Ecological Applications, 24(1), 2014, pp. 4–14

Conservation markets for wildlife management with case studies from whaling

Leah R. Gerber,[1,3] Christopher Costello,[2] and Steven D. Gaines[2]

[1]*Ecology, Evolution and Environmental Science, School of Life Sciences, Arizona State University, Box 874501, Tempe, Arizona 85287-4501 USA*
[2]*Bren School of Environmental Science and Management, University of California, Santa Barbara, California 93106 USA*

Abstract. Although market-based incentives have helped resolve many environmental challenges, conservation markets still play a relatively minor role in wildlife management. Establishing property rights for environmental goods and allowing trade between resource extractors and resource conservationists may offer a path forward in conserving charismatic species like whales, wolves, turtles, and sharks. In this paper, we provide a conceptual model for implementing a conservation market for wildlife and evaluate how such a market could be applied to three case studies for whales (minke [*Balaenoptera acutorostrata*], bowhead [*Balaena mysticetus*], and gray [*Eschrictius robustus*]). We show that, if designed and operated properly, such a market could ensure persistence of imperiled populations, while simultaneously improving the welfare of resource harvesters.

Key words: Balaena mysticetus; Balaenoptera acutorostrata; *bowhead whale; conservation; conservation market;* Eschrictius robustus; *gray whale; minke whale; tradable harvest quota; whaling.*

Introduction

Wildlife conservation programs face diverse threats, including habitat destruction, overexploitation, pollution, and climate change (Soule and Orians 2001). Collectively, these challenges can put species at risk of extinction. Even when the viability of a species is not at risk, there can be strong conflicts driven by the disparate perspectives and values of resources extractors and resource conservationists. To date, most efforts to meet these challenges have focused on regulatory and educational solutions (Armstrong and McCarthy 2007, Knight et al. 2008, Heller and Zavaleta 2009). By contrast, environmental markets play a relatively minor role in this arena. Market-based incentives, such as cap and trade (Sumaila et al. 2008, Flachsland et al. 2011), have helped resolve a number of environmental challenges. For example, in the management of natural resources, catch shares in fisheries (Costello et al. 2008, Abbott et al. 2010) have enhanced the sustainability of harvest in a number of settings. However, since such programs typically only allow participation by resource extractors, they have played little role in resolving the ethical debates that arise in the hunting of more charismatic species. Establishing property rights for environmental goods that allow trade to occur between resource extractors and resource conservationists may offer a path forward in conserving charismatic species like whales, wolves, turtles, and sharks. In this paper, we provide a conceptual model for implementing a conservation market for wildlife, and evaluate how such a market could be applied to three case studies for whales (minke [*Balaenoptera acutorostrata*], bowhead [*Balaena mysticetus*], and gray [*Eschrictius robustus*] whales).

How many animals should be killed is a key question for any hunted species. At a minimum, the question involves setting sustainable limits on harvest that allow harvests to be replaced by the productivity of the population. When there are strong ethical debates about the appropriateness of harvest, target levels may be substantially below those driven solely by a goal of sustainable harvests. Indeed, in such settings, many people may seek permanent bans on hunting. The issue of whale hunting provides a salient example (Perry et al. 1999, Clapham et al. 2007). The International Whaling Commission (IWC), charged with the global conservation and sustainable use of whales, introduced a moratorium on commercial whaling in 1986 as a temporary strategy to conserve depleted whale stocks while a more long-term plan was developed to manage whales. Fueled by interests who challenge the ethics of whaling, the ban has not been temporary. But, it has also not been effective. Despite the moratorium, scientific whaling (~1000 whales/year), whaling under objection to the IWC (~590 whales/year), and subsis-

Manuscript received 1 November 2012; revised 8 March 2013; accepted 25 April 2013. Corresponding Editor (ad hoc): K. Criddle. For reprints of this Forum, see footnote 1, p. 3.
[3] E-mail: leah.gerber@asu.edu

TABLE 1. Model parameters used to calculate conservation and whaler welfare for case studies.

Parameter	Description	Bering–Chuchki–Beaufort bowhead	Central north Atlantic minke	Eastern north Pacific gray whale
A	whaler demand parameter reflecting the number of whales desired to be hunted	15 056	15 056	15 056
B	whaler demand parameter reflecting the slope of the demand curve	1.37	1.37	1.37
m	conservationist demand parameter reflecting the marginal willingness to pay to conserve the last extant whale	116 000	116 000	116 000
K	carrying capacity of the whale population	13 858	72 130	25 808
N_0	initial population size	11 800	72 130	19 126

Notes: Data for bowheads (*Balaena mysticetus*) are from Brandon et al. (2007) and Gerber et al. (2007); for gray whale (*Eschrictius robustus*), data are from Loomis and Larson (1994), Gerber et al. (1999), Laake et al. (2009), and Punt and Wade (2010); and for minke whales (*Balaenoptera acutorostrata*), data are from Amundsen et al. (1995), Bulte and vanKooten (1997), Bulte et al. (1998), NAMMCO (1998), Horan and Shortle (1999), and Laake et al. (2009).

tence whaling (∼350 whales/year) continue today (IWC 2011*a*). Overall, whaling has more than doubled in the past 20 years. The lack of resolution despite decades of negotiations between pro- and anti-whaling nations has called into question the future of the IWC as a path to resolution (Gambell 1993, Holt 2002, Clapham et al. 2007). Under a general conservation market, quotas for the hunting of a target species would be traded in global markets. But unlike most catch share programs in fisheries, the conservation market would not restrict participation in the market; both pro- and anti-whaling interests could own and trade quota. The maximum potential harvest for any hunted species in any given year would be established in a transparent, scientifically defensible manner that ensures sustainability of the marketed species and maintains their functional roles in the ecosystem. The actual harvest, however, would depend on who owns the quota. In its simplest form, a conservation market would cap the maximum harvest at its existing level, and would provide a platform for conservationists to approach whalers with a financial offer to reduce their whale harvest. But other forms are possible; we discuss some of these issues here.

We attempt to spell out how such a conservation market might operate for whaling; similar analysis and insights apply to ethically charged debates concerning other hunted species. At one extreme (where whalers purchase all of the quotas), the harvest would equal the maximum sustainable level. At the other extreme (where conservationists purchase all quota), the harvest could be reduced to zero. Initially, "whale shares" would be allocated or auctioned to member nations of IWC (both pro- and anti-whaling). Owners of whale quota could exercise it, retire it, or trade it. Could such a market provide a transparent and effective vehicle for better resolution of the ongoing global debate on the ethics and appropriate levels of whaling? Is it possible for all stakeholders to be better off relative to the status quo? To answer these questions, we developed a simulation model that explores the performance of a whale conservation market.

