

Linking Dynamic Economic and Ecological General Equilibrium Models*

Although ecosystems provide myriad services to economies, only one service is considered in most renewable-resource models. The bioeconomic model introduced here admits a second service, and more importantly it accounts for how the two services are impacted by interactions within an eight species ecosystem and interactions within a regional economy. Endangered Steller sea lion recovery measures via alternative pollock quotas are shown to cause altered levels of all ecosystem populations, and altered levels of all economic variables. While non-use values associated with the ecosystem (e.g., existence values) are not considered, all species matter for the economy because they are all used indirectly as support for ecosystem services. Regional welfare gains from reduced quotas are in part due to the economy relying less on resource extraction and more on non-extraction.

* JEL Classification: Q2, Q57, and D58

This research was supported by the U.S. Environmental Protection Agency, grants #R 826281-01-0 and RD-83081901-0 and the John S. Bugas Endowment in the Department of Economics and Finance, U. of Wyoming. We are grateful for helpful comments and suggestions from Ed Barbier, Erwin Bulte, Michael Caputo, Robert Deacon, Shelby Gerking, Glen Harrison, John List, Rüdiger Pethig, and participants at an AERE workshop, San Diego, at the North Carolina State Camp Resources IX, and at Univ. of Maryland, University of Rhode Island and Chesapeake Bay Laboratory seminars.

Human economies are not self contained, they are embedded in ecological systems. These ecosystems provide services that "sustain and fulfill human life" (Daily, 1997, p. 3); in fact, all economic activity ultimately depends on ecosystem services (Dasgupta, 1993). The extent to which economies can draw upon ecosystem services has limits, and by some accounts the limits have been reached and depleted ecosystems are having negative impacts on living standards (Arrow, et al., 1995). Because most analyses that measure the welfare implications of economic activity omit ecosystems, assessing the welfare consequences of policies may be biased. The objective of this work is to add a necessary amount of underlying ecology to an economic model so that the welfare consequences of economic activity can be better assessed.

Economists have demonstrated a growing awareness that ecosystems services are important inputs into economic activity. There are two themes that recur in the literature: 1) ecosystems and economies are jointly determined, and 2) both systems are general equilibrium in nature. Regarding 1), joint determination was emphasized early on by Daly (1968), and more recently Crocker and Tschirhart (1992), Nordhaus and Kokkelenberg (1999) and Settle and Shogren (2002) among others have pointed to joint determination as a key ingredient in introducing biological issues into economics. Some authors have admitted considerably more ecological detail to capture the interplay between the systems (e.g., see Brown and Roughgarden, 1995, Carpenter et al., 1999, Brock and Xepapadeas, 2003, or Tilman, et al., 2005).

Regarding 2), general equilibrium (GE) theory has been referred to as the most important development in economics in the twentieth century (Sandler, 2001). We assert

that GE can be applied to ecology because ecosystems are subject to the same reality that economies are: “They are,...., highly nonlinear complex adaptive systems with extensive interconnections among components” (Arrow, et al., 2000). Including ecological variables in economic analyses without recognizing the general equilibrium nature of ecosystems can introduce errors for the same reasons that partial equilibrium compared to GE economic analyses can introduce errors in measuring welfare (Kokoski and Smith, 1987).

In this paper we address both themes by linking a dynamic economic computable general equilibrium (CGE) model with a dynamic general equilibrium ecosystem model (GEEM). Variables as output from the CGE model serve as input parameters into GEEM, and vice versa. To our knowledge this represents the first time dynamic applied general equilibrium models of either kind have been linked.¹

CGE/GEEM is applied to the Alaskan economy to evaluate welfare consequences of endangered Steller sea lion recovery measures via alternative pollock quotas (a primary prey species). The models are linked through two ecosystem services, fishing and recreation, to an eight species marine ecosystem. The linkage through the fisheries sector is novel in CGE. While each general equilibrium calculation corresponds to one year, fishing seasons are considerably shorter than one year. The off season is modeled by allowing fishing inputs to receive endogenous compensating differentials that carry them through the off season, and by including in welfare the value of off-season leisure enjoyed by unemployed fishery labor.

GEEM appeals to the oft-made analogies between economies and ecosystems by applying the concepts of rational behavior, efficiency and equilibrium to ecosystems

(Tschirhart, 2000, 2002).² Like CGE that relies on individual consumer and firm behavior to drive macro outcomes, the individual organism behavior in GEEM drives the ecological macro outcomes (i.e., population changes). The GEEM ecosystem is self contained; however, the CGE economy is not because the ecosystem provides critical inputs to economic production. This is consistent with Dasgupta's point that all human activity ultimately depends on nature.

Endangered Steller sea lion recovery measures are shown to cause altered levels of all ecosystem populations, and altered levels of all economic variables. While non-use values associated with the ecosystem (e.g., existence values) are not considered, all species matter for the economy because they are all used indirectly as support for ecosystem services. For two main reasons, welfare is increased with reductions in fish harvests. First, capital and labor move from the regulated open access fishery sector to other sectors where they both earn more on an annual basis, and second, the tourism industry grows owing to increased numbers of marine mammals. Regional welfare gains from reduced quotas are thus in part due to the economy relying less on resource extraction and more on non-extraction. We show the importance of incorporating more than one linkage between CGE and GEEM by indicating the direction of bias when the second linkage is omitted. Finally, we provide an estimate of the non-consumptive use value of marine mammals, demonstrating the potential of the method for non-market valuation.

CGE and GEEM are described in the next two sections. Economic and ecological data used in the simulations precede the policy analysis, followed by a brief conclusion.

The Economy Model

The linked CGE/GEEM is applied here to the state of Alaska and a marine ecosystem comprising Alaska's Aleutian Islands (AI) and the Eastern Bering Sea (EBS). A simplified view of the linked economy and ecosystem are represented in Figure 1. The economy consists of Alaskan households and producing sectors, linked to one another and the rest of the world through commodity and factor markets. All species in the food web are linked together through predator-prey relationships and several species provide inputs to economic production. The prominent groundfish of the system, pollock, support a very large fishery, and charismatic marine mammals, Steller sea lions (an endangered species), killer whales, and sea otter, provide important non-use inputs to the state's recreation sector.

An appropriate CGE method to link with GEEM is that pioneered by Ballard et al. (1985) and applied in the OECD GREEN model (Burniaux et al, 1991). The recursive dynamics of Ballard's methods are consistent with those in GEEM. The approach may be termed "myopically dynamic," as it consists of a sequence of static optimizations and resulting equilibria connected through the evolution of factor stocks and household savings (just as the GEEM model consists of a sequence of static optimizations and resulting short-run equilibria linked through the evolution of population stocks). Households are intertemporal optimizers whose savings decisions are based on myopic expectations over future prices.

The simplified Alaskan economy is modeled as having three production sectors: the fishery F , recreation and tourism R , and composite goods C .³ The fishery is modeled as a

single, vertically integrated industry consisting of catcher vessels, catcher processors, motherships and inshore processors. Recreation and tourism represents the Census Bureau's classification of Wildlife Related Recreation, and composite goods are a catch all for the residual private industries in Alaska. Profit-maximizing, price-taking firms employ harvests of pollock in the fishery, non-consumptive use of marine mammals (Steller sea lions, killer whales and sea otter) in recreation, and capital and labor in all sectors, to produce their outputs in a continuous, nonreversible, and bounded process. Outputs from the fishery, recreation, and composite goods are sold in regional markets and exported out of the region, while regional production is differentiated from imports for fish and composite goods following Armington (1969). Capital K and labor L are homogeneous, perfectly mobile within the region, and defined in service units per period. Sector i factor employment levels are given by K_i and L_i ($i = F, R, C$). As a high proportion of fishery factors are owned and reside outside the region (specifically in Washington state), factors in the fishery are modeled as being interregionally mobile. This treatment is not extended to other sectors to allow a focus on the regional effects of policy changes.⁴

Households consume fish, recreation, composite goods and save for future consumption. Within each period, household behavior is nested as in Ballard et al (1985).⁵ Households first choose the proportion of income allocated between current and future consumption, where savings fund future consumption by adding to the capital stock in future periods. Current disposable income is then divided between expenditures on recreation and an aggregate commodity. Finally, income allocated for the aggregate commodity is divided between purchases of fish and the composite good.

Equilibrium conditions and factor dynamics also follow Ballard et. al. With interregionally mobile fishery factors, foreign value added expenditures accumulate out of region. Model closure follows Waters, Holland and Weber (1997) and Coupal and Holland (2002) where an exogenous endowment is specified to balance the regional current account and the regional investment savings balance.

When the capital stock grows at the same rate as the effective labor force, the economy is on a balanced growth path; however, balanced growth is not a feature of the linked model, because species populations cannot grow continually. Unlike the growth of the effective labor force and capital stock, ecosystem populations are limited by photosynthesis and converge to steady states, with zero net growth. Thus the sectors reliant on ecosystem inputs will not be expected to grow at the rate of the human factor stocks.

Welfare measures follow Ballard et al. Annual equivalent variations EV_t measure welfare changes for any single period across policy scenarios. Cumulative aggregate welfare measures (including a terminal term) are found using discounted⁶ summations of EV_t given by P_{EV} , which provide a comparative measure as they based upon a common baseline price vector.

The novel linkage between the ecosystem and fishery and the factor market implications are presented in detail.⁷ Incorporating a fishery into a CGE framework raises issues that require two modifications to the standard fishery models. First, where most of the fishery literature employs effort as the single human factor of production,⁸ capital and labor must be included in CGE so that the fishery interacts with other sectors. Second, the non fishery sectors hire capital and labor in service units per time period, in this case one

year, but in the fishery factors are employed considerably less than one year and may earn more per unit than in other sectors. This is due to restricted season lengths and potential unemployment during the off season. The divergence in fishery factor prices are termed compensating differentials in the fashion of the unemployment risk differentials of Averett, Bodenhorn, and Staisiunas (2003) and similar to the factor price differentials of Kwon and Paik (1995).

