ECONOMIC IMPACTS OF CHANGES IN AN ALASKA CRAB FISHERY FROM OCEAN ACIDIFICATION

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A dynamic computable general equilibrium (CGE) model is linked to a bioeconomic model for the Bristol Bay red king crab (BBRKC) fishery to analyze regional economic impacts of ocean acidification (OA)-induced changes in fishery yields. Yield projections based on two alternative forms (linear versus nonlinear) of OA effects on the survival of juvenile BBRKC are compared to a baseline without OA effects. Results demonstrate considerable uncertainty in yields, and show that economic impacts are sensitive to the form of OA effects, and to changes in the world price of BBRKC (Q22, Q54, Q57, R13).

Keywords: Ocean acidification; Alaska crab fisheries; economic impacts; bioeconomic model; computable general equilibrium.

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1. Introduction

In this study, we calculate the economic impacts for the Alaska region of reductions in catch of a crab species [Bristol Bay red king crab (BBRKC); *Paralithodes camtschaticus*] due to ocean acidification (OA), using a regional dynamic computable general equilibrium (CGE) model linked to a bioeconomic model of the BBRKC fishery. Outcomes for our bioeconomic model are based on the concept of open-loop Nash equilibrium from dynamic game theory applied to the effects of OA on population dynamics estimated in Punt *et al.* (2014). This dynamic game represents important elements of the BBRKC industry including a quota market and the formation of a vessel-cooperative. Both elements have important welfare implications through quota share lease rates (QSLRs) that divide fishery income between vessels and quota owners. Our bioeconomic model and CGE model are linked via benchmark equilibrium in quota markets. The regional economic impacts calculated in this study include the accumulated impacts on output (i.e., production of goods and services in Alaska industries including BBRKC industry), employment, and welfare changes and temporal effects on resource rent and QSLRs for the BBRKC fishery. Fishery managers are interested in identifying the magnitude of economic impacts of fishery management actions [such as changes in total allowable catch (TAC)] and other exogenous perturbations (such as OA in this study).¹ Results from this study indicate that the regional economic impacts are sensitive to the functional form used to fit data from OA exposure experiments in BBRKC yield projections (i.e., linear versus nonlinear regressions), and to changes in the world price of king crab.

Fossil fuel emissions and deforestation have increased atmospheric carbon dioxide (CO₂) concentrations, which has led to corresponding increases in oceanic CO₂ concentrations, and hence, changes in carbonate chemistry of the oceans and decreases in ocean pH. Due to the increase in oceanic CO₂ concentrations, the average surface ocean pH has increased acidity by 30% relative to pre-industrial levels (Malakoff, 2012). As CO₂ levels continue to rise over the coming decades, the pH in the ocean will fall even further and the saturation state of calcium carbonate (CaCO₃) required for crab shell formation will decrease. A standard scenario predicts that average pH in surface waters will fall from the current level of 8.1 to 7.8 before 2100 (e.g., Malakoff, 2012).

This acidification trend could have substantial physiological effects on marine organisms, affecting growth, survival, reproduction, and behavior (Fabry *et al.*, 2008). Calcifying organisms may be particularly affected because the reduction in pH and/or decrease in saturation state of CaCO₃ makes it more difficult to excrete and sustain a calcified shell or exoskeleton. In addition, commercially important crab stocks in the waters off Alaska are sensitive to effects of OA because the saturation depth of CaCO₃ in the North Pacific Ocean is an order of magnitude shallower than in the North Atlantic

¹Magnuson–Stevens Fishery Conservation and Management Act National Standard 8 (16 U.S.C. §1852) requires that fishery conservation and management actions formally consider the importance of fishery resources to fishing communities (www.nmfs.noaa.gov/sfa/magact/MSA_Amended_2007%20.pdf). To satisfy National Standard 8, fishery managers must consider economic impacts of management actions on various interest groups.

(Doney *et al.*, 2009). As a result, the harvests of, and therefore the revenue from, crab fisheries in the waters off Alaska could decrease in the future because of OA. A decrease in revenue implies a reduction in the number of jobs in the fish harvesting and processing sectors, and decreases in income of the stakeholders engaged in the fisheries, which will generate a wide range of economic impacts on fishing-dependent communities.

The biological and ecosystem effects of OA can generate different types of socio-economic responses. First, OA can change harvests of commercially valuable fish species (as in the present study), resulting in change in employment and income of the stakeholders (economic impacts). Second, it can affect marine tourism and other ocean-related recreation activities including recreational fisheries. These types of activities generate both economic benefits (measured in consumer surplus) and economic impacts associated with the expenditures made for the activities. Third, the above two types of effects may generate social effects on the communities dependent on marine resource, including, for example, their demographics and livelihoods. The present study focuses on the first type effect, that is, the economic impacts of OA.

Although impacts are potentially catastrophic across a number of sectors, very few studies have analyzed the economic effects of OA because the number of species or ecosystems for which physical effects have been estimated is limited (Moore, 2015). Except for Cooley *et al.* (2015), existing studies of economic impacts of OA rely on simple biological models based on changes in shell growth rates or changes in weight as a proxy for market impacts. These simple models do not differentiate effects of OA on important subpopulations such as juvenile crab. Cooley and Doney (2009) used a simple multiplication method that applied projected harvest losses to baseline production value to provide a rough estimate of the economic losses for the US from declining mollusk populations arising from OA. Narita *et al.* (2012) used a simple partial-equilibrium model to analyze welfare effects of OA on global mollusk markets which has an advantage over the simple multiplication method of Cooley and Doney (2009) but does not account for general equilibrium effects. Cooley *et al.* (2015) linked a population dynamics model for sea scallops, which has a similar structure to population dynamics in Punt *et al.* (2014), to a bioeconomic model that uses static conditions for profit-maximization but does not compute market equilibrium, which is also like the bioeconomic model in Punt *et al.* (2014). Moore (2015) was the first rigorous utility-theoretic welfare analysis of OA based on an estimated system of inverse demand equations for the US mollusk market, but follows Cooley and Doney (2009) and Narita *et al.* (2012) by assuming producers will not respond to changing conditions, and reductions in harvest rates caused by OA are equal to projected changes in population growth rates. Under similar assumptions, Brander *et al.* (2012) used a global integrated assessment model to estimate the change in economic value from coral reef area loss around the world caused by OA. These previous studies did not calculate any economic impacts (i.e., the impacts measuring change in employment and income for a sub-national region). The present study is the first to calculate the economic impacts for a region from OA-induced changes in harvest of fish species (BBRKC) using a

regional dynamic CGE model coupled with a fully dynamic bioeconomic model of the BBRKC fishery that differentiates effects of OA on different subpopulations.