METHODS

General approach

Our model consists of three components: (1) a biological model of whale population dynamics, (2) an economic model of the conservation and whaling demand for whales, and (3) an allocation rule for quota shares, which are transferable. Our intent is to illustrate a general approach that can be refined as data on biological and economic parameters become available; for simplicity, we assumed that market behavior is static (i.e., without dynamic strategic behavior), though even these simple annual decisions give rise to interesting dynamics.

Whale population dynamics

Following Taylor et al. (Taylor et al. 2000), we assumed the whale population dynamics follow a deterministic, discrete time difference equation:

$$N_{t+1} = N_t + rN_t\left[1 - \left(\frac{Nt}{K}\right)^{\theta}\right] - Q_t \quad (1)$$

where N_t is the whale population at the beginning of period, r represents the intrinsic rate of increase of a population, K depicts carrying capacity, θ indicates the shape of the biological production function, and Q_t is the harvest of whales in year t. Table 1 summarizes biological and economic parameter values.

Allocation of rights

In our model, a manager would use a decision rule to stipulate a maximum allowable harvest of ($\bar{Q}_t$). A very simple decision rule is simply to set the cap at the current level of harvest (if this is deemed safe for the population), but more sophisticated rules are also possible. While a variety of algorithms could be employed to identify a sustainable harvest level (Porch and Fox 1990, Cooke 1999, Givens 1999, McAllister and Kirchner 2001, Reeves 2002, Brandon et al. 2007, Smith et al. 2008, Haltuch et al. 2009, Hillary 2009), we used the potential biological removal (PBR) approach as an illustrative example, because it is transparent, conservative, and already used to manage marine mammals in the USA (Taylor et al. 2000).

We used the PBR calculation (Taylor et al. 2000):

$$\bar{Q}_t = 0.5N_t r F_r \quad (2)$$

where N_t and r are as defined in the previous section, and the scalar F_r is a recovery factor between 0 and 1 (Taylor et al. 2000). We scaled the recovery factor such that $F_r = 0.1 + 0.4N_t/K$ so F_t cannot exceed 0.5 (this permits, at a maximum, a very conservative maximum level of harvest). However it is set, a total of $\bar{Q}_t$ whale shares are issued in year t. These are allocated among whalers (who receive $\alpha\bar{Q}_t$) and conservationists (who receive $(1 - \alpha)\bar{Q}_t$). The allocated shares are then traded between whalers and conservationists, depending on their demand curves for whale shares, resulting in a final harvest of whales $Q_t \leq \bar{Q}_t$.

Estimating welfare to whalers

We developed a simple simulation model of a whale conservation market to predict the consequences of various market designs on (1) whale populations, (2) whale hunting, (3) costs and benefits to whalers, and (4) costs and benefits to conservationists. To investigate whether whaling and anti-whaling stakeholders could simultaneously benefit under such a whale conservation market, we explored the expected buying, selling, and equilibrium price of whale conservation quota shares. In our model, two players compete for whale shares: We assumed that "whalers" derive value from the harvest of whales, and "conservationists" derive value from the unharvested whale population. We also assumed that these values are static; generalizations of this model would allow the demand for harvest rights to change over time, or even to evolve endogenously within the model.

Following Horan and Shortle (1999), the whaler's demand for hunting whales takes the linear form: $Q = A - B \times P$, where A is a demand parameter reflecting the maximum number of whales that whalers would like to hunt, B governs the change in value as subsequent whales are hunted, and P is the marginal value of each whale harvested (Fig. 1). This is the whaler's demand curve for harvest rights in a given year, which reflects the profitability of harvesting subsequent whales. Its negative slope reflects the fact that, at least beyond some point, each subsequently harvested whale brings in lower net benefits to harvesters.

To maintain simplicity, we also assumed that conservation demand is linear, but it is a function of the whale population size (because the model is in discrete time, we must measure this at a consistent point in the season; we adopted the convention of measuring it postharvest, but pre-growth). The conservationist's inverse demand for whaling permits takes the form $P = m = m/K(N - Q)$, where m is the willingness to pay to conserve the last whale in the population (i.e., the maximum amount a conservationist is willing to pay to save a whale), K is the carrying capacity of the population, and $N - Q$ is the postharvest whale population size. While we have assumed simple linear forms here, one could derive these demand curves from a more sophisticated dynamic optimization by the whalers and/or the conservationists.

Our model implicitly assumes that a conservationist would not be willing to pay to increase the whale population above the carrying capacity, that a larger whale population leads to a higher conservation welfare (though at a diminishing rate), and that the conservationist receives some positive utility from a whale population of any size >0. For a given set of parameter values, these demand curves define a market in which we calculate the whale quota share trading price and quantity of whales harvested in market equilibrium (P_t^*, Q_t^*). This equilibrium outcome will vary annually as the whale population size fluctuates. The actual harvest is Q_t^*; a corner solution emerges when $Q_t^* \leq 0$, in which case the conservation demand is greater than the whaler demand, so conservationists buy all quota and no harvest takes place.

Having specified the allocation rule and demand functions, we can now calculate the welfare impacts on each player in each period. Whaler welfare represents the benefits from selling shares to conservationists $\alpha(\bar{Q}_t - Q_t)$ and from harvesting the whales (Q_t). If whalers sell shares at price P_t, then their welfare is the revenue from those sales, which is $P_t(\alpha\bar{Q}_t - Q_t)$, plus the welfare they gain from being allowed to harvest the Q_t whales they end up harvesting. By contrast, if whalers buy shares at price P_t, then their welfare is the welfare from harvesting Q_t, minus what they had to pay to secure the permits. Whaler welfare from harvesting Q_t is illustrated in the gray area in Fig. 1a. Integrating under the whaler demand curve gives welfare:

$$\int_0^{Q_t} \frac{A - Q}{B} dQ = \frac{AQ_t - 0.5Q_t^2}{B}.$$

Thus, the total whaler welfare in a period under a conservation market is

$$W_{\mathrm{w}}^{\mathrm{market}} = P_t(\alpha\bar{Q}_t - Q_t) + \frac{AQ_t - 0.5Q_t^2}{B}.$$

As a basis for comparison, we also computed the whaler's welfare without a whale conservation market. Under the assumption that whalers harvest the full $\bar{Q}_t$ every year, whaler welfare is $W_{\mathrm{w}}^{\bar{Q}} = \bar{Q}_t(A - 0.5\bar{Q}_t)/B$. Whaler welfare under a complete ban on whaling is $W_{\mathrm{w}}^{\mathrm{no-take}} = 0$.