Expressions (2.1) – (2.4) summarize production in the fishery sector:⁹

$$TAC_t = a + bN_4 \quad (2.1) \qquad H_F = d_F T^{a_F} N_4 \quad (2.2)$$

$$\text{minimize} \quad \hat{w}L_F + \hat{r}K_F \quad \text{subject to} \quad T = d_F^m L_F^{a_F^m} K_F^{(1-a_F^m)} \quad (2.3)$$

Equation (2.1) introduces government into the model in the form of a fishery manager. Homans and Wilen (HW, 1997) developed a model of a regulated open-access fishery to reflect that fishery managers set total allowable catch, TAC , and fishing season length, T . The heavily-regulated Alaskan pollock fishery fits this institutional arrangement. To mesh an HW type model with the CGE framework, the fishery manager chooses period t 's TAC according to (2.1) where N_4 is the population of pollock. No harvests are allowed whenever the actual biomass is less than the minimum level set by the manager. For given TAC and technology, the season length is determined from the aggregate harvest function in (2.2), where a_F and d_F are parameters and H_F is aggregate harvest. The industry is assumed to harvest up to their limit so that $H_F = TAC$.

The season length is the time needed to land the TAC given the fish stock and is increasing in TAC (HW, 1997). Following the fishery manager's choices for TAC and T , the industry is assumed to minimize the cost of harvesting according to (2.3) by employing

capital and labor to work time T . The production function exhibits constant returns to scale, a^m_F , and d^m_F are parameters, and \hat{w} and \hat{r} are the fishery wage and rental rate of capital that may diverge from the market wage and rental rate in other sectors. The associated cost function is linearly homogenous in time, allowing the total costs of harvesting to be written as $C(\hat{w}, \hat{r})T$. This setup with the industry choosing K and L for a given season length incorporates the two modifications defined above.

The divergence of fishery factor prices from market factor prices in the other sectors is endogenous to the system and arises from the restricted season length. Entry is assumed to dissipate all rents in open access models. But these are partial equilibrium models and factors are either not defined over time or if they are defined, they are instantaneous rates or daily rates as in Clark (1976). What these factors are doing off season is not an issue, because there is no off season in the models. In the CGE setting where all other sectors are operating year round, the fishery experiences an off season during which factors are either unemployed or employed elsewhere, often outside the region. In reality, unemployment is common and it may be either voluntary, or involuntary owing to factor immobility between seasons.¹⁰ In either case, rational factors may demand higher than market payments in season in anticipation of being unemployed off season. If they do, seasonal factor payments will not be driven down to market levels in season, leaving positive seasonal factor price differentials.¹¹ One might argue that these above market payments are not really compensating differentials, because they are merely covering the opportunity costs of factors in the off season. This is certainly not true for voluntary unemployment because the factors are enjoying leisure. But even for

involuntarily unemployment, rational factors will anticipate some transition time before reemployment, and will enjoy factor price differentials if the transition time is equal to or less than what they anticipate.

Let W and R be the market determined factor prices for labor and capital in other sectors. Because labor and capital are defined in service units per year, W and R are annual payments. Let $\beta \in (0,1)$ be the percent of the year the fishery is active so that market factor prices in the fishery are βW and βR . If there are intra-seasonal differentials in the fishery, they must be reflected in factor prices that deviate from market prices such that $C(W\beta, R\beta) < C(\hat{w}, \hat{r})$. Assuming any differentials impact labor and capital uniformly and linearly, let δ be a factor price divergence term so that the factor prices in the fishery are:

$$\hat{w} = \beta\delta W \quad \text{and} \quad \hat{r} = \beta\delta R \quad (2.4)$$

where $\delta = 1 \Rightarrow$ no differentials and $\delta > 1 \Rightarrow$ positive differentials.¹²

In developing the simulation model the available data provides estimates for β and δ . But the data is inadequate to determine whether factors were voluntarily or involuntarily unemployed or whether they were reemployed during the off season. Therefore, without strong evidence one way or another and for demonstration purposes the assumption made here is that labor is voluntarily unemployed, i.e., enjoying leisure, and capital is idle or employed outside the Alaskan economy. Labor's leisure time in the off season will be accounted for in welfare measures.

Equilibrium for the industry is given by a pseudo zero-profit condition that allows for intra-season factor price differentials:

$$\pi_F = P_F H_F - C(\beta\delta W, \beta\delta R)T = 0 \quad (2.5)$$

In this representation, total factor payments over the season equal total revenue divided by season length, or average revenue per time. An exogenous increase in TAC or H_F increases season length for a given fish stock and δ falls to maintain equality in (2.5). Intuitively, the longer season implies less off-season time for the factors, and they require a smaller factor price differential in season to get through the off season. To summarize, after the fishery manager sets TAC by (2.1) and T by (2.2), the factor demands and the factor price divergence δ are endogenous and determined by (2.3) and (2.5).

To understand the fisheries contribution to welfare changes, it helps to inspect the consequences on labor payments. Let \bar{L} be the annual labor stock and $L_F(T, \hat{w})$ the labor factor demand function from the fishery cost minimization in (2.3). Labor in the recreation and composite sectors is the residual $(\bar{L} - L_F)$. Annual household labor payments including the value of leisure are:

$$labor\ payments = \hat{w}L_F(T, \hat{w}) + vL_F(T, \hat{w})(1 - \beta) + W[\bar{L} - L_F(T, \hat{w})] \quad (2.6)$$

where v is the value of leisure and $\hat{w} = W\beta(T)\delta(T)$. Of course, W also depends on season length, but for simplicity in this analytical treatment, assume that the change in the market wage for other sectors is small and can be ignored (this is not the case in the simulations). The first term in (2.6) is the payment to fishery labor, the second term is the value of leisure enjoyed by fishery labor, and the third term is the payment to non-fishery labor.

Figure 2 (also employed in the results) demonstrates the relationship between fishery factor payments, market factor payments, and δ . In a steady state, let T^0 be the season length and the average revenue per time from (2.5) is downward sloping as shown

by the solid line. At T^0 factor payments are $C(\hat{w}^0, \hat{r}^0)$ which exceeds market-based factor payments $C(W, R)$ owing to the compensating differentials. For a discrete reduction in TAC , because the fish stock has not changed, the season length falls to T^1 . With the decrease in season length, ΔT , the change in fishery labor is:

$$\frac{\Delta L_F}{\Delta T} = \frac{\Delta L}{\Delta T} + \frac{\Delta L}{\Delta \hat{w}} W \frac{\Delta \delta}{\Delta T} > 0 \quad (2.7)$$

The shorter season means less labor and capital in the fishery, but these remaining factors enjoy a higher differential $(C(\hat{w}^1, \hat{r}^1) - C(W, R))$ per time employed as δ adjusts upward. Thus in (2.7) when T goes down less labor is needed to produce fish (first term), and less labor is demanded because the wage differential increases and labor is more expensive (second term). From (2.6), the change in labor payments is:

$$\frac{\Delta \left(\begin{matrix} labor \\ payments \end{matrix} \right)}{\Delta T} = W \delta(T) \beta(T) \frac{\Delta L_F}{\Delta T} + L_F(\cdot) W \left[\delta \frac{\Delta \delta}{\Delta T} + \beta \frac{\Delta \beta}{\Delta T} \right] - v L_F(\cdot) \frac{\Delta \beta}{\Delta T} + v(1-\beta) \frac{\Delta L_F}{\Delta T} - W \frac{\Delta L_F}{\Delta T} \quad (2.8)$$

with signs given below terms. For a reduction in TAC and a shorter season, the first term is the decrease in fishery payments owing to labor exiting the fishery. The second term is the change in payments to the remaining fishery labor. Its sign is ambiguous because it shows that while payments per labor unit are higher owing to a greater wage differential, they are made over a shorter season. The third term is the increased leisure payment to the remaining fishery labor that works a shorter season, the fourth term is the decreased leisure payment to labor exiting the fishery, and the fifth term is the increased payments in other sectors as exiting fishery labor joins these sectors.

In the empirics welfare changes will depend on the value of leisure. The impact on

welfare of changing the value of leisure can be seen using (2.8). A decrease (increase) in v in (2.8) directly transfers to a change in welfare, because it means that labor values its leisure less (more). To measure the change in welfare, we can look at the change in (2.8) with respect to v . This change is:

$$-L_F(\cdot) \frac{\Delta\beta}{\Delta T} + (1-\beta) \frac{\Delta L_F}{\Delta T} \quad (2.9)$$

+
+
+

The first term represents the additional leisure enjoyed by labor that remains in the fishery after the season is shortened, and the second term is leisure that labor exiting the fishery loses entirely. The results depend on the relative magnitudes of the terms, and are in general ambiguous (although calculated in the numerics).

The Ecology Model

All energy in the ecosystem, shown in Figure 1, originates from the sun and is turned into biomass through plant photosynthesis. Photosynthesis is carried out in the AI by individuals of various species of algae, or kelp, and in the EBS by individuals of various species of phytoplankton. All individual animals in the system depend either directly or indirectly on the kelp and phytoplankton plant species. In the EBS, zooplankton prey on phytoplankton and are prey for pollock. The endangered Steller sea lions prey on pollock, while killer whales prey on the sea lions. In the AI, killer whales also prey on sea otter that in turn prey on sea urchin that in turn prey on kelp.