Effects of OA in the regional CGE model are based on impacts on yields over time, which are affected by a complex set of biological and economic relationships. A separate bioeconomic model was necessary to analyze these complex relationships. In contrast to previous studies on economic effects of OA, the bioeconomic model in this paper is based on dynamic economic theory. The bioeconomic model in this paper employs three overarching principles for the institutional structure of the BBRKC fishery: Management based on maximum sustainable yield (MSY),² the formation of a vessel-cooperative, and a quota market that operates under the Bering Sea Aleutian Islands Crab Rationalization Program that allocates catch of BBRKC. This program has other important features, such as processor quota shares, and the fishery is subject to many other regulations, but this paper does not address these.

The bioeconomic model in this paper is extension of the bioeconomic model and dynamic maximum economic yield (MEY) theory in [Rosenman \(1986\)](#). Compared to competition, sole-ownership defines dynamic MEY by internalizing a dynamic stock externality ([Smith, 1969](#)) which we assume in this paper can be accomplished by a vessel-cooperative. The dynamic MEY theory in this paper is related to open-loop Nash equilibrium for a renewable resource ([Hansen *et al.*, 1985](#)) using the endogenous mergers solution proposed in [Rodrigues \(2001\)](#) applied to the formation of a vessel-cooperative. In this paper, we simplify and impose minimal effects of fisheries management except that MSY is a necessary condition for quota market equilibrium that is satisfied over time, and that quota market price is set at the start of a dynamic game as a constant fraction of the ex-vessel price which is given. We solve this game using the concept of open-loop Nash equilibrium in which players (i.e., vessel operators) maximize expected net present value of fishing operations that are subject to QSLRs and decreasing returns to scale.

[Gordon \(1954\)](#) assumed decreasing returns are inoperative in the fishing industry and that biological compensation was always responsible for curtailing exploitation. However, [Scott \(1955\)](#) criticized this fundamental assumption and suggested an alternative hypothesis that the limits to exploitation depend on economic costs to the fleet and decreasing returns to scale. We allow for Scott's critique of Gordon's version of sole-ownership by including nonlinear costs of catching crab. These costs represent decreasing returns to scale for fixed capacity fishing vessels and dynamic adjustment costs for year to year changes in catch.³

The bioeconomic model presented in this paper is based on Scott's hypothesis about economic costs but there is a complication because outcomes can be unsustainable if

²Current guidelines from the National Marine Fisheries Service for National Standard 1 state "The Magnuson-Stevens Act establishes MSY as the basis for fishery management" (50 C.F.R. §600.310(b)(2)(i)). See also definitions of optimum yield, overfished, and overfishing, in Magnuson-Stevens Fishery Conservation and Management Act, 16 U.S.C. §1802.

³See [Asche \(2009\)](#) about the importance of dynamic adjustment costs for fishing operations. In addition, adjustment costs are relevant to fisheries economics literature on irreversible investment, e.g., [Clark *et al.* \(1979\)](#).

Figure 1. QSLR for a given TAC with MEY and industry competitive equilibrium

marginal costs are a small fraction of ex-vessel price which is true for the bioeconomic model in this paper based on cost data for the BBRKC fishery. In this case, low variable costs lead to dynamic MEY with stock depletion, which is like [Clark \(1973\)](#), and unlike [Grafton et al. \(2007\)](#) because their results depend on bioeconomic models that satisfy the inequality that MEY is less than MSY. Instead, sustainability is a condition for quota market equilibrium in this paper with a price that equates quota demand with quota supply determined by the level of TAC. For each given level of TAC, quota market price is higher in a competitive equilibrium than under dynamic MEY, which makes sense because a sole-owner or vessel-cooperative can achieve lower harvest costs by economizing stock externalities. This property is illustrated using microeconomic principles in Fig. 1 which is a textbook diagram for static market equilibrium with a linear demand function and a vertical supply curve at MSY. The difference between this demand curve and marginal costs is the QSLR. Figure 1 demonstrates an industry competitive equilibrium is associated with a QSLR that is greater than the corresponding rate for MEY.

Multistage population dynamics are typically not used in bioeconomic models because of their complexity but recently age- and size-structured models were used to analyze MEY (e.g., [Dichmont et al., 2010](#); [Tahvonen, 2009a,b](#)). The bioeconomic model in this paper is based on a size-structured population dynamics module that is borrowed from [Punt et al. \(2014\)](#) which is a simplified version of the full stock assessment model used to manage BBRKC. The complexity of population dynamics in our bioeconomic model is a necessary feature to differentiate effects of OA on different subpopulations. In the population dynamics module, OA impacts survival of juvenile crab thus causing a downward trend in recruitment to the adult population over time. The modeling strategy in this paper follows the general philosophy of CGE models by imposing a rigorous theoretical structure, based on market equilibrium and comparisons of alternative equilibrium states. Uncertainty is a primary consideration, and sensitivity analysis is used to bracket results. In addition the

strategy in this paper calibrates benchmark equilibrium in their respective quota markets to link bioeconomic and CGE models. Bioeconomic models are dynamic and dynamic optimization with forward-looking behavior is a first principle, and therefore, the quota market benchmark in the bioeconomic model is solved using open-loop Nash equilibrium.⁴ The link between the bioeconomic model and the CGE model in this paper is imperfect because savings and investment in the CGE model does not assume forward-looking behavior. However, the bioeconomic model and CGE model are similar enough that the quota market in each model responds in the same way to effects of OA in terms of the key unifying variable, the QSLR. The calibration of quota market equilibrium in each model is a crucial point to understanding the justification for linking the bioeconomic model to the CGE model in this paper. Punt *et al.* (2014) used a much simpler economic module in their bioeconomic model that did not consider effects of quota market equilibrium which are present in the CGE model and the bioeconomic model in this paper. Therefore, our method for linking these models is based on a rigorous definition of quota market equilibrium in each.