Estimating welfare to conservationists

Conservationists derive welfare from the existence and size of the (living) whale population. But conservationists also derive welfare from the ability to buy (or sell) rights in a conservation market. The downward-sloping

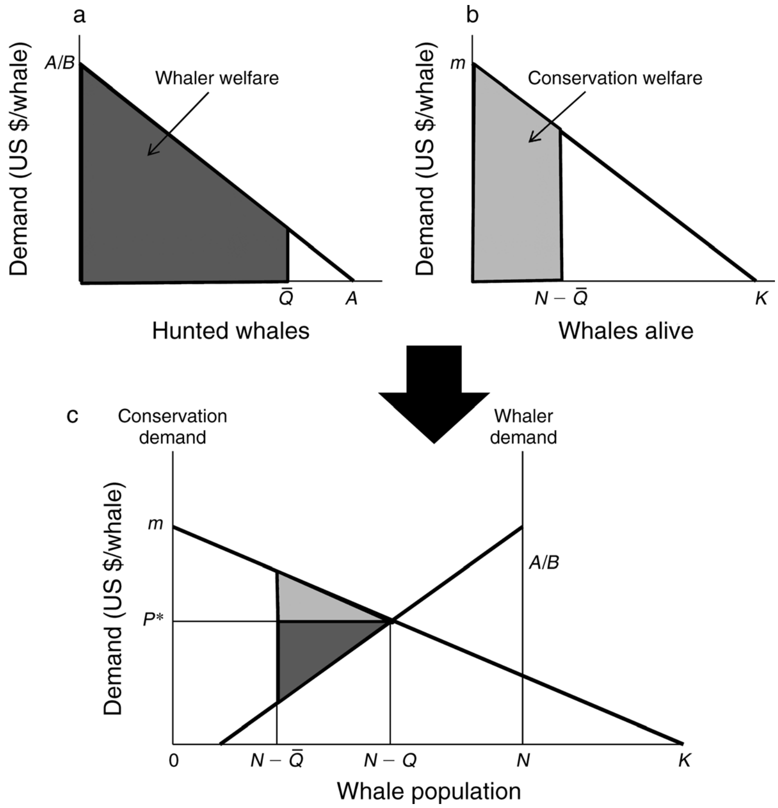

FIG. 1. (a) Whaler demand for hunting whales, which saturates at A. The first whale hunted has a higher value (A/B), where A is a demand parameter reflecting the maximum number of whales that whalers would like to hunt, and B governs the change in value as subsequent whales are hunted. If the full quota ($\bar{Q}$) is hunted, whaler welfare is indicated by the dark-gray area. (b) Conservation demand for live (postharvest) whales saturates at carrying capacity (K), and saving the last whale from extinction has the highest value (m). If the population of whales is represented as N and the full quota is hunted, conservation welfare is indicated by the light-gray area; note that the marginal value of a whale is higher for a conservationist than for a whaler. (c) Whale conservation market, illustrating implications of market transaction for increased welfare level, showing that equilibrium in the whale market is where the demand curves cross. If $\bar{Q}$ whales are allocated to whalers, $Q < \bar{Q}$ are killed. Price of whales is P^*, and Q is the annual equilibrium harvest.

demand curve reflects the fact that adding a whale to the population increases conservation welfare, but at a diminishing rate. The population of live whales is the total number minus the harvest (Fig. 1b). Conservation welfare is simply the area under the conservation demand curve to point $N_t - \bar{Q}_t + Q_t^{\mathrm{c}}$, which is

$$\int_0^{N_t-\bar{Q}_t+Q_t^{\mathrm{c}}} \left(m - \frac{m}{K}\times y\right) dy = m(Q_t^{\mathrm{c}} - \bar{Q}_t + N_t)\left(1 - 0.5\,\frac{(Q_t^{\mathrm{c}} - \bar{Q}_t + N_t)}{K}\right)$$

plus or minus any rights sold (or bought), at price P_t, from whalers, $P_t((1 - \alpha)\bar{Q}_t - Q_t^{\mathrm{c}})$. Thus, conservation welfare under a whale conservation market is

$$W_{\mathrm{c}}^{\mathrm{market}} = P_t[(1-\alpha)\bar{Q}_t - Q_t^{\mathrm{c}}] + m(Q_t^{\mathrm{c}} - \bar{Q}_t + N_t)\left(1 - 0.5\,\frac{(Q_t^{\mathrm{c}} - \bar{Q}_t + N_t)}{K}\right)$$

where Q_t^{c} is the number of whales conserved. Without a whale conservation market, whalers hunt the full quota, $\bar{Q}_t$, and conservation welfare can be calculated based on the live population, $N_t - \bar{Q}_t$:

$$W_{\mathrm{c}}^{\bar{Q}} = \int_0^{N_t-\bar{Q}_t} \left(m - \frac{m}{K}\times y\right) dy = m(N_t - \bar{Q}_t)\left[1 - \frac{0.5(N_t - \bar{Q}_t)}{K}\right].$$

For a moratorium, where no whales are harvested, the welfare is shown as the gray area in Fig. 1b, or

$$W_{\mathrm{c}}^{\mathrm{no-take}} = \int_0^{N_t} \left(m - \frac{m}{K}\times y\right) dy = N_t\left(\frac{m - 0.5mN_t}{K}\right).$$

Thus, conservation welfare under a complete moratorium can be compared to welfare under a market- or a quota-based system.

Simulations

To illustrate some hypothetical scenarios for how this kind of market might operate, we developed a very