GEEM combines two disparate ecological modeling approaches: optimum foraging models and dynamic population models. The former approach has been likened to consumer theory (Stephens and Krebs, 1986) and describes how individual predators

search for, attack and handle prey to maximize net energy intake per unit time. Optimum foraging models do not account for multiple species in complex food webs and do not track species population changes. Dynamic population models track population changes by using a difference or differential equation for each species. The familiar logistic-growth model used extensively in the economics literature is the simplest example, although extensions include resource competition models (e.g., Gurney and Nisbet 1998) and the Lotka-Volterra predator/prey model and its variations. However, the parameters in the dynamic equations represent species-level aggregate behavior: optimization by individual plants or animals or by the species is absent. Alternatively, GEEM employs optimization at the individual level as in foraging models, and uses the results of the optimization to develop difference equations that track population changes.

In GEEM, demand and supplies are developed somewhat similarly to CGE. Species are analogous to industries, and individual plants and animals are analogous to firms. Plants and animals are assumed to behave as if they maximize their fitness net energy flows. Where perfectly competitive firms sell outputs and buy inputs taking market-determined prices as signals, plants and animals transfer biomass from prey to predators taking 'energy prices' as signals. (Plants can be thought of as preying on the sun.) An energy price is the energy a predator loses to the atmosphere when searching for and capturing prey. A key difference between economic markets and ecological transfers, however, is that in the latter the prey does not receive this energy price. Therefore, the biomass transfer is not a market because there is no exchange. Nevertheless, predators' demands and preys' supplies are functions of the energy prices.

A brief sketch of GEEM is provided here, but for details see Tschirhart (2002, 2003, and 2004) and Finnoff and Tschirhart (2003). The three basic equations that comprise GEEM are given by (3.1) – (3.3). The first equation is a general expression for the fitness net energy flow through a representative animal from species i .

$$R_i = \sum_{j=1}^{i-1} [e_j - e_{ij}] x_{ij} - \sum_{k=i+1}^m e_i [1 + t_i e_{ki}] y_{ik} - f^i \left(\sum_{j=1}^{i-1} x_{ij} \right) - \beta_i \quad (3.1)$$

$$N_i x_{ij}(\mathbf{e}_i) = N_j y_{ji}(\mathbf{x}_j(\mathbf{e}_j)) \quad (3.2)$$

$$N_i^{t+1} = N_i^t + N_i^t \left[\frac{2N_i^t}{s_i v_i^{ss} N_i^{ss}} \left(1 - \frac{N_i^t}{2N_i^{ss}} \right) (R_i(\cdot) + v_i) - \frac{1}{s_i} \right] \quad (3.3)$$

R_i is in power units (e.g., Watts or kilocalories/time).¹³ The species in (3.1) are arranged so that members of species i prey on organisms in lower numbered species and are preyed on by members of higher numbered species. The first term on the right side is the inflow of energy from members of prey species (including plants) to the representative individual of species i . The choice variables or demands, x_{ij} , are the biomasses (in kilograms/time) transferred from the member of species j to the member of species i , e_j are the energies embodied in a unit of biomass (e.g., in kilocalories/ kilogram) from a member of species j , and e_{ij} are the energies the member of species i must spend to locate, capture and handle units of biomass of species j . These latter energies are the energy prices. There is one price for each biomass transfer between a predator and prey species. As in economic CGE models, the prices play a central role in each individual's maximization problem, because an individual's choice of prey will depend on the relative energy prices it pays. Individuals are assumed to be price takers: they have no control over the energy price paid to capture prey, because each is only one among many individuals in a predator species capturing one

of many individuals in a prey species.

The second term is the outflow of energy to animals of species k that prey on i . The e_i is the embodied energy in a unit of biomass from the representative individual of species i , and y_{ik} is the biomass supplied by i to k . The term in brackets is the energy the individual uses in attempts to avoid being preyed upon. It is assumed to be a linear function of the energy its predators use in capture attempts: the more energy predators expend, the more energy the individual expends escaping. t_i is a tax on the individual because it loses energy above what it loses owing to being captured. The third and fourth terms in (3.1) represent respiration energy lost to the atmosphere which is divided into a variable component, $f^i(\cdot)$, that depends on energy intake and includes feces, reproduction, defending territory, etc., and a fixed component, β_i , that is basal metabolism.

Time in the Alaskan ecosystem is divided into yearly reproductive periods. Each year a general equilibrium is determined wherein the populations of all species are constant, each plant and animal is maximizing its net energy (using the derivatives of (3.1) for first-order conditions), and aggregate demand equals aggregate supply between each predator and prey species. For each price that equates a demand and supply transfer there is an equilibrium equation given by (3.2). Each plant and animal is assumed to be representative individuals from its species; therefore, the demand and supply sums are obtained by multiplying the representative individual's demands and supplies by the species populations given by the N terms.

A representative plant or animal and its species may have positive, zero or negative fitness net energy in equilibrium. Positive (zero, negative) net energy is associated with

greater (constant, lesser) fitness and an increasing (constant, decreasing) population between periods. (The analogy in a competitive economy is the number of firms in an industry changing according to the sign of profits.) Fitness net energies, therefore, are the source of dynamic adjustments. If the period-by-period adjustments drive the net energies to zero, the system is moving to stable populations and a steady state. The predator/prey responses to changing energy prices tend to move the system to steady state.

The adjustment equation for the i^{th} species (a top predator in this case) is given by (3.3) where $R_i(\cdot) = R_i(x_{ij}; N^t)$ is the optimum fitness net energy obtained by substituting the optimum demands and supplies as functions of energy prices into objective function (3.1). N^t is a vector of all species' populations and it appears in $R_i(\cdot)$ to indicate that net energies in time period t depend on all populations in time period t . In the steady state, $R_i(\cdot) = 0$. Also, s_i is the lifespan of the representative individual, v_i is the variable respiration, v_i^{ss} is the steady-state variable respiration, and N_i^{ss} is the species steady-state population. The first and second terms in brackets in (3.9) are the birth and death rates. Expression (3.9) reduces to the steady state if $R_i(\cdot) = 0$ (in which case $v_i = v_i^{ss}$ and $N_i^t = N_i^{ss}$). Because the biomass demands depend on the period t populations of all species, the population adjustment for species i depends on the populations of all other species. In addition, out of steady state $R_i(\cdot)$ and v_i change across periods. These changes distinguish the GEEM approach from most all ecological dynamic population models, because the latter rely on fixed parameters in the adjustment equations that do not respond to changing ecosystem conditions.

Model Specification

The economic specification is based on a benchmark of 1997. The benchmark dataset is shown in Table 1. Data sources are given in the Technical Appendix and include reports from the U.S. Department of Commerce, Bureau of Census, Bureau of Labor Statistics, the Alaskan Bureau of Economic Analysis, and others.

The fishery is parameterized through a mix of estimation and calibration. Parameter estimates for the quota and harvest functions are estimated using time series of data on quotas, biomass, harvests, and inputs. Calibration is employed for remaining parameters.

Unlike prices in the non-fishery sectors (which are set to one) prices in the fishery are set according to (2.4). β is obtained by noting that in 1997 the season was 111 days. If a fully employed year is taken as 250 days, $\beta = 111/250 \approx 0.444$. Labor data is used to obtain δ , and capital is assumed to exhibit the same divergence. The fishery employed 6035 full-time equivalent workers (FTE) in 1997 (Northern Economics Inc. and EDAW, 2001) with total labor bill of \$293,570,000, yielding \$48,645 per FTE. The annual wage per FTE in all Alaskan sectors for 1997 was \$43,368.¹⁴ The differential is therefore $\delta = \$48,645/\$43,368 \approx 1.12$. Finally, the factor payments for labor and capital are $\beta\delta W = \beta\delta R = 0.497$ indicating that fishery factor payments relative to the payments in other sectors are offset downward owing to the shorter season, but offset upward owing to the factor price differential.

Given the benchmark, most other parameters (apart from elasticities of substitution) are found through calibration as in Ballard et al. and De Melo and Tarr (1992) and presented in the Technical Appendix. Estimates of elasticities of substitution are taken

from the literature and displayed (with sources) in Table 2.¹⁵

Parameterization of economic dynamics requires benchmark growth rates of capital services and effective labor. The amount of resident saving and size of regional capital stock in the benchmark year gives the growth rate of regional capital. Under the assumption of balanced growth in the **absence** of natural resource inputs, the regional effective labor force is also assumed to also grow at this rate.

In applying GEEM to the Alaskan ecosystem, ecological studies of the Alaskan and other ecosystems were used. A reasonable time series of pollock biomass estimates exists for the period 1966 through 1997, and the rest of the data are from 1966 or interpolated to that date. Data were obtained for plant and animal populations, benchmark plant biomasses and animal biomass demands, and parameters that include embodied energies, basal metabolisms, and plant and animal weights and lifespans. Sources include numerous National Marine Fisheries Service publications and ecological journal articles. Details on data sources can be found in Finnoff and Tschirhart (2003) and the Technical Appendix.

Using this data, calibration yielded estimates for parameters in the plant and animal respiration and supply functions. Calibration consists of simultaneously solving for each species the net energy expressions set to zero, first-order conditions or the derivatives of the net energy expressions set to zero, and the equilibrium conditions.

Policy Analysis

The NMFS in 2001 issued a Supplemental Environmental Impact Statement (SEIS) containing alternative management strategies that specify various pollock catch limits and no fishing zones to protect both the sea lions and the fishery. Using the linked CGE

models, the effects of the management strategies on economic welfare are examined, and extended to investigate the value of marine mammals to recreation.

Rules for catch limits are given by the regulator's choice of b in the quota function (2.1). Holding N_4^{\min} constant, b is varied by 30% and 170% of its 1997 harvest levels. (Numerous other harvest levels were examined but not reported. The 30% (170%) results are indicative of all runs below (above) the benchmark harvest.) All general equilibrium calculations and population updates were made with the nonlinear programming software package GAMS.

The benchmark sequence is initiated using the 1997 benchmark data, then simulated for 100 years.¹⁶ In the benchmark sequence, all quantities evolve at a constant rate, but the rate may vary over sectors owing to the reliance of the fishery and recreation sectors on biological natural resource inputs. Further, given heterogeneous growth of the natural resources, benchmark relative prices do not remain constant.