An outline of the paper follows with background information in Sec. 2 on the Alaska crab fisheries. Section 3 describes the regional CGE model. Section 4 describes our BBRKC bioeconomic model. Section 5 describes how the yield projections are derived and how they are used in the CGE model simulations. Data sources for the CGE model are summarized in Sec. 6. Results with the CGE model follow in Sec. 7. Section 8 concludes.

2. Alaska Crab Fisheries

North Pacific crab stocks are economically valuable, and vulnerable to the impacts of OA. The BBRKC stock is one of the largest crab fisheries in the Bering Sea and Aleutian Islands (BSAI) region of the North Pacific. The BBRKC fishery was closed in 1994 and 1995, but recovered before rationalization in 2005 (Kruse *et al.*, 2010). In 2009–2011, it produced an annual average of 8.5 million pounds of finished products, and was estimated to have generated real first-wholesale revenues (i.e., revenues received by processors at the first sale of finished products) of about \$113 million per year (Garber-Yonts and Lee, 2013). The BBRKC stock was included in the BSAI Crab

⁴An anonymous reviewer commented that the model in Reimer *et al.* (2014) would provide a much stronger basis than the bioeconomic model in this paper for how fishers are likely to respond to systemic changes from effects of OA on the BBRKC stock. Like Reimer *et al.*, this paper applies Nash equilibrium to consider incentives under rationalization. Therefore, the insights of Reimer *et al.* should apply to the bioeconomic model in this paper. However, the model in Reimer *et al.* does not satisfy first principles of the bioeconomic model in this paper because as a simplification Reimer *et al.* assumed the stock level is constant, clearly a restrictive assumption, which they justify by considering adjustment to new incentives in a brief time interval following rationalization of the BBRKC fishery. Footnote 16 in Reimer *et al.* explains “Relaxing the stationary stock or ex-vessel price assumptions would require — at minimum — the computation of an open-loop Nash equilibrium.” In contrast to Reimer *et al.*, the bioeconomic model in this paper spans decades and is necessarily more complex because of multistage population dynamics with differential effects of OA on juveniles and adults.

Rationalization Program.⁵ The fishery for BBRKC is managed cooperatively by the National Marine Fisheries Service (NMFS), the North Pacific Fishery Management Council (NPFMC), and the State of Alaska. Management of BBRKC is based on a stock assessment model that is used to estimate an overfishing limit (OFL), the level of catch that corresponds to a proxy for the fishing mortality rate which achieves MSY (i.e., F_{MSY}) (Amendment 24 to the Fishery Management Plan for BSAI King and Tanner Crabs). The Acceptable Biological Catch is an OFL buffer that accounts for uncertainty and ensures the probability of exceeding the OFL is less than 50%, and is used as an upper bound for the TAC, which in turn determines the market supply of BBRKC in the CGE model.

3. Regional CGE Model

This section describes the main features of our Alaska dynamic CGE model.⁶ The model equations are available upon request. Since OA is a dynamic process that will occur over many years, our CGE model is based on a forward-moving dynamic formulation to calculate the endogenous variables including price variables in each period (year), with the change in BBRKC harvest given as an initial perturbation in each period. A “sector” refers to a group of industries of which there are three in this study — a fish harvesting sector (consisting of nine fish harvesting industries), a fish processing sector (consisting of nine fish processing industries), and a nonseafood sector (consisting of the remaining 14 nonseafood industries). We consider different assumptions about the mobility of capital for of these sectors and the mobility of labor in and out of the Alaska region.

3.1. Production and consumption

There are 32 producing industries, and corresponding 32 commodities, each produced by its own industry. The production technology for each industry is represented by a constant returns to scale, constant elasticity of substitution (CES) value-added function. Each industry is assumed to use labor and capital as primary production inputs. Intermediate inputs are used in fixed proportions (i.e., Leontief). Value added and intermediate inputs are combined in fixed ratios to produce output. Cost minimization of these production functions subject to a single-period budget constraint yields the regional industries’ conditional factor demand functions for labor and capital.

⁵A voluntary cooperative IFQ program was implemented in 2005 to allocate BSAI crab resources among harvesters, processors, and coastal communities (www.npfmc.org/crabrationalization).

⁶Seung and Waters (2010) used a static CGE model for Alaska fisheries that calculated the impacts of various shocks, including a change in pollock TAC and a change in world price of pollock. One of the important contributions of the present study, compared with Seung and Waters (2010), is that the present study uses a dynamic CGE model that calculates *temporal* and *cumulative* impacts of OA which cannot be calculated within the static framework used in Seung and Waters (2010).

There are three household categories, which are aggregations of the nine household types in IMPLAN (Minnesota IMPLAN Group, 2004) data. Household consumption preferences are represented by CES utility functions. Each type of household is assumed to consume (i) goods and services produced in the region and (ii) imports from the rest of the world (ROW) which is an aggregation of the US states outside of Alaska and foreign countries. Utility maximization for each type of household subject to a single-period budget constraint yields its demand function for each commodity.