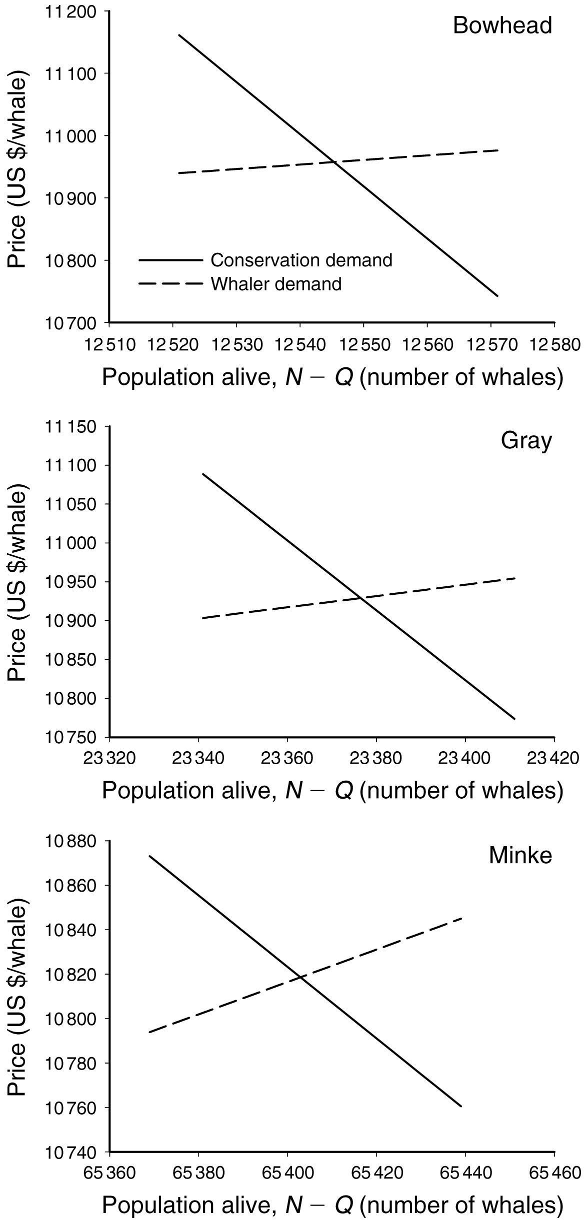

FIG. 2. Market equilibrium for population steady state for case studies, where all initial shares go to whalers. Because the market equilibrium changes annually due to changes in whale population size over time, which influences conservationists' demand, and thus, whaler welfare from selling whale shares, here we ran the model to equilibrium and show the market equilibrium for steady-state conditions. Parameter estimates for the market equilibrium at steady state (and year 1) are shown in Table 2.

simple simulation. This model can be used to predict the consequences of various market designs on (1) whale populations, (2) whale hunting, (3) costs and benefits to whalers, and (4) costs and benefits to conservationists. The equilibrium quantity of whales that are actually harvested, Q_t^*, is a function of demand parameters and whale population size, which can change over time. For a given set of parameter values, we calculated the market equilibrium (Fig. 1c), allowing for the possibility of corner solutions $Q_t = 0$ (conservationists end up with all of the rights), and $Q_t = \bar{Q}_t$ (whalers end up with all of the rights). We also calculated the marginal willingness to pay for each party in equilibrium, P_t.

In our model, the value of a whale and the possibility for trading quotas is determined by the market, which changes every year (i.e., each year the regulator sets a cap and the two sides trade to a new equilibrium, which affects the population and the next year's quota). For our case studies, we simulated the model over time until the population reaches steady state (i.e., $N_{t+1} = N_t$) and document the population size and whaler and conservation demand (Fig. 2). In order to quantitatively examine the performance of alternative management strategies on both conservation and whaling welfare, we compared whaler and conservation welfare to a no-trading quota-based system (Fig. 3). Each year, a new equilibrium is achieved based on the changing whale population size, which, in turn, influences the annual market equilibrium. For any market transaction, the price is the equilibrium price in the case of an interior solution. A corner solution indicates that the conservation demand curve is above the whaler demand curve and conservationists will buy all quotas from whalers. Here, we assumed that there is no market power for each agent in the market, and they will trade at a fair price, namely the average price between A/B and $m - m/K \times N$. Finally, given the sparse economic data available, we also evaluated the sensitivity of model results to alternative assumptions about parameters A, B, and m.

To provide real-world context for how a whale conservation market might play out, we ran simulations to estimate the cost associated with saving all whales over a 20-year period. With the total $\bar{Q}$ available, market transactions dictate the number of whales saved by conservationists and the number of whales harvested by whalers. For this simulation, we assumed that whalers are allocated all quotas ($\bar{Q}$) each year. The cost for each year depends on the market equilibrium, which is influenced by whale population status, as well as whaler and conservation demand. There are three possible outcomes of market behavior in any given year: (1) Conservationists will buy all quotas (corner solution) from the whaler (this is the case if the conservation demand curve is above the whaling demand curve and the equilibrium harvest level Q^* is smaller than zero); (2) whalers will harvest all $\bar{Q}$ (corner solution; this is the case if whalers value the last unit of harvest more highly than conservationists value the first unit of conservation); and (3) whalers end up harvesting less than the maximum, which suggests that $\bar{Q}$ is greater than the equilibrium harvest level Q_t^*; hence, the conservationist will buy $\bar{Q} - Q^*$ from whalers (under the scenario when all quotas are allocated to whalers).