Economic Impacts

The direct impacts of the management strategies are on the fishery sector and pollock population, although indirect impacts reverberate throughout both systems. In understanding the economic consequences it is useful to first quickly view the underlying ecological impacts. Populations of pollock, sea lions, sea otter and killer whales for the 30% and 170% management strategies are shown for the first fifty years of the policy in Figure 3 (the second fifty years offer no changes in the trends).¹⁷ Reduced pollock harvests (30%) result in long-term increases in pollock, phytoplankton, sea urchins, sea lions and killer whales, and long-term decreases in zooplankton, kelp, and sea otters. The recreation

sector benefits from more sea lions and killer whales, but is hurt by fewer sea otter.

Welfare changes (from the reference) presented in Table 3 are the present value of the cumulative sum of equivalent variations P_{EV} ¹⁸ over the planning horizon. In the welfare calculations, leisure accruing to regional labor in the fishery during the off-season was valued at full, three quarters and half the wage rate. Across leisure values, decreasing the quota always results in cumulative welfare gains (P_{EV}). The greater the leisure value, the smaller the gains. For brevity, in the following discussion we focus on the 30% reduced quota, noting that the 170% increased quota produces opposite results.

Welfare changes in Table 3 panel (a) are dependent on leisure values, but the value of leisure does not effect the CGE calculations, because leisure is not a choice variable: it is forced on labor by the season-length decision of the fishery manager. To measure the change in welfare, return to the change in (2.8) with respect to v , which is equivalent to moving down Table 3 panel (a) from 100% wage to 75% to 50% wage. Results indicate that the leisure lost exceeds the additional leisure; therefore, the lower the value of leisure the less is the welfare loss as shown in Table 3 panel (a).

Figure 2 again helps shed light on the fishery's contribution to the welfare changes. If T^0 is the season length in the first period of the benchmark, under the 30% reduction the fishery manager lowers harvests and because the fish stock has not changed, the season length falls to T^l . The shorter season means less labor and capital in the fishery, but these remaining factors again enjoy a higher differential as δ adjusts upward. Shorter seasons result in fewer fishery workers who enjoy higher differentials per time worked and greater off-season leisure, while the workers who leave the fishery are employed at market wages

in other sectors for the full year with no leisure.

In the second period following the reduced harvest strategy the fish population is greater and the price of fish is higher. Both changes cause the average revenue curve to shift upward. The fishery manager sets a greater *TAC* by (2.1) because of the greater fish population, and the season length increases to T^2 although it is less than the initial season length. δ adjusts downward and the differential falls to $C(\hat{w}^2, \hat{r}^2) - C(W, R)$. Some workers now return to the fishery from the other sectors, leaving their full-year market wages for higher part-year wages and leisure. In addition, because the fish population is greater, the fishery factors are more productive. Over the remainder of the planning horizon, the season lengths remain between T^0 and T^1 and the factor price differential remains between the initial low value and the second period high value.

With shorter seasons the fishery releases capital and labor, those regionally supplied reemployed in the recreation and composite sectors. But the factor impacts are not uniform. While the benchmark capital labor ratio for fishery firms is 1.245, for the proportion of factors regionally owned the capital labor ratio is 0.563. More regional labor is released than capital, creating a relative surplus of regional labor and a relative shortage of regional capital. Figure 4 displays the gains in composite and recreational good factor employment as percentage changes from the benchmark scenario (for the first fifty years of the policy alternatives, the second fifty years offer no changes in the trends). The release of fishery factors pushes down the market wage, but the opposite holds true with the rental rate of capital owing to the disproportionate releases of the two factors.¹⁹ Lower wages do not reduce total labor factor payments, however, because the drop in the wage is more than

offset by the rise in employment in the non fishery sectors, and the released factors are reemployed for the entire year instead of for the fishing season (fifth term in (2.8)). The coupled effects of more factors employed for the entirety of each year and the factor price changes cause factor payments to rise, in turn causing household incomes to rise.

The lower *TAC* results in a substantial increase in the regional price of fish. Imports of fish fall with the increased composite price, but not by as much as the decline in regional production given the relatively inexpensive import price. Although total fish output falls, the proportion supplied for domestic consumption increases with high regional price.

The repercussions of the policy and factor market reallocations cause regional prices of recreation and the composite good to fall. Composite production increases as it becomes relatively inexpensive. Domestic demand and exports therefore increase, with exports outpacing domestic demand given lower regional prices. Recreation production is aided by smaller fish harvests that yield greater populations of two marine mammals. This productivity improvement lowers unit costs and allows the price of recreation to fall. As relatively less expensive, domestic recreation demand rises, but by less than the rise in exports (see Figure 4). For the flipside of an increased *TAC*, while domestic demand X^D_R falls initially by more than exports X^E_R , eventually they converge and switch in relation to aggregate output X_R . The switching occurs as factor costs (and domestic unit price) rise rapidly overtime as factors are pulled into the fishery, accentuating the decline in regional demand arising from lowered incomes.

Under the policy of reduced harvests, with rising household incomes and the

accompanied declines in output prices, households spend more and save less as the price of saving rises. But, the value of regional investment also falls with the declines in output prices. Given the large reduction in fishery exports there is also an imbalance of imports over exports, requiring an inflow of foreign funds to maintain the current account (foreign funds representing regional borrowing of foreign funds). Declining household savings retards the growth of the capital stock, in turn reducing the growth in future household incomes. The contracted fishery sector and lower rate of capital formation are similar (in reverse) to the effects shown in Kwon and Paik (1995) who show that distortions can lead to rapid capital formation. The consequences of impacts on capital are clearly shown in the welfare estimates. The difference between the welfare gains from a reduced *TAC* and the welfare losses from an increased *TAC* diminishes over time because the capital stock slowly decreases (increases) under reduced (increased) *TAC*.

Ecosystem Impacts

Figure 3 shows that all populations move to new steady states, in as little as 10 years for phytoplankton (not shown) but as many as 30 years for killer whales. Phytoplankton are short-lived (less than one year) and reproduce rapidly, whereas killer whales are long-lived (twenty years) and reproduce slowly.²⁰

To appreciate the general equilibrium nature of the population changes, consider the 170% harvests in some detail. The immediate affect of the higher harvest is to lower the pollock population. In the subsequent period the lower population increases the energy price sea lions pay to capture pollock and the sea lion demand for pollock decreases. Sea lion net energy decreases as a result and their population falls. These changes work their

way up the food web as the killer whale population reacts in the same way to the fall in sea lions as the sea lion population reacted to the fall in pollock. The further up the food web from pollock, the less pronounced the impact. Where pollock populations fall by about 24%, sea lion and killer whale populations fall by about 13% and 9%, respectively. This is partly because sea lion and killer whales consume other prey besides pollock, and this is accounted for in GEEM. Down the food web, zooplankton experience less predation risk owing to fewer pollock, hence they demand more phytoplankton, their net energy increases and their population rises. General equilibrium style feedbacks mitigate to some degree the harvesting-induced fall in the pollock population. That is, smaller sea lion populations and larger zooplankton populations mean respectively less predation on, and more prey for, the pollock.

The impacts of harvesting are also felt on the other side of the food web. As shown in Figure 3, the sea otter population falls initially but then shows a long-term increase. The changes in the otter population are small, but the signs of the change are interesting. When the energy price killer whales pay for sea lions increases, the killer whales demand fewer sea lions and more of the substitute sea otter prey. The change in relative energy prices for prey causes, in ecological terms, *switching* behavior by the killer whales, and the killer whales consume more sea otter and fewer sea lions.²¹ Additionally, more otter consumed leads to higher killer whale net energies and higher populations, while the fewer sea lion consumed leads to lower killer whale net energies and lower populations. The changes in sea lion populations dominate sea otter population changes so that the net change in the killer whale population is negative. Individual killer whale's behavioral response to

changing prey energy prices causes a short-term fall in sea otter, but reduced killer whale populations cause a long-term rise in sea otter.

Marine Mammal Valuation

To demonstrate the usefulness of linking the economy to GEEM, we quantify those portions of welfare changes attributable to marine mammals. The simulations were rerun with marine mammal inputs to recreation across the two *TAC* strategies held at their reference levels (although of course in the ecosystem they are changing and the pollock population is also dependent on those changes; thus by holding the inputs at their reference levels the economic influence of these population changes are simply not recognized in this sector). The portion of welfare change solely attributable to changes in marine mammals can then be inferred as the difference in periodic equivalent variations between the simulations with and without the impacts fishing has on the recreation industry.²² This measure removes all components of the welfare changes attributable to the structure of the fishery (which is identical in both linked and non-linked scenarios).

Cumulative welfare changes and mean annual ecosystem valuations per percentage change in marine mammals for alternative quota rules are displayed in Table 4 (noting the welfare changes for a decrease (increase) in *TAC* are positive (negative) with increases (decreases) in marine mammals). Under decreased (increased) *TAC* the cumulative welfare change is roughly \$16 million (\$26 million) greater (lower) than if the marine mammal changes are omitted. Thus, the welfare gains (losses) of a decreased (increased) *TAC* will be understated (overstated) if the non-consumptive use value of marine mammals were not tied to the fishery as it is in the linked general equilibrium approach.

On a marginal basis, each one percent annual change in marine mammals in relation to the reference is worth roughly \$110,000. While per percentage changes in marine mammals are small, they are found with an elasticity of substitution with factor inputs of one (inherent in the Cobb Douglas recreation production function) which undoubtedly lowers their importance to the sector. Further, in the benchmark they are only a small fraction of Alaska's ecological inputs, and they only provide an estimate of the non-consumptive use values in recreation. Moreover the total values may be understated because non-use values associated with the ecosystem (e.g., existence values) are not considered. Turcin and Giraud (2001) conducted a willingness to pay survey that asked how much households were willing to pay for continuing the Federal Steller Sea Lion Recovery Program. They found Alaskan households willing to pay in total \$25 million, and extrapolating to U.S. households the figure is \$8 billion. Interestingly, households in the area of Alaska that contains critical habitat for the sea lions were willing to pay considerably less and in some cases negative amounts. These results do not indicate the existence value for changes in the sea lion populations, but they do suggest that the value may be substantial.