3.2. Factor markets and mobility

Labor in the economy is assumed to be homogenous and perfectly mobile across all industries in the region. Therefore, there is only one single wage rate that is determined endogenously in each period in the model. Labor is partially mobile among regions depending on the interregional (i.e., Alaska versus ROW) differentials in wage rates. Capital in the model is sector-specific. For example, capital in fish harvesting sector is not used in the other two sectors. This is a reasonable assumption for Alaska fisheries where fish harvesting sector's capital (mostly fishing vessels) are not likely to be used for producing nonseafood commodities produced in the nonseafood sector. Total capital stock in each sector is fixed in each period. Given the amount of total capital stock for each sector in each period, each sector's capital is perfectly mobile only among the industries within the sector.⁷ This implies that there are three returns to capital that are endogenously determined in the model. Each seafood sector's (i.e., fish harvesting sector and fish processing sector) capital is partially mobile among regions, similar to interregional labor mobility. The assumption that factors are partially mobile between regions is consistent with the dynamic features in regional factor markets, and implies that interregional differentials in returns to the factors resulting from an exogenous perturbation persist until regional factor markets adjust completely in the long run. Table 1 summarizes the types and mobility of the factors of production.

3.3. Resource rent and QSLR

Resource rent is generated in the CGE model because the supply of crab is fixed for each period, based on a yield projection from the bioeconomic model, and represents the return above the normal return (i.e., the level of factor income that is determined in competitive market). It is calculated as the difference between the ex-vessel revenue and the opportunity costs (normal return) of the primary inputs and the costs of the intermediate inputs (e.g., fuel, food) used in catching fish. Here, we treat quota rents as additional factor payments. QSLR is then calculated by dividing the resource rent by the ex-vessel revenue.

⁷Total capital stock in the nonseafood sector is assumed to grow at a certain annual rate, which is updated each period. Once the total capital stock for the nonseafood sector is updated in each period, the capital stock is allocated to different nonseafood industries such that the return to capital is equalized across the nonseafood industries.

Table 1. Types and mobility of labor and capital.

	Labor	Capital
Number of types	One, homogenous	Three sector-specific capital types for H, P, and NS.
Inter-industry mobility	Perfectly mobile across all industries	Each sector's capital is mobile only among the industries in the sector.
Interregional mobility	Partially mobile	Each of seafood sector's (H and P) capital is partially mobile.
Return to factor	Single wage rate is endogenously determined	Three different returns to capital are endogenously determined.

Note: H = harvesting sector, P = processing sector, NS = nonseafood sector.

Specifically, for a fish harvesting industry,

$$(PV)X = (1 + RTS)[wL + rK] \tag{1}$$

where PV is net price of a unit of value added (i.e., net of intermediate input cost); X is output (harvest) level⁸; RTS is a variable representing the share of the value added allocated to the resource rent; w is market wage rate; L is labor; r is market return to capital; and K is capital. So $(PV)X$ measures total factor payments; $(wL+rK)$ normal factor payments; and $RTS(wL + rK)$ resource rent. Based on previous reports (e.g., [NPFMC](#)), the QSLR is set to 0.75 (i.e., 75% of the ex-vessel price) for BBRKC and 0.50 for all other fish species in the base year.⁹

Since we use a general equilibrium model, the changes in resource rent and QSLR arising from the OA-induced changes in the BBRKC yields will be different from those that would be obtained from a partial equilibrium analysis. That is, the changes in resource rent and QSLR calculated in this study will reflect the changes occurring not only in the BBRKC industry but also changes in other sectors in the economy while the corresponding results from a partial equilibrium analysis would reflect only the changes in the BBRKC industry, ignoring the “general equilibrium” effects from other sectors.

3.4. Dynamics

The human population in the region (Alaska) is assumed to grow at a rate of 0.97% per annum. Labor stock in each period is updated based on change in population size and net labor in-migration. Net labor in-migration is determined after solving a static CGE in each period and is added to labor stock at the beginning of the next period. Capital stock in seafood sectors changes depending on its in- and out-migration between Alaska

⁸The supply of BBRKC in each period is determined by open-loop Nash equilibrium in the bioeconomic model presented in Sec. 4.
⁹For the 2012/2013 season, the mean QSLR for class A IFQ in the BBRKC fishery was estimated to be 65% of the ex-vessel price. See Table 33 in [Garber-Yonts and Lee \(2013\)](#). This table also reports a mean QSLR for Bering Sea snow crab which is about 50% of the ex-vessel price.

and the ROW. Total capital stock in the nonseafood sector is assumed to grow at a rate of 1.4% per annum. Investment is determined via annual increase in capital in nonseafood sector. Regional savings consist of household savings, enterprise savings, state and local government savings, and federal government savings.¹⁰ However, the determination of investment is independent of regional savings. It seems appropriate to treat the inflow of external savings as a residual that responds to the level of investment in the region since regions are usually highly open economies and investment funds appear to be geographically mobile in the United States. Therefore, if the region has more savings than needed for investment, surplus savings flow out of the region, and vice versa.

The CGE model used in this study is a forward-moving dynamic model. The structure of the dynamic CGE model in this study is similar to that of Seung and Kraybill (2001), Shoven and Whalley (1992), and Ballard et al. (1985). In the present study, there are two kinds of adjustment behavior to be considered. First, in the goods market, the adjustments of prices and quantities occur in a short period, say in a year, reducing excess demand to zero (Walrasian equilibria). Second, in factor markets, adjustment takes multiple periods because of lagged responses of factor supplies, represented by the factor migration elasticities.

Static equilibria are sequenced through time to reflect a change in capital stock, which is due to investment, and a change in labor stock, which is due to labor migration and population growth. The calculation of equilibrium in each period begins with an initial capital endowment in each sector and a labor endowment for the economy as a whole. In this study, the sequence of equilibria generated without any policy implementation or an exogenous perturbation (OA in this study) is called “continuous benchmark” while that generated with a policy perturbation or an exogenous perturbation is called “continuous counterfactual.” The policy impacts are calculated by comparing the continuous counterfactual with the continuous benchmark. For more details on the structure of our dynamic CGE model, including how the welfare changes¹¹ for the three types of households resulting from OA, are

¹⁰Rates for these savings are calculated by the base-year data in IMPLAN, and are fixed at their base-year rates.