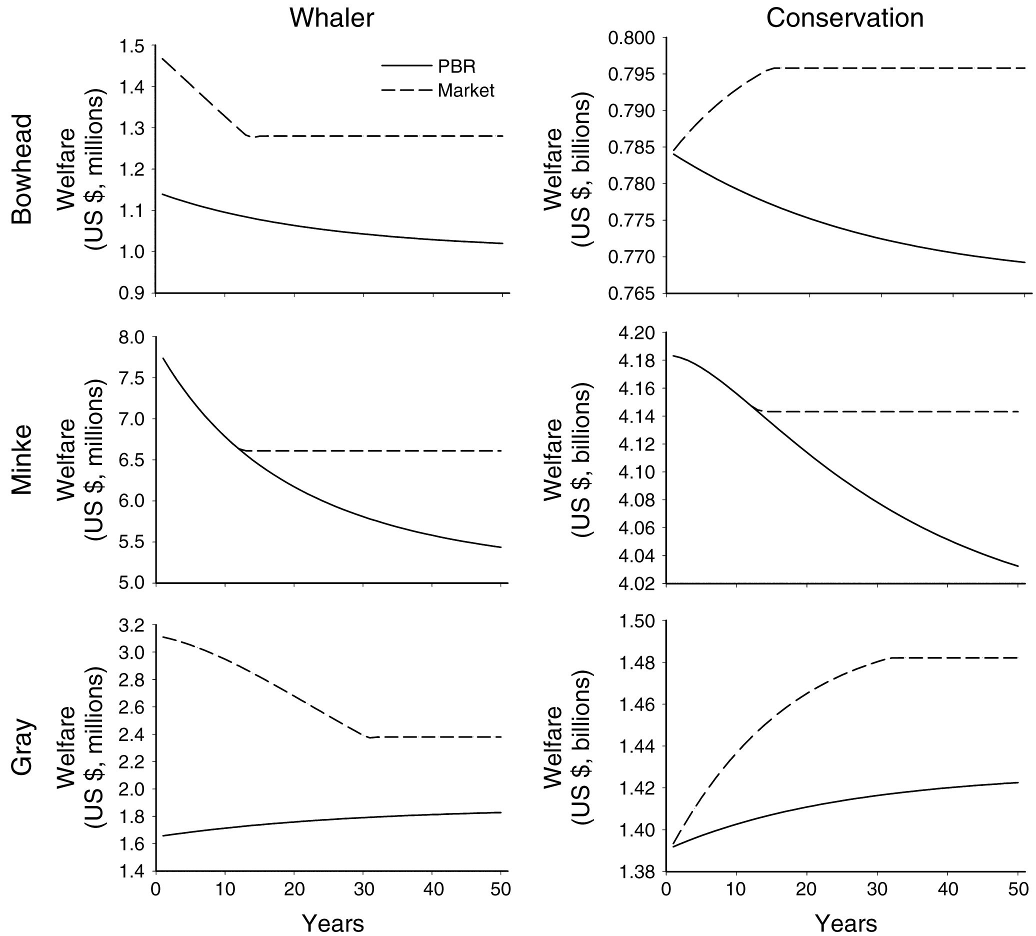

FIG. 3. Model prediction of whaler and conservationist welfare (benefits minus costs) over time under a market- vs. a quota-based system (potential biological removal; PBR) for each case study. Both conservationists and whalers are made better off with a market-derived system compared to a quota-based system. Dashed lines are welfare under a whale conservation market, and solid lines are welfare under a quota system ($\bar{Q}_t$) for allowable harvest. Market scenarios assume that quota shares are allocated to whalers. The shape of whaler welfare under a market arises because of changes in whale population size over time, which influences conservationists' demand and, thus, whaler welfare from selling whale shares. Parameters used for simulations are in Table 1.

Estimating anti-whaling budgets and conservationist willingness to pay

Would conservationists be willing to pay something to reduce whale harvest? Because no platform for such transactions currently exists, it is hard to say. But as a basis for comparison to the market-based approach, here we estimated roughly how much anti-whaling constituents currently spend annually to achieve their objective. Several nonprofit organizations conduct anti-whaling campaigns around the world. The larger of these organizations (e.g., World Wildlife Fund [WWF] and Greenpeace) have offices in multiple countries, operating with separate, but related, campaigns and budgets. All organizations working on anti-whaling reported that it is nearly impossible to estimate an accurate annual budget for their efforts. A comprehensive literature review suggests that the reported total annual expenditures for Greenpeace USA, Greenpeace International, Sea Shepard, WWF-International, and WWF-UK is \$25 000 000 (all currency in U.S. dollars), which represents a conservative estimate of money spent by nonprofit organizations on anti-whaling each year (L. Peavey, *unpublished data*).

Our example is only meant to be illustrative, since we have not conducted primary surveys or other means to estimate the parameters of the conservation demand curve. Rather, we took as a starting point estimates reported in the literature for conserving gray whales. To obtain a conservative estimate for the parameter m, we used the consumer price index to inflate the willingness to pay (WTP) estimates from Loomis and Larson (1994), and scaled up to the number of households in California (where their survey was based). We then calculated the linear demand curve for whale conservation that produced the WTP estimates reported in the paper. The resulting choke price is $m = \$116\,000$, which

TABLE 2. Market equilibrium in year 1 and steady state (SS).

Parameter	Bowhead		Minke		Gray	
	Year 1	SS	Year 1	SS	Year 1	SS
Equilibrium price (P)	11 487	10 957	7 558	10 818	13 650	10 929
Equilibrium quotas (Q)	−682	46	4 700	236	−3 645	84
Population size (N)	11 800	12 591	67 429	65 639	19 126	23 461

Notes: The negative values indicate a corner solution, suggesting that the conservationists will buy all potential biological removal (PBR) from the whalers. Negative equilibrium quotas indicate a corner solution where conservationists buy all shares and no harvest will occur.

is the maximum willingness to pay to conserve a single whale. This rough estimate admittedly glosses over many complexities in deriving an estimate for m, such as the relevant population over which to aggregate, the public goods nature of demand, and so on. That said, the choke price is conservative, as the household survey by Loomis and Larson (1994) did not consider the efforts of conservation groups. To estimate whaler demand parameters A and B, we relied on values reported for minke whales from Amundsen et al. (1995) and Horan and Shortle (1999).

RESULTS

Whaler and conservationist market equilibrium

To illustrate how our approach might apply to real-world management, we considered three case studies (Fig. 3). We chose our case studies based on stocks that are experiencing some level of whaling and for which there are reliable data available for population size and carrying capacity. First, the Bering–Chukchi–Beaufort stock of bowhead whales represents an example of the application of our approach to aboriginal subsistence whaling. Second, Eastern North Atlantic minke whales highlight the possible consequences for whaling under scientific permit. Third, we applied our approach to Eastern North Pacific gray whales, which are currently taken under objection. For each case study, we estimated the market equilibrium in the first year and steady state (Table 2, Fig. 2), whaler and conservation welfare over time (Fig. 3), and the cost to purchase shares.

The bowhead whale was heavily exploited by pre-20th-century whaling. The Bering–Chukchi–Beaufort Seas stock has been increasing at an annual rate of over 3% since 1978, when reliable census data were first collected (Gerber et al. 2007). For bowhead whales, there are a number of political issues surrounding whether or not the moratorium should be supported. Most IWC member nations (including the United States) support aboriginal subsistence whaling (ASW). Approximately 70 whales are taken annually. Assuming that the initial allocation would be to ASW, it would be the prerogative of ASW to decide if and how many whale shares would be sold to conservationists. If quota is traded, the market equilibrium points P_t^* and Q_t^* can be identified where these two demand curves cross (Fig. 2). Fig. 2 illustrates the market equilibrium for P^* and Q^* for the parameters in Table 1 and the equations $Q = A - B \times P$ and $P = m - m/K(N - Q)$ (Table 2). These assumptions give rise to an equilibrium price (P^*) for buying a Bowhead whale of \$10 957 for a steady-state population size of 12 591. While we assumed a linear demand curve, if some level of harvest is perceived as "necessary" for tribal subsistence or cultural reasons, whalers would not sell beyond that point. If we assume that there is an extremely high value to harvest even a few whales, the choke price grows, suggesting that the ASW will not sell all quota (Fig. 3). To put these figures into context, the recent (2012) IWC meeting focused largely on ASW, and this meeting cost ~\$2 000 000 (IWC 2011*b*).

North Atlantic minke whales highlight the possible consequences of a whale conservation market for commercial whaling. Minke whales are globally protected by the moratorium, with the significant exceptions of commercial catches under objection and subsistence catches in the North Atlantic and scientific whaling in the North Pacific. In the North Atlantic, stocks are thought to be in a healthy state (NAMMCO 1998). The current best estimate of the Central North Atlantic stock of minke whales numbers 72 130 and is approaching carrying capacity (NAMMCO 1998). Approximately 550 are harvested each year (IWC, data *available online*).[4] Our model suggests that a market-derived equilibrium price (P^*) is \$10 818 for buying a minke whale for a steady-state population size of 65 639 (current population size is 72 130). Here, because the steady-state population size is less than initial abundance, potential biological removal (PBR) declines with time.