Conclusion

Although ecosystems provide myriad services to economies, only one service is considered in most renewable-resource models. The bioeconomic model introduced here admits a second service, and more importantly it accounts for how the two services are impacted by interactions within an eight species ecosystem. Steller sea lion recovery measures via alternative pollock quotas are shown to cause altered levels of all ecosystem populations,

economic factor reallocation, changes in all regional prices, incomes, demands, outputs, imports, exports, and differential rates of factor accumulation.

Of the eight species modeled, four are used directly in the economy either as consumption goods (fish) or non consumption goods (marine mammals). While non-use values associated with the ecosystem (e.g., existence values) are not considered, all species matter for the economy because the other four species are used indirectly as support for ecosystem services. A portion of the regional welfare gains from reduced quotas follow from an economy relying less on resource extraction and more on non-extraction. This result is consistent with a report from the Panel on Integrated Environmental and Economic Accounting which states: “economic research indicates that many renewable resources, especially in the public domain, are today more valuable as sources of environmental service flows than as sources of marketed commodities.” (Nordhaus and Kokkelenberg, 1999, p. 177).

The CGE/GEEM linked modeling approach can be applied to numerous other conflicts that arise when economic development and environmental conservation appear at odds. For example, in a terrestrial economy/ecosystem there may be the same consumptive and non-consumptive links used here in addition to pollution that can interfere with species respiration patterns, habitat loss that would reduce space available for plants and, therefore, food for animals, and introduced exotic species that compete with native species.

CGE models are useful in judging alternative economic policies for their effects on resource allocation and on the distribution of net benefits. The objective of linking GEEM to CGE is to account for resource allocation in ecosystems as well so that the scope of

policies that can be judged is broadened. To carry out the objective we have responded to two popular themes in economics and ecology: 1) that the systems are jointly determined, and 2) that both systems are general equilibrium in nature. While the economic and ecological underpinnings of this linked approach can be extended and improved in many ways, CGE/GEEM is a step toward integrating disciplines with common structures and goals.

References

- Abler D.G., A.G. Rodríguez, & J.S. Shortle.1999. "Parameter Uncertainty in CGE Modeling of the Environmental Impacts of Economic Policies," *Environmental and Resource Economics* 14: 75–94.
- Amir, S. 1979. "Economic Interpretations of Equilibrium Concepts in Ecological Systems," *Journal of Social Biological Structures* 2: 293-314.
- Armington, P. 1969. "A Theory of Demand for Products Distinguished by Place of Production," *IMF Staff Papers* 16: 159-178.
- Arrow, K., B. Bolin, R. Costanza, P. Dasgupta, C. Folke, C. S. Holling, B.-O. Jansson, S. Levin, K.-G. Mäler, C. Perrings and D.Pimentel.1995."Economic Growth, Carrying Capacity and the Environment." *Science* 268:520-21.
- Arrow, K., G. Daily, P. Dasgupta, S. Levin, K. Mäler, E. Maskin, D. Starrett, T. Sterner and T. Tietenberg. 2000. "Managing Ecosystem Resources." *Environmental Science & Technology* 34: 1401-1406.
- Averett, S., H. Bodenhorn, and J. Stasiunas. 2003. "Unemployment Risk and Compensating Differentials in Late-Nineteenth Century New Jersey Manufacturing." *NBER Working Paper 9977* National Bureau of Economic Research, Cambridge, MA.
- Ballard, C. L., D. Fullerton, J. B. Shoven, and J. Whalley. 1985. *A General Equilibrium Model for Tax Policy Evaluation*. Chicago: The University of Chicago Press.
- Bohringer, C., and T. F. Rutherford, 1997. "Carbon Taxes and Exemptions in an Open Economy: A General Equilibrium Analysis of the German Tax Initiative." *Journal of Environmental Economics and Management* 32: 189-203.
- Boyce, J.R. 2004. "Instrument Choice in a Fishery," *Journal of Environmental Economics and Management* 47:183-206.
- Bovenberg, A. L. and L. H. Goulder. 1996. "Optimal Environmental Taxation in the Presence of Other Taxes: General Equilibrium Analyses." *American Economic Review* 86: 985-100.
- Brock, W.A. and A. Xepapadeas. 2003. "Valuing Biodiversity From an Economic Perspective: A Unified Economic, Ecological, and Genetic Approach." *American Economic Review* 93: 1597-1614.
- Brown, G. and J. Roughgarden. 1995. "An Ecological Economy: Note on Harvest and Growth." In C. Perrings, K. Mäler, C.Folke, C.Holling and B.Jansson, eds.*Biodiversity Loss*. New York:Cambridge Un.Press, pp. 150-189.
- Burniaux, J.M., J.P. Martin, G. Nicoletti and J.O. Martin. 1991. "A Multi-Region Dynamic General Equilibrium Model for Quantifying the Costs of Curbing Co₂ Emissions: A Technical Manual." *OECD Dept. of Economics and Statistics Working Paper # 104*, OECD.

- Carpenter, S.R., D. Ludwig and W.A. Brock. 1999. "Management of Eutrophication for Lakes Subject to Potentially Irreversible Change." *Ecological Applications* 9: 751-771.
- Chen, P. and P. Edin. 2002. "Efficiency Wages and Industry Wage Differentials: A Comparison Across Methods of Pay." *Review of Economics and Statistics* 84: 617-631.
- Clark, C. W. 1976. *Mathematical Bioeconomics: The Optimal Management of Renewable Resources*, 2nd ed. (1990) New York: Wiley.
- Coupal, R. H., and D. Holland. 2002. "Economic Impact of Electric Power Industry Deregulation on the State of Washington: A General Equilibrium Analysis." *Journal of Agricultural and Resource Economics* 27: 244-60.
- Crocker, T.D. and J. Tschirhart. 1992. "Ecosystems, Externalities and Economies," *Environmental and Resource Economics* 2: 551-567.
- Daily, G.C. 1997. *Nature's Services*, ed. G.C. Daily, Washington, D.C.: Island Press.
- Daly H. 1968. "On Economics as a Life Science," *Journal of Political Economy* 76: 392-406.
- Dasgupta, P. 1993. "Natural Resources in an Age of Substitutability." In A.V. Kneese and J.L. Sweeney eds. *Handbook of Natural Resource and Energy Economics*, Vol. III, NY: Elsevier.
- De Melo, J. and D. Tarr. 1992. *A General Equilibrium Analysis of US Foreign Trade Policy*. Cambridge: MIT Press.
- Eichner, T. and R. Pethig, 2003. "Ecosystem and Economy: An Integrated Dynamic General Equilibrium Approach." Working Paper, University of Siegen.
- Espinosa, J. A. and V. K. Smith. 1995. "Measuring the Environmental Consequences of Trade Policy: A Nonmarket CGE Analysis." *American Journal of Agricultural Economics* 77: 772-777,
- Espinosa, J. A. and V. K. Smith, 2002. "Environmental Levies With Non-Separable Damages: Taxing Air Pollution in the EU Economies." Working paper, North Carolina State University.
- Estes, J.A., M.T.Tinker, T.M.Williams, and D.F. Doak. 1998. "Killer Whale Predation on Sea Otters Linking Oceanic and Nearshore Ecosystems." *Science* 282: 473-6.
- Finnoff, D., and J. Tschirhart, 2003. "Protecting an Endangered Species While Harvesting its Prey in a General Equilibrium Ecosystem Model." *Land Economics* 79: 160-180.
- Fullerton, D. and G.E. Metcalf. 200. "Environmental Controls, Scarcity Rents, and Pre-Existing Distortions." *Journal of Public Economics* 80: 249-267.

- Goulder, L.H., I.W.H. Parry, R.C. Williams and D. Butraw. 1999. "The Cost-Effectiveness of Alternative Instruments for Environmental Protection in a Second-Best Setting." *Journal of Public Economics* 72: 329-360.
- Goulder L.H. and S.H. Schneider. 1999. "Induced Technological Change and the Attractiveness of CO₂ Abatement Policies." *Resource and Energy Economics* 21: 211-253.
- Gurney, W.S.C. and R.M. Nisbet. 1998. *Ecological Dynamics*. New York: Oxford U. Press.
- Hannon, B. 1973. "The Structure of Ecosystems." *Journal of Theoretical Biology* 41: 535-546.
- Herendeen, R. 1991. "Do Economic-Like Principles Predict Ecosystem Behavior Under Changing Resource Constraints?" In T. Burns and M. Higashi, eds. *Theoretical Studies Ecosystems: The Network Perspective*. New York: Cambridge University Press.
- Homans, F.R. and J.E. Wilen. 1997. "A Model of Regulated Open Access Resource Use." *Journal of Environmental Economics and Management* 32: 1-21.
- Jin D., P. Hoagland, T.M. Dalton. 2003. "Linking Economic and Ecological Models for a Marine Ecosystem," *Ecological Economics* 46: 367-385.
- Jorgenson, D.W. and P.J. Wilcoxon. 1990. "Environmental Regulation and U.S. Economic Growth." *RAND Journal of Economics* 21: 314-340.
- Jorgenson, D.W. and P.J. Wilcoxon. 1993. "Reducing U.S. Carbon Dioxide Emissions: An Assessment of Different Instruments." *Journal of Policy Modeling* 15: 491-520.
- Kokoski, M.F. and V.K. Smith. 1987. "A General Equilibrium Analysis of Partial-Equilibrium Welfare Measures: The Case of Climate Change." *American Economic Review* 77: 331-341.
- Kwon, J.K. and H. Paik, 1995. "Factor Price Distortions, Resource Allocation, and Growth: A Computable General Equilibrium Analysis." *Review of Economics and Statistics* 77: 664-676.
- Manne A. and R. Richels. 1992. *Buying Greenhouse Insurance: The Economic Costs of CO₂ Emission Limits*. Cambridge, Ma.: MIT Press.
- Nordhaus, W.D. and Z. Yang. 1996. "A Regional Dynamic General Equilibrium Model of Alternative Climate Change Strategies." *American Economic Review* 86: 741-765.
- Nordhaus, W.D. and E.C. Kokkelenberg, eds. 1999. *Nature's Numbers*, Washington, D.C.: National Academy Press.
- Northern Economics Inc. and EDAW. 2001. "Section 2: fishing and processing sector profiles," in *Sector and Regional Profiles of the North Pacific Groundfish Fisheries*, <http://www.fakr.noaa.gov/npfmc/NorthernEconomics.htm>.