¹¹The welfare changes were calculated for the three types of Alaska households based on their income and changes in prices, and derived as the sum of the stream of the present discounted values of the changes in per capita expenditures. In particular, we first calculate per capita expenditure (PCE) for each period for each of the three types of households as: $PCE_{z,h,t} = \frac{e_{z,h,t}(p_{0,t}, U_{z,h,t})}{POP_{z,h,t}/POP_h}$ where z is either 0 (benchmark) or 1 (counterfactual), h denotes household type, t denotes time period, $e(p, U)$ is the expenditure function, p is a benchmark price vector, U is utility, and $POP_{z,h,t}$ and POP_h are household type h 's population in the t th period and the base period, respectively. We do not consider the population growth per se as a reason to change household expenditures in future years. Rather, we first calculate the *per capita* welfare change from OA, and then multiply it by the base-year population size (POP_h). See Ballard et al. (1985, Chapter 7) for details. Next, we calculate the sum of the stream of the present discounted values of per capita expenditures (PVE) from the first period to a terminal period (T) as: $PVE_{z,h,T} = \sum_{t=0}^T \frac{PCE_{z,h,t}}{(1+d)^t}$ where d is the discount rate which is assumed to be 3% for these calculations. Note this discount rate is applied to consumption expenditures of Alaska households and is different from the discount rate for fishermen in the bioeconomic model. The present value of welfare change (PVW) for household h from an exogenous shock is then calculated as $PVW_h = PVE_{1,h,T} - PVE_{0,h,T} + \frac{PCE_{1,h,T}}{d(1+d)^T} - \frac{PCE_{0,h,T}}{d(1+d)^T}$. This value is the sum of the stream of the present discounted values of the *change* in PCEs. The household income is the sum of (i) factor income (labor income and capital income), (ii) transfer payments from various levels of governments, and (iii) inter-household transfer payments. Because we used a single-region CGE model for Alaska, the welfare changes accruing to the non-Alaskan households were not included in the welfare calculations.

calculated, see [Seung and Kraybill \(2001\)](#), [Shoven and Whalley \(1992\)](#), and [Ballard et al. \(1985\)](#).

4. BBRKC Bioeconomic Model

The bioeconomic model in this paper is an extension of the dynamic MEY theory in [Rosenman \(1986\)](#) with size-structured population dynamics to differentiate sub-populations, a downward trend in recruitment caused by effects of OA on the survival of juvenile crab, and a quota market that allocates TAC which is limited to MSY over time.

4.1. Dynamic MEY and open-loop Nash equilibrium

Open-loop Nash equilibrium is defined by a sequence of QSLRs τ_t (i.e., dollars-per-crab) that satisfy MSY in the limit and a dynamic optimization problem that depends on τ_t . For a vessel-cooperative,¹² this dynamic optimization problem also defines dynamic MEY conditional on τ_t . Given an initial vector of numbers of crab¹³ in each size-class N_{-1} , this dynamic optimization problem assumes that a vessel-cooperative with an infinite time horizon has an objective to maximize with respect to scalar fishing effort x_t a quadratic form for catch-at-size (column) vector Y_t subject to (i) a catch equation, (ii) ex-vessel-unit-value (i.e., dollars per crab) vector V_t , (iii) recruitment vector R_t that depends on nonstationary effects of OA in a parameter vector $\mathbf{h}_{0t}$ which is given, and (iv) population dynamics in numbers-at-size vector N_t . Solutions to this dynamic optimization problem, conditional on τ_t , are necessary for open-loop Nash equilibrium:

$$\begin{aligned} \text{Max}_{\{x_t\}_{t=0}^{\infty}} E \sum_{t=0}^{\infty} \beta^t & \left(V_t' Y_t + \frac{1}{2} Y_t' \mathbf{d}_3 Y_t - \frac{1}{2} (Y_t - Y_{t-1})' \mathbf{A} (Y_t - Y_{t-1}) \right) \\ Y_t &= \mathbf{Q}^D N_t x_t \\ \text{s.t.} \quad V_t &= \mathbf{d}_0 + \mathbf{d}_1 N_t + \mathbf{d}_2 Y_t - \tau_t \mathbf{1} \\ R_t &= \mathbf{h}_{0t} + \mathbf{H}_0 (N_{t-k} - Y_{t-k}) \\ N_t &= \mathbf{h}_1 N_{t-1} + \mathbf{h}_2 Y_{t-1} + R_t, \quad t = 0, \dots, \infty. \end{aligned} \quad (2)$$

Parameters in the objective function include a (scalar) discount factor $0 < \beta < 1$ (assumed equal to 0.95 for all projections which implies a discount rate for fisherman close to 5%), a diagonal private nonlinear variable cost matrix $\mathbf{d}_3 < 0$ that represents

¹²Following [Rosenman \(1986\)](#), we assumed fishermen and vessels are identical and normalize the number of each to unity. Assuming a representative fisherman/vessel is only a convenience as the model includes a theory of aggregation. See footnote 4 in [Sargent \(1978\)](#).