Finally, eastern North Pacific gray whales have been protected since the 1930s, apart from some subsistence whaling (Gerber et al. 1999). The eastern North Pacific population includes ~19 000 individuals (Laake et al. 2009), with a pre-exploitation level of ~25 000 (Punt and Wade 2010). This stock was recently delisted from the Endangered Species Act (ESA; Gerber et al. 1999). Recent data indicate that ~120 whales are taken annually for aboriginal subsistence by Russia (IWC 2012). Our model suggests that an equilibrium price (P^*)

[4] http://iwc.int/catches#comm

TABLE 3. Sensitivity of model results to small changes (−10%; +10%) in A, B, and m, while holding other parameters constant.

Parameter	A	B	m
Equilibrium price (P*)	9 860; 12 052	12 170; 9963	10 953; 10 959
Equilibrium quotas (Q*)	42; 50	50; 42	50; 42
Population size (N*)	12 722; 12 468	12 455; 12 710	12 455; 12 710

Note: See Table 1 for variable definitions.

for buying a gray whale is \$10 929 for a steady-state population size of 23 461.

These numbers are not meant to predict the specific outcome of a whale conservation market, but rather to illustrate the concept of a whale conservation market with believable input data. Given uncertainty in economic parameters, we also examined the sensitivity of model results to small changes in A, B, and m (i.e., we considered elasticity as 10% change of a single parameter while holding other parameters constant). Equilibrium quotas and population size are not sensitive to small changes in these three parameters, and parameter B and m have the same effect on equilibrium quotas and population size (Table 3).

Modeling whaler and conservation welfare

We used our model to examine whether conservationists and whalers could be made better off (i.e., increased welfare) relative to both a no-harvest scenario and a quota-based system without conservation ownership. While the shape of the welfare functions vary for each stock, a whale conservation market leads to reduced take compared to the quota-based approach without conservation ownership for all case studies (Fig. 3). More importantly, a well-designed whale conservation market simultaneously enhances conservation welfare and whaler welfare relative to the status quo. In some sense this is unsurprising: Allowing voluntary trade, rather than forbidding it, tends to make both parties in an economic transaction better off.

For minke whales, because the initial population is at carrying capacity, conservationists have no incentive to buy shares, since the market equilibrium harvest level is always greater than the PBR; hence, for the first 10 years, the whalers harvest all the PBR. Here, harvest declines over time from a PBR level of 721 to 236 in year 20 (for context, current harvest is ~500 whales per year). At year 11, the population declines to a level where PBR is greater than market harvest equilibrium, and conservationists begin to purchase quotas from the whalers in order to buffer the declining population.

It is interesting to note that the equilibrium price is quite similar for the three case studies. This is partially an artifact of our parameter choices, which are similar (or the same) across species. However, for both bowhead and gray whales, the initial population is smaller than the carrying capacity and the steady-state population, so conservationists buy all quota from the whalers until year 13 and 30, respectively. The welfare for the whaler abruptly changes at this point, when an interior solution is achieved (for corner solutions, equilibrium price is assumed as the average of the whaler and conservationist price). At this point, PBR is greater than the market equilibrium harvested level; thus, the conservationist will purchase progressively fewer whales from the whalers at a decreasing price (i.e., conservation welfare increases and then stabilizes). For all case studies, conservationists are made better off by the increased whale population and whalers are made better off by more efficiently allocating the quota between selling to conservationists and harvesting the whales to sell in the market. For example, for gray whales, welfare under a quota system increases and eventually stabilizes, but never exceeds, the welfare level derived from the market approach. Furthermore, welfare for both whaling and conservation increases with whale population size, highlighting both the conservation and whaling benefits of our approach.

How much does it cost to save the whales?

Our results suggest that the per-whale opportunity cost to whalers from reducing harvest would depend on the species, but could be in the ballpark of \$10 000 for gray, minke, and bowhead whales. We also used our model to estimate the cumulative cost of purchasing all whale shares over a 20-year period (i.e., the annual cost is calculated as the product of the equilibrium price and the number of whales traded in the market). This 20-year cost is roughly \$114 million (saving a total of 8424 whales). The framework can also be applied to estimate the cost of reducing mortality by a fixed percentage for individual stocks.

While our model assumes that a conservationist would not be willing to pay to increase the whale population above the carrying capacity, it is possible that some conservation constituencies may be willing to pay to conserve whales regardless of population status. Although we assumed downward-sloping demand, this curve may be more elastic for people with strongly held moral objections to whaling. Thus, we also considered the scenario where conservationists will pay any price to end whaling and that current harvest levels can never be exceeded. Under that objective, the equilibrium price is irrelevant, because there ultimately is no market. Rather, the conservationist would have to pay the whaler his capitalized opportunity cost of whaling (i.e., the area under the whaling demand curve; Fig. 1a). The resulting cost of eliminating harvest of all bowhead, minke, and gray whales, respectively, over the next 20 years is $149 million (13 800 whales). This cost of approximately $7.5 million per year can be compared to our conservative estimate of annual expenditures on anti-whaling organizations ($25 million).

Discussion

We have described a broad participation conservation market as a mechanism to regulate the harvest of charismatic species such as whales. The approach can be generally applied to other sources of whale mortality, such as fisheries interactions, ship strikes, and climate change, though obvious challenges exist and market design, monitoring, and enforcement will be crucial. For example, it has been argued that one justification for whaling is that whales consume resources that could otherwise be available for consumption by humans (Gerber et al. 2009). If whalers are willing to pay more for a whale than are conservationists, a whale conservation market would allow a country to increase whaling to a sustainable level given a perceived conflict with fisheries. Similarly, a whale conservation market could be designed to encourage fishing techniques that reduced whale bycatch. If fishing companies that incidentally catch whales had to buy whale quota to compensate for their bycatch, there would be a strong financial incentive for fisheries to adopt strategies and technologies that reduce whale bycatch. Ship strikes could be handled similarly by requiring differential fees based on certified adherence to operating practices designed to reduce the frequency of impacts, or through adopting certified monitoring equipment that would catalog actual strikes and bill vessels accordingly. Such an approach would provide a strong financial incentive for ships to avoid whale strikes. Finally, if climate change influences the viability of whales (e.g., if whale's food supply decreases), then the quota must be adjusted for the market to continue to function in the new reality of an altered climate.

Under current international law, any country may opt out of whaling agreements (Gambell 1993, McDorman 1998, Holt 2002, 2007). It may be precisely because no price tag exists that anti-whaling operations have lacked widespread success. Furthermore, the evidence suggests that both whalers and anti-whalers have already put a price tag on whales. Whalers expend millions of dollars annually to harvest whales, many of which are traded in global markets. Available data suggest that a minimum value for annual profit from all global whaling activity is on the order of $31 million. A conservative estimate of money spent annually by nonprofit organizations on anti-whaling is $25 million, suggesting that these two competing values of whales are of similar magnitudes (Costello et al. 2012). Have these large expenditures had measurable conservation impacts? A generous estimate of the efficacy of anti-whaling campaigns is the self-report by the Sea Shepherd Society, which estimates their multi-million-dollar 2008 campaign saved about 350 minke whales in Antarctic waters (Costello et al. 2012). Our results indicate that it may be possible for anti-whaling interests to purchase a considerable fraction of the whale shares for comparable investments in a whale conservation market.

