evolving rapidly, and our simulations were calibrated to a baseline year (cumulative landings limit system) that precedes the most recent developments in the fishery and ecosystem. Our model necessarily includes many simplifications of the ecological and human system, including: aggregation of some species into groups, a simple loop of climate and oceanography, deterministic stock-recruitment functions, and constant fish prices. Simplifications in the fleet dynamics include setting quotas at constant levels, simulating vessels that have perfect knowledge of the spatial distribution of expected revenue, handling dynamics at the fleet (port) level instead of at the level of individual vessels, placing no restrictions on the timing of landings (i.e. processor and market capacity), and omitting investment and disinvestment (i.e. vessels and fishers entering or exiting the fishery). Lian *et al.* (2010) have estimated that individual quotas on the West Coast could lead to a 50–66% decline in the number of vessels. Our model predicts an eventual halving of total fishing effort for the ITQ scenarios with penalties as compared to cumulative landings limits, but consolidation is not explicitly modelled. ITQs may also cause conflicts related to allocation, fleet consolidation, and economic and social equitability (McCay, 1995), and none of these factors are addressed here. Economics and social science are needed to begin to measure these impacts at the port or community level (Norman *et al.*, 2007; Leonard and Watson, 2011; Kaplan and Leonard, 2012).

Supplementary data

The following supplementary data are available at *ICES Journal of Marine Science* online:

Figures A.1, A.2. Atlantis domain and initial relative abundance of four rockfish species
Figure A.3 Model of the price of scarce quota for six rockfish species
Table B1. Ratio of catch reported in 2004 PacFIN logbooks to simulated catch
Table B2. Overlap of rockfish (*Sebastes* spp.) distributions and each fleet's fishing area
Table B3. Percent of total catch per fleet comprised of six rockfish species
Table B4. Effort per fleet over first five years of the simulation
Table B5. Biomass of each functional group at Year 30
Figure B.1. Relative trawl effort for the Astoria limited-entry trawl fleet
Figure B.2. Trawl effort (h) for the San Francisco limited-entry trawl fleet
Figure B.3 Example of effect of quota system on the timing of fishing effort

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