¹³Following [Punt et al. \(2014\)](#), population dynamics are based on numbers of crab in each size-class. A (column) vector with fractions retained times weight-at-size was applied to derive yield curves and other model outputs (see [Appendix A](#)). Yield, in units of weight (i.e., metric tons), is the scalar form of retained catch. In the objective function above, only retained catch counts for ex-vessel revenues and costs apply to the total number of crabs handled.

decreasing returns, and a symmetric positive definite dynamic adjustment cost matrix $\mathbf{A}$. The ex-vessel value (column) vector V_t has a vector $\mathbf{d}_0$ (which can be stochastic) that includes a choke-price (i.e., intercept) parameter for a (linear) inverse demand function minus (linear) variable costs. In addition, V_t has elements in a diagonal matrix $\mathbf{d}_1 > 0$ that are stock externality parameters,¹⁴ elements in a diagonal matrix $\mathbf{d}_2 < 0$ that are slope parameters for a linear inverse demand function,¹⁵ and a nonstationary QSLR (or equivalent landings tax) τ_t which is a scalar coefficient for a (column) vector of ones, $\tau_t \mathbf{1}$. Let $\mathbf{I}$ denote the identity matrix. We simplify diagonal matrices by assuming a scalar $\alpha = 10^{-4}$ (dollars per crab-squared) for dynamic adjustment costs, with $\mathbf{A} = \alpha \mathbf{I}$, and scalars d_i with $\mathbf{d}_0 = d_0 \mathbf{1}$ and $\mathbf{d}_i = d_i \mathbf{I}$ for $i = 1, 2, 3$.

We denote the benchmark ex-vessel choke price for the baseline with scalar $p > 0$ dollars per crab, and the linear variable cost coefficient with scalar $c > 0$ dollars per crab.¹⁶ By definition, $d_0 = p - c$ and $\mathbf{d}_0 = (p - c) \mathbf{1}$. An endogenous scalar variable $\tau \geq 0$ dollars per crab was computed that produces a dynamic MEY path to MSY.¹⁷ This path is interesting and we studied it to evaluate effects of OA on alternative open-loop Nash equilibrium states. Econometric estimates of parameters (e.g., α, d_i) could be obtained in future work. We were deliberately parsimonious in the number of economic parameters in the bioeconomic model to conduct sensitivity analysis and accommodate a more complex set of biological relationships. Biological parameters were estimated using the simplified stock assessment model from [Punt et al. \(2014\)](#) and these values are reported in [Appendix A](#).

¹⁴We assumed a stock externality parameter of $d_1 = 101 \times 10^{-6}$ dollars per crab-squared to emphasize the importance of dynamic stock effects. Smaller values for this parameter (quickly) close the gap between dynamic MEY and an industry competitive equilibrium.

¹⁵Red king crab is primarily an export commodity. In another paper, we used US Census Bureau Foreign Trade Data to construct a panel of frozen king crab exports with 42 countries from 1999 to 2012 to econometrically estimate export demand functions, and calculated a slope coefficient for an linear inverse demand function of $-d_2 = 9 \times 10^{-6}$ dollars per crab-squared. From Table 3 in “Zeros in Space: Exports of Alaska King Crab” by M. Dalton (available from the author upon request): The estimated \$/ton² for Japan (JPN) is -0.04 which calculates to $0.04\$/ (10^3 \text{ kg})^2$ and at 3 kg/crab gives $0.04 \times (9/10^6) \$/ \text{crab}^2$. Therefore d_2 here corresponds to the normalized value of unity (1.0). Median $\$/ \text{kg}^2$ is -3 (Singapore) and -1.15 is at the 60% quantile (United Arab Emirates). However, the calculation is complicated because units from the bioeconomic model are ex-vessel crabs, and units in the trade data are for finished products. Based on an average product recovery rate (PRR) of 2 kg = 1 processed crab implies $0.04\$/ (10^3 \text{ kg})^2$ at 2 kg/crab gives $0.04 \times (4/10^6) \$/ \text{crab}^2 = [0.04 \times 4/9] \times (9/10^6) \$/ \text{crab}^2$. If instead of JPN with 0.04, the scalar is set such that term in brackets is equal to 1, i.e., $s \times 4/9 = 1$ implies $s = 9/4 = 2.25$ which is close enough to the median value 3. Therefore, we judged the assumed value for d_2 to be reasonable.

¹⁶Average ex-vessel prices were calculated from landings data for 2006–2010. Ex-vessel prices for red king crab are variable, and the median value for these years was 28.76 dollars per crab in 2009 which was taken as the base year value, and used for the choke price (i.e., intercept) parameter in the inverse demand function. For conversion, an average weight of about 3 kg for an unprocessed red king crab was calculated from landings data. In addition, an average product recovery rate of about 2/3 was calculated from production data, which gives an average quantity of about 2 kg of finished product per crab. We calculated an average expense per crab for fuel, bait, and other crew provisions (e.g., food), from economic data for each year 2006–2010, and for 2009, these variable costs were estimated at $c = 1.59$ dollars per crab.

¹⁷Conditional on other parameters, this variable depends on nonlinear (quadratic) variable costs embodied in parameter coefficient $d_3 \leq 0$ that are treated as private costs related to decreasing returns to scale for fixed capacity fishing vessels. By iteration, we solved for $-d_3 = 18 \times 10^{-4}$ dollars per crab-squared and a value for $\tau = 20.09$ dollars per crab which is close to 70% of the base year ex-vessel price.

Catch vectors in the objective function depend on selectivity coefficients for the directed fishery in a diagonal matrix $\mathbf{Q}^D$. Recruitment vector R_t is based on an affine spawner–recruit (ASR) function from Runge and Johnson (2002, Eq. 5), which is used to approximate a Beverton–Holt (BH) spawner–recruit function at MSY. The yield curve derived from an ASR function is an upper-bound that is close to the BH yield curve near the steady-state of the bioeconomic model at MSY (see [Appendix A](#)). Since the open-loop Nash equilibrium converges geometrically to a steady-state, errors due to omitting some nonlinear effects in recruitment are bound to be small. Behavior in bioeconomic rational expectations models is based on consistent expectations and forecasts for decision rules. Linear forecast rules are employed to solve the dynamic game. Therefore, the assumption of an ASR function is a device for deriving linear forecasting rules to form rational expectations but could be a significant restriction on population dynamics.¹⁸ An ASR function is composed of vector $\mathbf{h}_0$, (which can be stochastic) that is constant (i.e., stationary) in the baseline without OA, and matrix $\mathbf{H}_0$ (with nonzero entries in the first row only) for spawning stock biomass at the time of spawning with a k -year lag between spawning and recruitment. Numerical parameters for these matrices are presented below with population dynamics and a nonstationary spawner–recruit function. Population dynamics for N_t consist of recruitment plus the product of stock growth and survival parameters for lagged numbers-at-size in a lower-triangular matrix $\mathbf{h}_1 > 0$, and a diagonal matrix for catch-at-size $\mathbf{h}_2 < 0$. Numerical values for these parameters, their relationship to parameters in a population dynamics model and MSY are presented in [Appendix A](#).