Similarly, nations and indigenous people with a long history of whaling assert a cultural right to hunt whales for food or spiritual reasons (~19% of total whale harvest). Under the current system, these groups are increasingly ostracized in a battle of competing ethical beliefs. Under a whale shares market, firmly held beliefs would be expressed as holding shares for whale quota even in the face of lucrative offers to sell. Rather than opting out of international agreements and setting their own standards under the guise of "scientific whaling," proponents of whaling could be assured that the whale quota they choose not to sell provides a valid right to harvest that number of whales.

Others may argue that whaling countries may never sell their shares to conservationists, or that conservationists may never sell their shares. For the market to function as we have articulated, whale conservation shares must flow to the party who values the shares the most. For example, if a whaling nation is allocated n shares of whale based on historical use, conservationists could offer to pay to reduce their harvest to $n - 1$. Our models suggest that the value of n to a whaler might be quite low, while the value to a conservationist of saving that first whale (i.e., reducing the harvest from n to $n - 1$) might be quite high. There is little evidence from other markets that no trading would occur: In every environmental market we are aware of, an interior equilibrium is reached where environmental damage is reduced to some extent, though typically not to zero. The possibility of whale market failure could be addressed by auctioning some of the shares or by several options for initial allocation of the whale quota.

Empirical work on conservation willingness to pay across various stakeholder groups is an important next step in applying our model. In this paper, we relied on published literature to provide illustrative calculations, but we have not directly attempted to estimate the aggregate demand curve for conservation, nor have we explicitly modeled the public good nature of whales or the free-rider problem. In fact, there is likely variation in WTP for different species (Richardson and Loomis 2008, Eiswerth and Kooten 2009, Wallimo and Lew 2011), which may have important consequences for market equilibrium.

While data are not available to accurately estimate either whaler or conservation demand, the shape and slope of these curves may have important implications for market equilibrium. For example, it is possible that some conservation constituencies may be willing to pay to conserve whales regardless of population status (i.e., the demand curve is flat), or that there is a more complex, nonlinear shape to this curve. This underscores the importance of future research on both whaler and conservation demand.

It is also important to recognize that whale harvesters are not homogeneous in the character of their objective functions or in the cost of their hunting and processing activities. Thus, another interesting extension of our model would be to include multiple categories of harvesters (e.g., commercial and noncommercial; Criddle 2004), and to separately model their equilibrium harvest levels. With empirical data on whaler and conservation demand this could be modeled as an optimal control problem (Smith et al. 2008). For instance, Bulte et al. (1998) found that an annual static model may generate different management strategies compared to a dynamic approach. A fully dynamic model specification would allow for forward-looking whaling firms and/or conservationists to engage in market behavior that improved their long-run position in the market by manipulating the current price and population levels.

Another important concern with the efficiency of a whale market is that, on one side, ownership is a private good (a dead whale benefits the whaler who hunts it), whereas on the other side, ownership is a public good (a live whale benefits everyone who values living whales, including whalers). This asymmetry will likely lead to whales for conservation being undervalued in this market. While it is possible that this "free riding" by environmentalists on such defensive purchases of credits (Stewart 1988, Horan and Bulte 2004, Blanco et al. 2009) would weaken the conservation demand for whales, allowing trade will converge closer to the socially optimal solution than a simple "cap" without trade. Furthermore, the same concern applies to the private conservation of land, yet The Nature Conservancy is now the third largest private landowner on the planet. Perhaps most importantly, we have not argued that a conservation market like the one proposed here will lead to a socially optimal harvest level, but rather that it can improve the welfare of both harvesters and conservationists.

Examples of nontrivial ethical debates being resolved through international agreements are rare in practice (Guzman and Landsidle 2008), which underscores the need for alternative solutions that respond to changing norms of international behavior (Weeks 2009). A well-designed whale conservation market could address many of these important challenges and would do so in a more effective, rapid, and efficient manner than has the status quo. More generally, market-based incentives offer a promising approach to effectively manage charismatic species like whales, wolves, turtles, and sharks. A starting point for many of these markets might be to establish current levels of legal take as the baseline and to provide a platform that allows conservation buy-back to reduce that amount. In most cases, even this simple and intuitive mechanism does not exist today. More generally, establishing property rights for environmental goods and allowing trade to occur between resource extractors and resource conservationists may apply to a much broader class of environmental and resource challenges facing society today and into the future.

Acknowledgments

We thank Ray Hilborn, Doug DeMaster, Monica Medina, and Ryan Wulff for insightful discussions on the manuscript. We are grateful to Biao Huang and Lindsey Peavey, who contributed to many insightful discussions and assisted with model implementation and data collection.

Literature Cited

Abbott, J. K., B. Garber-Yonts, and J. E. Wilen. 2010. Employment and remuneration effects of IFQs in the Bering Sea/Aleutian Islands crab fisheries. Marine Resource Economics 25:333–354.

Amundsen, E. E., T. Bjorndal, and J. M. Conrad. 1995. Open access harvesting of the Northeast Atlantic minke whales. Environmental and Resource Economics 6:167–185.

Armstrong, D. P., and M. A. McCarthy. 2007. Big decisions and sparse data: adapting scientific publishing to the needs of practical conservation. Avian Conservation and Ecology 2:14.

Blanco, E., J. Rey-Maquieira, and J. Lozano. 2009. Economic incentives for tourism firms to undertake voluntary environmental management. Tourism Management 30:112–122.

Brandon, J. R., J. M. Breiwick, A. E. Punt, and P. R. Wade. 2007. Constructing a coherent joint prior while respecting biological realism: application to marine mammal stock assessments. ICES Journal of Marine Science 64:1085–1100.

Bulte, E., H. Folmer, and W. Heijman. 1998. Dynamic and static approaches to mixed good management: The case of minke whales in the Northeast Atlantic. European Review of Agricultural Economics 25:73–91.

Bulte, E., and G. C. vanKooten. 1997. Environmental valuation and declining marginal utility of preservation: The case of the minke whales in the NE Atlantic. Journal of Agricultural and Resource Economics 22:393–393.

Clapham, P. J., S. Childerhouse, N. J. Gales, L. Rojas-Bracho, M. F. Tillman, and R. L. J. Brownell. 2007. The whaling issue: conservation, confusion, and casuistry marine policy 31:314–319.