- Perroni, C. and R.M. Wigle. 1994. "International Trade and Environmental Quality: How Important are the Linkages?" *Canadian Journal of Economics* 27: 551-567.
- Sandler, T. 2001. *Economic Concepts in the New Century*. New York: Cambridge Univ. Press.
- SEIS (Supplemental Environmental Impact Statement). 2001. *Steller Sea Lion Protection Measures in the Federal Groundfish Fisheries off Alaska*. NMFS, Alaskan Region.
- Seung, C. K., T.R. Harris, J.E. Englin, and N.R. Netsiul. 2000. "Impacts of Water Reallocation: A Combined Computable General Equilibrium and Recreation Demand Model Approach." *Annals of Regional Science* 34: 473-487.
- Settle, C. and J.F. Shogren. 2002. "Modeling Native-Exotic Species Within Yellowstone Lake." *American Journal of Agricultural Economics* 84: 1323-1328.
- Shoven, J.B., and J. Whalley. 1992. *Applying General Equilibrium*. Cambridge MA: Cambridge University Press.
- Stephens, D.W. and J.R. Krebs. 1986. *Foraging Theory*. Princeton: Princeton University Press.
- Tilman, D., S. Polasky and C. Lehman. 2005. "Diversity, Productivity and Temporal Stability in the Economies of Humans and Nature." *Journal of Environmental Economics and Management*. Forthcoming.
- Tschirhart, J. 2000. "General Equilibrium of an Ecosystem." *Journal of Theoretical Biology* 203: 13-32.
- Tschirhart, J. 2002. "Resource Competition Among Plants: From Optimizing Individuals to Community Structure." *Ecological Modelling* 148: 191-212.
- Tschirhart, J. 2003. "Ecological Transfers Parallel Economic Markets in a General Equilibrium Ecosystem Model." *Journal of Bioeconomics* 5: 193-214.
- Tschirhart, J. 2004. "A New Adaptive System Approach to Predator-Prey Modeling." *Ecological Modelling* 176: 255-276.
- Turcin, B. and K. Giraud. 2001. "Contingent Valuation Willingness to Pay With Respect to Geographically Nested Sample: Case Study of Alaskan Steller Sea Lion." *Western Reg. Project Tech. Meetings Proc.* (W-133): 1-10.
- Waters, E.C., D.W. Holland and B.A. Weber. 1997. "Economic Impacts of a Property Tax Limitation: A Computable General Equilibrium Analysis of Oregon's Measure 5." *Land Economics* 73:72-89.
- Watts, G., W.R. Noonan, H.R. Maddux and D.S. Brookshire. 2001. "The Endangered Species Act and Critical Habitat Designation," in J.F. Shogren & J. Tschirhart, eds. *Protecting Endangered Species in the United States: Biological Needs, Political Realities, and Economic Choices*. New York, NY Cambridge University Press.
- Weninger, Q. and K.E. McConnell. 2000. "Buyback Programs in Commercial Fisheries: Efficiency Versus Transfers." *Canadian Journal of Economics* 33: 394-412.

Table 1 Value of Benchmark Variables, in Million \$

Variable	Value	Definition	Variable	Value	Definition
K_F	365.608	Fishery Capital	ω_K^{AK}	11263.68	Regional Capital Endowment
L_F	293.567	Fishery Labor	ω_K^{σ}	307.325	Foreign Capital
Q_F^M	0.244	Fish Imports	ω_L^{AK}	9625.415	Regional Labor Endowment
Q_F	659.420	Aggregate Fish Output	ω_L^{σ}	190.064	Foreign Labor
K_R	894.368	Recreation Capital	C_{AF}^T	24.443	Household Fish Demand
L_R	766.398	Recreation Labor	C_R^T	737.244	Household Recreation Demand
Q_R	1660.766	Aggregate Recreation Output	C_{AC}^T	19925.64	Household Composite Goods Demand
K_C	10311.029	Composite Goods Capital	S	201.764	Household Savings
L_C	8755.514	Composite Goods Labor	I_F	7.638	Fishery Investment
Q_C^M	10938.005	Composite Goods Imports	I_R	15.554	Recreation Investment
Q_C	30004.549	Aggregate Composite Goods Output	I_C	178.572	Composite Goods Investment
X_F^D	32.080	Regional Fishery Demand	X_F^E	627.340	Fish Exports
X_R^D	752.798	Regional Recreation Demand	X_R^E	907.968	Recreation Exports
X_C^D	20104.217	Regional Composite Goods Demand	X_C^E	9900.331	Composite Goods Exports

Table 2 Elasticities of Substitution

Elasticity Definitions			Source
σ_C	Composite goods: labor and capital	0.8672	Average of all reported industries other than agriculture, forestry and fishery industries as reported in Ballard et al.
σ_1^R	Households: current consumption goods	0.867	Averages of values in Ballard et al.
σ_2^R	Households: current and future consumption	1.60042	Averages of values in Ballard et al.
$\sigma_{F,I}^H$	Income elasticity of the demand for food	0.3	de Melo and Tarr (1992)
MU_I^T	Marginal utility of income with respect to income	-1.09	de Melo and Tarr (1992)
σ_C^C	Composite demand: regional goods and imports	2.12	Average of all industries other than agriculture in de Melo and Tarr (1992)
σ_F^C	Fish demand: regional goods and imports	1.42	Value for agriculture in de Melo and Tarr (1992)
σ_C^T	Composite supply: regional goods and exports	2.79	Average of all industries other than agriculture in de Melo and Tarr (1992)
σ_F^T	Fish supply: regional goods and imports	3.9	Value for agriculture in de Melo and Tarr (1992)
σ_R^T	Recreation supply: regional goods and imports	2.79	Value for agriculture in de Melo and Tarr (1992)
σ_F^K	Fishery capital demand: regional factors and imports	1.7	Value for agriculture in de Melo and Tarr (1992)
σ_F^L	Fishery labor demand: regional factors and imports	1.7	Value for agriculture in de Melo and Tarr (1992)

Table 3 **Discounted Cumulative Welfare Impacts**

Welfare Measure	Value of Leisure	Quota Rule	100 Year Horizon (Million 1997 \$)
P_{EV}	100% Wage	30%	\$1,210.54
		170%	-\$8,665.10
	75% Wage	30%	\$1,674.54
		170%	-\$8,129.02
	50% Wage	30%	\$2,138.54
		170%	-\$7,592.94

Table 4 **Marine Mammal Valuations**

Welfare Measure	Value of Leisure	Quota Rule	Discounted Cumulative Welfare Change Linked Model – Non-Linked (Million 1997 \$)	Mean Annual Welfare Change Per % Change in Marine Mammal Inputs: Linked Model – Non-Linked (1997 \$)
EV_t	100%	30%	\$16.52	\$109,626
		170%	-\$26.90	-\$114,458
	75%	30%	\$16.53	\$109,677
		170%	-\$26.91	-\$114,493
	50%	30%	\$16.54	\$109,728
		170%	-\$26.92	-\$114,529