Conditions for sustainability were excluded from the constraint set in the dynamic optimization because such conditions are unnecessary if costs implicit in vector $\mathbf{d}_0$ are a sufficiently large fraction of ex-vessel prices. Dynamic MEY tends to a yield level that is less than MSY if fuel and other variable costs are close to ex-vessel prices (i.e., $c/p \rightarrow 1$). If costs are a relatively small fraction of ex-vessel price, then we solve for $\tau > 0$ such that yields tend to MSY, i.e., $\lim_{t \rightarrow \infty} y_t = \text{MSY}$.

Our baseline projection without effects of OA is dynamic MEY with recruitment based on a constant $\mathbf{h}_0$ from a given set of initial conditions for fishing effort x_{-j} and numbers-at-size N_{-j} , $j = 1, \dots, J$. These conditions were estimated using our simplified stock assessment model.

¹⁸Negative density dependence (i.e., compensation) is the standard assumption in population dynamics models for marine fish stocks. However, compensatory effects can be weak or depensation may be present (e.g., [Keith and Hutchings, 2012](#)). ASR functions are density-dependent but more restrictive than BH. [Touzeau and Gouzé \(1998\)](#) derived BH and (strictly) linear spawner–recruit (LSR) relationships and showed that LSR is related to BH but without juvenile mortality from cannibalism by adults. In addition, BH and LSR, and ASR relationships leave out juvenile competition. An ASR relationship is easy to derive using the population dynamics in [Touzeau and Gouzé \(1998\)](#). A numerical analysis (available from the authors) was conducted to compare population dynamics with BH and ASR relationships in a simple two-stage model (i.e., juveniles and adults), and also, to compare ASR relationships to population dynamics with juvenile competition. Results showed that ASR, BH, and dynamics with juvenile competition were fairly close with initial conditions not extremely different from the population equilibrium (e.g., initial conditions close to zero).

Our OA projection is dynamic MEY from the set of initial conditions for the baseline with a sequence $\{\tau_t\}_{t=0}^{\infty}$ which responds to a nonstationary trend in recruitment $\{h_{0t}\}_{t=0}^{\infty}$. To simplify, let $h_{0t} = h_0 g_t$, with $0 \leq g_t \leq 1$ for all t , denote the scalar first component of vector $\mathbf{h}_{0t}$ which has zeros elsewhere because juvenile crabs are assumed to recruit only to the first size-class. The exact relationship between τ_t and g_t can be derived using the linearity of first-order necessary conditions, which we derived using matrix calculus, for the dynamic optimization above. The details of this derivation are not important here. The main result is almost trivial. Every term in the first-order condition for time period $t \geq 0$ is scaled by g_t^2 except for $\mathbf{d}_0 - \tau_t \mathbf{1}$ which is scaled by g_t . A transformation which divides that first-order condition by g_t^2 leaves a single instance $(p - c - \tau_t)/g_t$. Let $\nu > 0$ denote the benchmark QSLR expressed as a fraction of ex-vessel choke price net of linear variable costs. Suppose $\tau_t = (p - c)(1 - (1 - \nu)g_t)$. If $g_t = 1$ for all t , then $\tau_t = \nu(p - c)$, as it is defined. If $g_t \rightarrow 0$, then $\tau_t \rightarrow (p - c)$, as demonstrated. Finally, $p - c - \tau_t = (p - c)(1 - \nu)g_t$, which implies that the transformed (i.e., dividing by g_t^2) system of first-order conditions is stationary.

4.2. Effects of OA on recruitment

Punt et al. (2014) used survival data from OA exposure experiments that were performed on juvenile red king crabs (Long et al., 2013). Data from these experiments were used to estimate effects of OA on survival parameters in a stage-structured pre-recruit dynamics model, and this model was linked to a post-recruit population dynamics model that is a simplified version of that used for management (see Appendix A). This coupled population dynamics model was used with an OA projection from Caldeira and Wickett (2003). A sequence of yield curves was derived for a linear trend in pH from 2010 to 2100, and then, each curve was used to compute MSY. This MSY projection was used to construct an ASR relationship with a constant slope, and a downward trend in the intercept term. This trend represents effects of OA linked explicitly to pre-recruit survival from the coupled pre- and post-recruit population dynamics model. We approximated these sequences of yield curves using a deterministic trend applied to an ASR function in the post-recruit model. The post-recruit population dynamics and ASR function were used to compute ex-vessel profits and fishery net income, which is ex-vessel profits plus quota share income (Fig. 2). These results are suggestive, but not informative for fishery dynamics and performance with an ITQ program.

This pre-recruit model was linked to a post-recruit population dynamics model that is identical to the one above, and this coupled model was used to project a sequence of yield curves for 100 years with an OA trend in recruitment. The MSY for each yield curve was computed, which provided a sequence of numbers, starting with baseline MSY for the population dynamics model above, and in this case, ending with zero (during year 2100 of the projection). Let g_t denote MSY in year t of the projection divided by the starting value (i.e., year zero of the projection) with $g_0 = 1$, and $g_t \rightarrow 0$.