Cooke, J. G. 1999. Improvement of fishery-management advice through simulation testing of harvest algorithms. ICES Journal of Marine Science 56:797–810.

Costello, C., S. Gaines, and L. R. Gerber. 2012. Conservation science: A market approach to saving the whales. Nature 481:139–140.

Costello, C., S. D. Gaines, and J. Lynham. 2008. Can catch shares prevent fisheries collapse? Science 321:1678–1681.

Criddle, K. 2004. Economic principles of sustainable multi-use fisheries management, with a case history economic model for Pacific halibut. American Fisheries Society, Bethesda, Maryland, USA.

Eiswerth, M., and G. C. v. Kooten. 2009. The ghost of extinction: Preservation values and minimum viable population in wildlife models. Ecological Economics 68:2129–2136.

Flachsland, C., S. Brunner, O. Edenhofer, and F. Creutzig. 2011. Climate policies for road transport revisited (II): Closing the policy gap with cap-and-trade. Energy Policy 39:2100–2110.

Gambell, R. 1993. International management of whales and whaling: an historical review of the regulation of commercial and aboriginal subsistence whaling. Arctic 46:97–107.

Gerber, L. R., D. P. DeMaster, and P. M. Kareiva. 1999. Gray whales and the value of monitoring data in implementing the US Endangered Species Act. Conservation Biology 13:1215–1219.

Gerber, L. R., A. C. Keller, and D. P. DeMaster. 2007. Ten thousand and increasing: Is the western Arctic population of bowhead whale endangered? Biological Conservation 137:577–583.

Gerber, L. R., L. Morissette, K. Kaschner, and D. Pauly. 2009. Should whales be culled to increase fishery yield? Science 323:880–881.

Givens, G. H. 1999. Multicriterion decision merging: Competitive development of an aboriginal whaling management procedure. Journal of the American Statistical Association 94:1003–1014.

Guzman, A. T., and J. L. Landsidle. 2008. The myth of international delegation. California Law Review 96:1693–1723.

Haltuch, M. A., A. E. Punt, and M. W. Dorn. 2009. Evaluating the estimation of fishery management reference points in a variable environment. Fisheries Research 100:42–56.

Heller, N. E., and E. S. Zavaleta. 2009. Biodiversity management in the face of climate change: A review of 22 years of recommendations. Biological Conservation 142:14–32.

Hillary, R. M. 2009. Assessment and tag program adaption methods for exploratory fisheries in the CAMLR Convention Area: an example application for Division 58.43a. CCAMLR Science 16:101–113.

Holt, S. J. 2002. The whaling controversy. Fisheries Research 54:145–151.

Holt, S. J. 2007. Whaling: Will the phoenix rise again? Marine Pollution Bulletin 54:1081–1086.

Horan, R. D., and E. H. Bulte. 2004. Optimal and open access harvesting of multi-use species in a second-best world. Environmental and Resource Economics 28:251–272.

Horan, R. D., and J. S. Shortle. 1999. Optimal management of multiple renewable resource stocks: An application to Minke whales. Environmental and Resource Economics 13:435–458.

IWC [International Whaling Commission]. 2011*a*. Catch limits. IWC, Cambridge, UK.

IWC [International Whaling Commission]. 2011*b*. Report of the finance and administration committee. Pages 103–118 *in* G. P. Donovan, editor. Annual report of the International Whaling Commission 2011, St. Helier, Jersey. IWC, Cambridge, UK.

Knight, A. T., R. M. Cowling, M. Rouget, A. Balmford, A. T. Lombard, and B. M. Campbell. 2008. Knowing but not doing: Selecting priority conservation areas and the research-implementation gap. Conservation Biology 22:610–617.

Laake, J., A. Punt, R. Hobbs, M. Ferguson, D. Rugh, and J. Breiwick. 2009. Re-analysis of gray whale southbound migration surveys 1967–2006. NOAA Technical Memorandum NMFS-AFSC-203. Department of Commerce, Springfield, Virginia, USA.

Loomis, J. B., and D. M. Larson. 1994. Total economic values of increasing gray whale populations: Results from a contingent valuation survey of visitors and households. Marine Resource Economics 9:275–286.

McAllister, M. K., and C. H. Kirchner. 2001. Development of Bayesian stock assessment methods for Namibian orange roughy *Hoplostethus atlanticus*. South African Journal of Marine Science 23:241–264.

McDorman, T. L. 1998. Canada and whaling: an analysis of Article 65 of the Law of the Sea convention. Ocean Development and International Law 29:179–194.

NAMMCO [North Atlantic Marine Mammal Commission]. 1998. NAMMCO Scientific Committee Report. NAMMCO, Tromsø, Norway.

Perry, S. L., D. P. DeMaster, and G. K. Silber. 1999. The great whales: history and status of six species listed as endangered under the U.S. Endangered Species Act of 1973. Marine Fisheries Review 61:1–74.

Porch, C. E., and W. W. Fox. 1990. Simulating the dynamic trends of fisheries regulated by small daily bag limits. Transactions of the American Fisheries Society 119:836–849.

Punt, A. E., and P. R. Wade. 2010. Population status of the eastern North Pacific stock of gray whales in 2009. NOAA Technical Memorandum NMFS-AFSC-207. Department of Commerce, Springfield, Virginia, USA.

Reeves, R. R. 2002. The origins and character of 'aboriginal subsistence' whaling: a global review. Mammal Review 32:71–106.

Richardson, L., and J. Loomis. 2008. The total economic value of threatened, endangered and rare species: An updated meta-analysis. Ecological Economics 68:1535–1548.

Smith, A. D. M., et al. 2008. Experience in implementing harvest strategies in Australia's south-eastern fisheries. Fisheries Research 94:373–379.

Soule, M. E., and G. H. Orians, editors. 2001. Conservation biology: research priorities for the next decade. Island Press, Washington, D.C., USA.

Stewart, J. W. 1988. Free-trade: There'll be no free ride for this deal. Canadian Medical Association Journal 138:403.

Sumaila, U. R., L. Teh, R. Watson, P. Tyedmers, and D. Pauly. 2008. Fuel price increase, subsidies, overcapacity, and resource sustainability. ICES Journal of Marine Science 65:832–840.

Taylor, B. L., P. R. Wade, D. P. DeMaster, and J. Barlow. 2000. Incorporating uncertainty into management models for marine mammals. Conservation Biology 14:1243–1252.

Wallimo, K., and D. K. Lew. 2011. Public willingness to pay for recovering and downlisting threatened and endangered marine species. Conservation Biology 26:830–839.

Weeks, D. 2009. The International Whaling Commission: Is maintaining the status quo good governance? Social Alternatives 28:29–35.