Figure 1 Economy Ecosystem Interaction

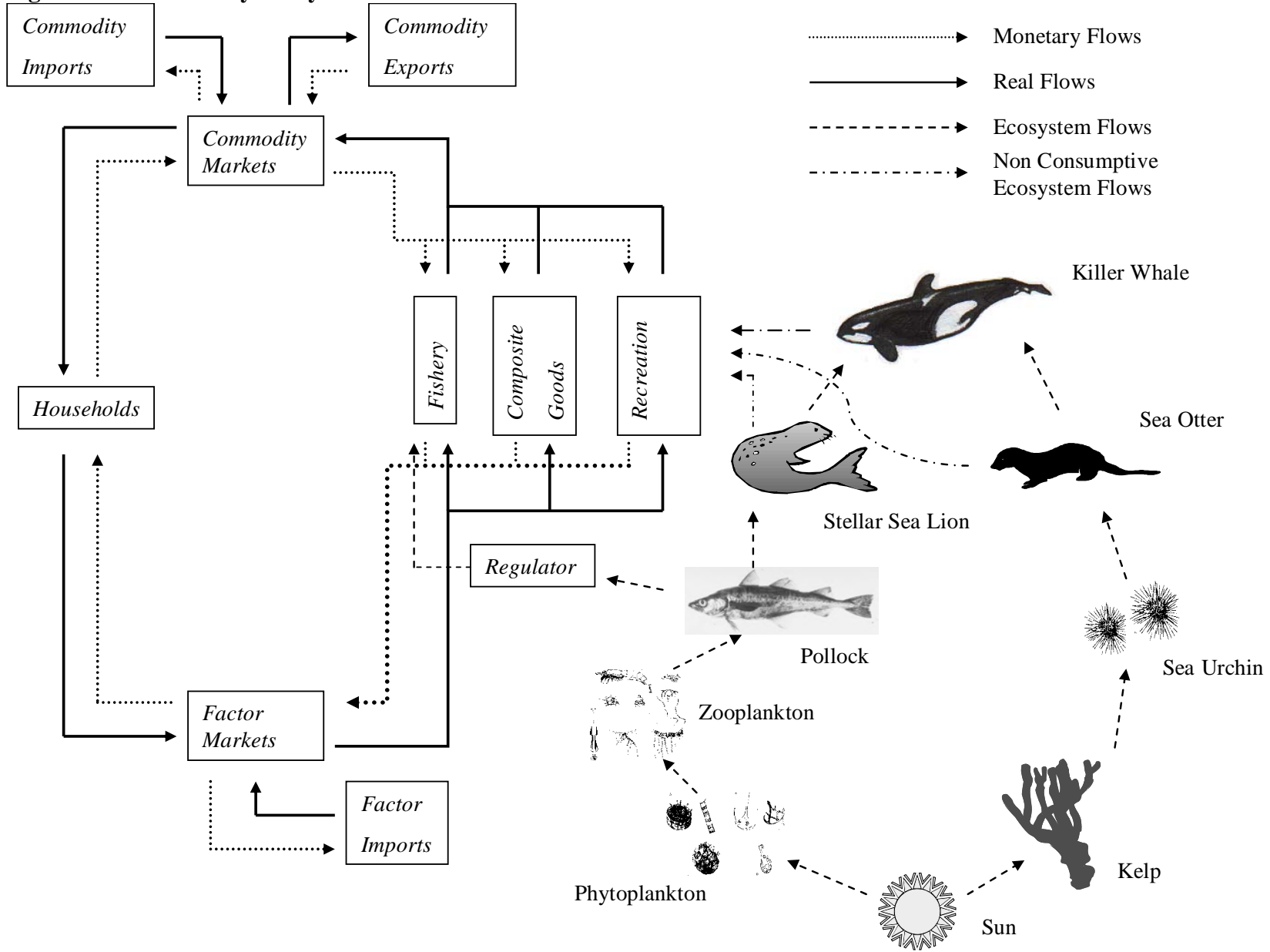


Figure 2 Fishery Intra-season Factor price differentials

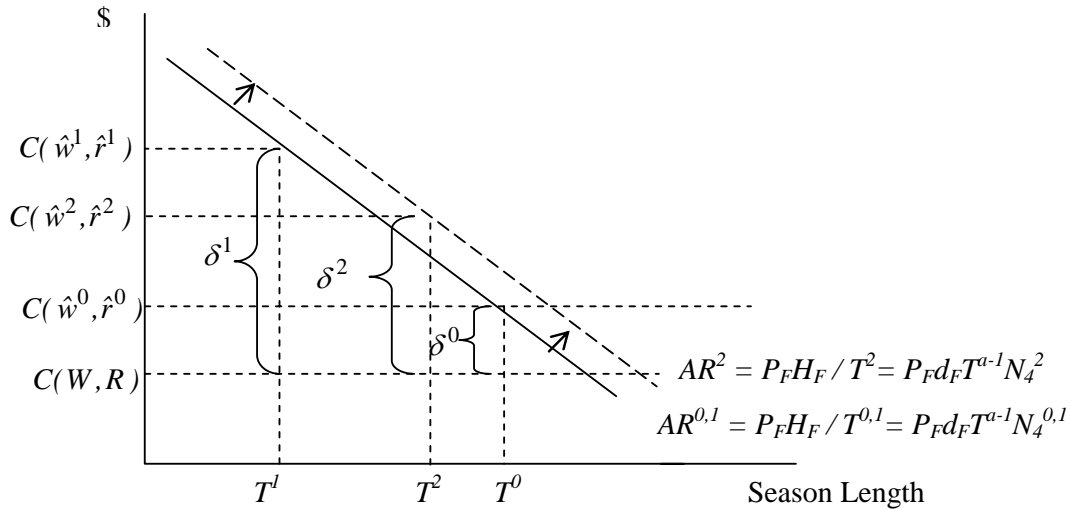


Figure 3 Ecosystem Populations

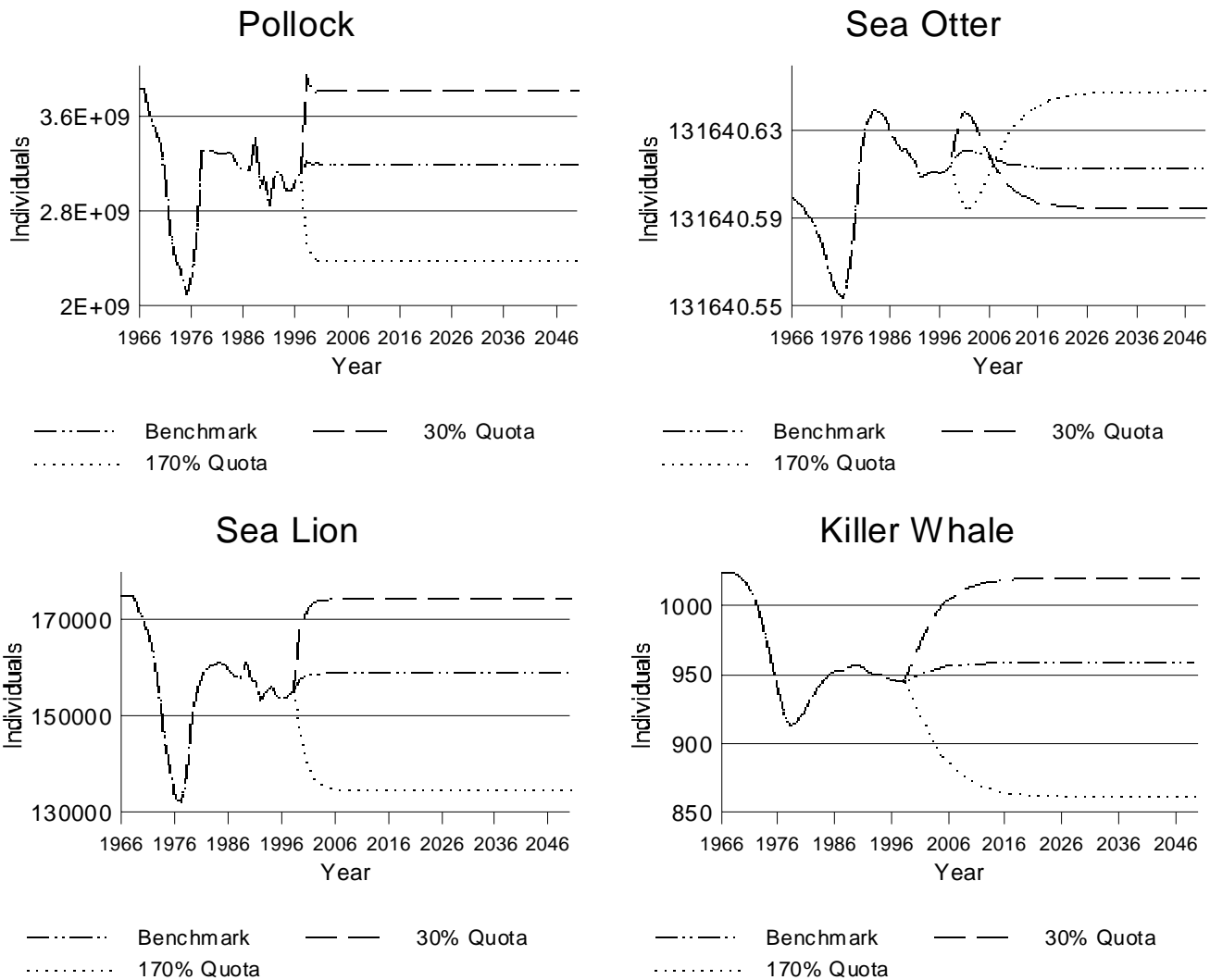
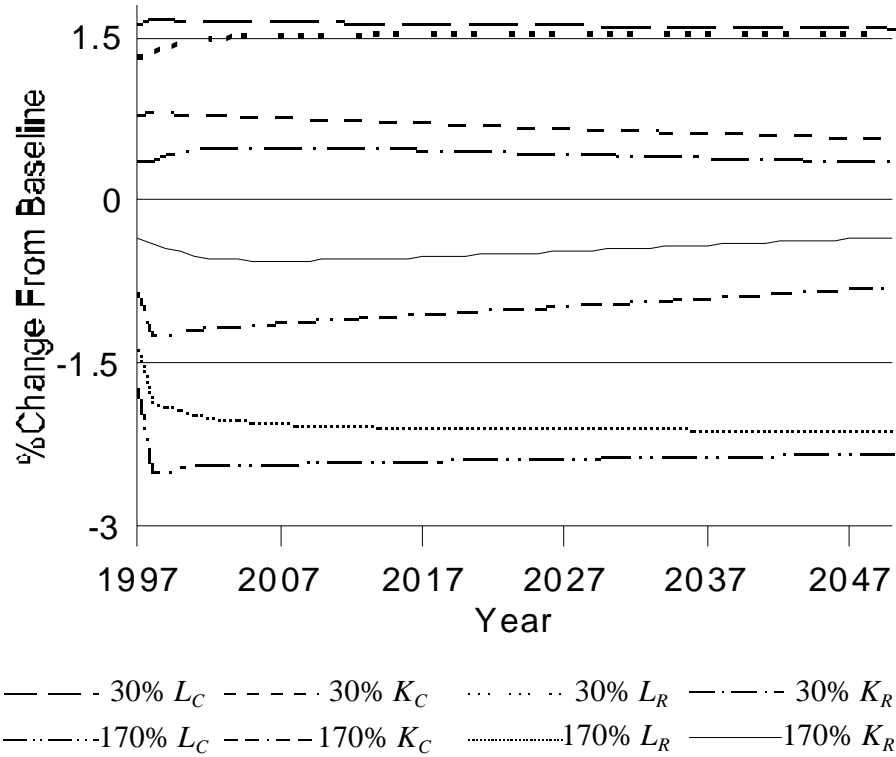
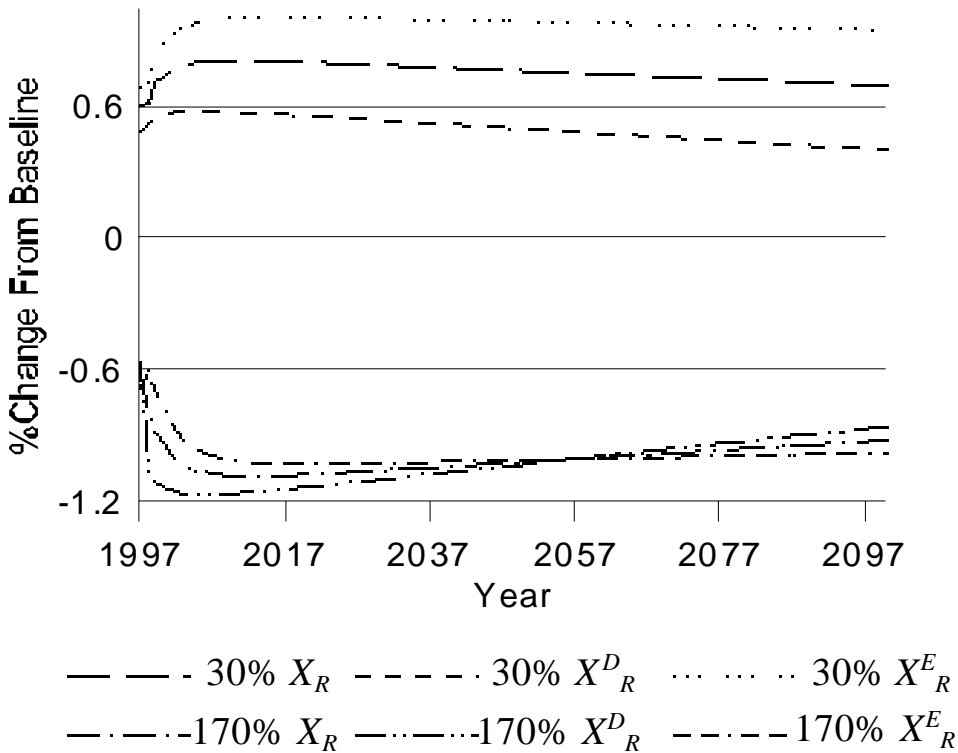


Figure 4 Economic Variables

Composite and Recreation Factor Employment



Recreation Demand



¹ A large literature introduces environmental issues into the CGE framework. Studies assessing the costs of environmental protection (Jorgenson and Wilcoxon 1990, 1993) have been augmented by those that include contributions of environmental resources to consumer welfare in a separable (Perroni and Wigle, 1994) and non-separable (Espinosa and Smith, 1995, 2002) fashion. A body of literature has also investigated the consequences of optimal environmental taxation in the presence of preexisting distortions (Bovenberg and Goulder, 1996, Goulder, Parry, Williams and Butraw, 1999, and Fullerton and Metcalf, 2001). There have been many notable contributions concerning global warming and the expected impacts of climate change. Early literature focused on the costs of proposed CO₂ abatement strategies (including Manne and Richels 1992, Nordhaus and Yang 1996, and Bohringer and Rutherford 1997) while recent examples expanding this to look at the benefits and costs of mitigating climate change (Goulder and Schneider, 1999). In this work environmental quality is viewed as an aggregate stock degraded by economic pollution. The natural system underlying environmental quality is neglected, ignoring the mediating behavior of the economic and ecological systems. Amir (1979) and Crocker and Tschirhart (1992) present linked economic/ecological analytical models while Eichner and Pethig (2003) develop the integration further. Of the few analyses that attempt empirical economic/ecological linkages, Watts et al. (2001) use a CGE model to investigate the economic impacts of preserving several endangered fish species, and Seung et al. (2000) use a dynamic CGE model in conjunction with a recreation demand model to assess the impacts of water reallocation policies. Neither of these papers has a separate ecosystem model. Jin, Hoagland, and Dalton (2003) merge a static economic input-output model of New England with a static ecological input-output model of a marine foodweb, but this approach omits dynamic and behavioral considerations. The work presented herein is differentiated from all of the above because the ecosystem is represented by a stand-alone, behaviorally based, dynamic, general equilibrium model. Just as the economic system consists of agents exhibiting behavior, the ecosystem also consists of agents exhibiting behavior, although the agents are plants and animals.

² However, the similarities only go so far and there are features in GEEM that are not found in economic models (Tschirhart, 2003). For example, predators and prey do not engage in voluntary exchange, but in biomass transfers.

³ The sector and regional profiles follow the Steller Sea Lion Supplemental Environmental Impact Statement (SEIS, U.S. Dept. of Com., 1991).

⁴ The fishery is unique as a significant portion of its factor employment is of ex-regional factors and they are based elsewhere than Alaska. In this sector we therefore differentiate between regional and foreign factors in the same fashion as imports, but do not extend the treatment to include the other sectors. This restriction allows us to focus on the regional consequences of alternative policies.

⁵ CES utility functions are employed in the top two nests, a Stone-Geary form in the bottom nest.

⁶ By consumers' rate of time preference and by the human population growth rate.

⁷ The recreation sector is also reliant on marine mammals. The industry combines labor and capital with non-consumptive use of populations of marine mammals to deliver a "recreational experience." The recreation industry maximizes profits subject to a Cobb-Douglas production function (consistent with the fishery specification):

$$\max_{L_R, K_R} \pi_h = P_R^X X_R - WL_R - RK_R \quad s.t. \quad X_R = d^R L_R^{a^R} K_R^{b^R} N_{AT}^{c^R} \quad \text{where } d^R, b^R, c^R, \text{ and } d^R \text{ are parameters, } R \text{ subscripts for the}$$

recreation sector, and N_{AT} the contribution of Alaska's natural resources to the sector. This measure includes BSAI aggregate marine mammal populations taken as a linear combination of the three marine mammals. N_{AT} enters recreation production as a shift parameter, exogenous to the recreation firms but endogenous to the joint system.

⁸ Exceptions include Boyce (2004) and Weninger and McConnell (2000), who present an analysis that deliberately separates fixed and variable inputs in a partial equilibrium model of a fishery regulated through *TAC*'s and a limited entry program.

⁹ We are indebted to Robert Deacon for his invaluable input in the development of this section.

¹⁰ The Alaskan Department of Labor and Workforce Development provides information about fishing jobs in Alaska on various websites (e.g., http://www.labor.state.ak.us/esd_alaska_jobs/careerstreams.htm). The job descriptions suggest that workers can save money, and pay can be substantial if the fishing is good. College students are encouraged to apply and then return to college in the off season. Boyce (2004) examines rents in fisheries and assumes that fishing inputs cannot be redeployed during the off season.

¹¹ Chen and Edin (2002) investigate inter-industry wage differentials for time wages in comparison to piece rates and make the argument that differentials are more likely to exist for time wages, consistent with the definition here.

¹² Factor price distortions commonly enter the CGE literature in the form of pre-existing distortions and taxes (Shoven and Whalley, 1992, Ballard et al., 1985, and Bovenberg and Goulder 1996). The divergences here are not distortions in the usual sense and correspond more to the factor price differentials of Kwon and Paik (1995): β is merely an accounting adjustment to correct for a shorter work year, and a $\delta > 1$ may be welfare enhancing since some positive differentials are desirable.

¹³ According to Herendeen (1991) energy is the most frequently chosen maximand in ecological maximization models, and energy per time maximization as adopted here originates with Hannon (1973), and expanded in Crocker and Tschirhart (1992) and to the individual level in Tschirhart (2000). Energy per time is also the individual's objective in the extensive optimum foraging literature (e.g., Stephens and Krebs 1986).

¹⁴ Institute of Social and Economic Research, University of Alaska Anchorage, 2003.

http://citizensguide.uaa.alaska.edu/4.COMPARISON_TO_OTHER_PLACES/4.5.PublicEmployeesandWages.htm

¹⁵ A limited sensitivity test using the low and high elasticity estimates of De Melo and Tarr were performed with only minor changes in results. The more rigorous Monte Carlo approach following Abler, Rodrigues and Shortle (1999) is left for future research.

¹⁶ Sequence length and a discount rate of 4% were chosen as representative for Federal projects.

¹⁷ Predicted populations (given actual harvests) prior to the 1997 calibration year and projections beyond 1997 are displayed.

¹⁸ In the absence of balanced growth in the reference sequence, we deflate all prices to 1997 levels using a modified Laspeyres formula $CPI_t = \left[\frac{\sum P_t Q_0}{\sum P_0 Q_0} \right] * 100$ where CPI_t is the price index in period t , P_t current price of each commodity, Q_0 is the market quantity of each commodity in the baseline period (1997) and P_0 is the price of each commodity in the baseline period. This follows the same general fashion of the BLS Consumer and Producer Price indices.

¹⁹ Both wages and the rental rate of capital maintain their relative positions below and above the reference under the 30% rule, but the percentage change from the reference for the rental rate of capital gradually rises over time as capital becomes increasingly scarce with reduced growth.

²⁰ Average lifespan enters into the population update equation, (3.3), similar to the way the less tangible species growth rates enters into the often-used but simplistic logistic update equation; thus, the lifespans are important in determining whether population oscillations occur and how quickly populations will converge to steady state.

²¹ Killer whale switching behavior has been documented by Estes et al. (1998).

²² Values attributable to ecosystem inputs were found as $EV_t^L - EV_t^{NL}$ where L refers to ecosystem linkages being accounted for, and NL not accounted for (not linked).