Figure 2. Comparative statics with effects of OA for 50 years. Equilibrium yield for each level of MMB decreases over time (a). Associated effects for ex-vessel profits (b) are stronger than those for fishery net income (c)

For convenience, we summarized this sequence with a two-parameter Gompertz function, which has the same shape as the OA trend derived from the coupled population dynamics model, and is almost identical.¹⁹

A simple and transparent translation of g_t into the population dynamics module of our bioeconomic model is to apply it as a scalar coefficient for the yield-curve with an ASR function (see [Appendix A](#)) which is a function of the fishing mortality rate F such that

$$y_t^{\text{OA}}(F) = g_t \times y_{\text{ASR}}(F). \quad (3)$$

An ASR function has the important property that the MSY is scalable while the fishing mortality rate (F_{MSY}) is unaffected because recruitment is $r_t = aq_t + bg_t$ for the

¹⁹For reference, the Gompertz function that tracks OA effects for MSY over time based on the nonlinear regression model for OA effects on survival of juvenile crab in [Punt et al. \(2014\)](#) is $1.02065e^{-0.0204426e^{0.0598159t}}$. For an alternative scenario, the exponential function $1.02065e^{-0.0346577t}$ was used to track OA effects based on the linear regression model for OA effects on survival in [Punt et al. \(2014\)](#). Further details including comparison of these functions and MSY values from [Punt et al. \(2014\)](#) are available from the authors.

spawning stock $q_t = r_t s$ at the stationary spawner per recruit level s which implies that recruitment is

$$r_t = \frac{bg_t}{1 - as}. \quad (4)$$

Consequently, MSY, and associated male mature biomass (MMB), are scaled by g_t for the population dynamics model with an ASR function. This property suggests setting the first component of the vector $\mathbf{h}_{0t}$ in the dynamic optimization to the scalar $h_{0t} = h_0 g_t = bg_t$ which we did.

4.3. Effects of OA on quota lease rates and fishery income

Quota lease rates contain important information for fishermen and managers because these rates represent the shadow value of additional recruitment at MSY. Unfortunately, lease rates for the BBRKC fishery were not available. We used an informal estimate, close to 75% of ex-vessel price, and note that a lease rate this high can lead to problems for management (Pinkerton and Edwards, 2009). Concerns about quota lease rates as high as 75% of ex-vessel prices were reported for BBRKC in documents by the NPFMC on performance of the BSAI Crab Rationalization Program.²⁰

High lease rates imply a vessels' average variable costs (e.g., crew food, fuel, bait) must be low relative to ex-vessel prices otherwise profits would be negative. We estimated that in recent years these average variable costs were about 5% of ex-vessel prices for the BBRKC fishery. Therefore, fishing mortality rates for dynamic MEY are constrained in our bioeconomic model by the fishing mortality rate for MSY (i.e., $F_{MEY} \leq F_{MSY}$). This structure unites IO and the quota market with a regulatory limit on catch. In addition to linear costs, our bioeconomic model contains nonlinear (i.e., quadratic) cost terms. We assumed these cost terms are large enough to result in a quota lease rate for our baseline projection that is about 75% of the ex-vessel price at MSY. However, our conclusions do not depend on the exact value.

The crab season that started in 2009 is year zero for our projections. The ex-vessel price for 2009 was the median for 2006–2010, which was used to calibrate a (linear) demand function. Consequently, all values in our projections are evaluated in real year 2009 dollars. We computed open-loop Nash equilibrium with yields that converge over time to MSY. Computing this equilibrium involved solving a high-order system of linear difference equations. The high-order lags in this system imply initial conditions were necessary for fishing mortality rates and population numbers-at-size dating back to 1998.

We compared our baseline projection to an OA projection (Fig. 3). Declining recruitment causes yields to fall, which increases the shadow value of the stock. Therefore, quota lease rates must rise to keep the demand for quota by an efficient fleet

²⁰See bottom paragraph on p. 2 in http://www.npfmc.org/wp-content/PDFdocuments/catch_shares/Crab/CrewCoop-Measures213.pdf.

Figure 3. Comparison of the OA projection to baseline. Initial yield is greater than 7000 tons. Dynamic MEY reduces annual yields to less than 5000 tons, the stock rebuilds, and yields converge to baseline MSY (a). The OA projection does not recover to baseline MSY, and yields follow a downward trend that approaches zero by 2100 (a). For the OA projection, declining recruitment causes an upward trend in quota lease rates (b). Falling yields and rising lease rates affect ex-vessel profits (c), which worsens the effects of OA relative to the corresponding reductions for net benefits (d)

equal to supply at the (decreasing) MSY. Ex-vessel profits are affected by both falling yields and rising lease rates, which worsen effects of OA for fishermen because they receive a diminishing share of fishery income over time. For our projections, the present discounted value of ex-vessel profits decreases by 16%, this percentage change for quota income is 7%, and overall, the present discounted value of fishery income is reduced by 9% with OA effects present. Trying to improve outcomes for fishermen by, for example, attempting to regulate lease rates could compromise the economic efficiency of ITQs. More cooperation lowers lease rates by improving efficiency. The maximum degree of cooperation among fishermen corresponds to minimizing stock externalities which implies a minimum quota lease rate and therefore a maximum share of fishery income.

Bioeconomic projections applied in this paper are counterfactual paths that are intended to determine the maximum economic value associated with a management

goal of MSY. By following dynamic MEY, these paths are not intended to forecast all of the details related to year-to-year changes in management. For this paper, the relevant comparison of bioeconomic projections is between dynamic MEY transitions to MSY with, and without, effects of OA. The use of dynamic MEY transitions facilitates this comparison by associating with each projection a specific dollar value with an explicit microeconomic foundation (i.e., derived from optimizing behavior). For this comparison, the difference in dollar values is an expected discounted present value of direct economic losses in ex-vessel profits, or net fishery income (i.e., ex-vessel profits plus quota lease payments).

5. BBRKC Yield Projections and CGE Model Simulations

From the bioeconomic model, we derive three sets of annual BBRKC yield projections for the period 2010–2100. In addition, each set of projections includes estimates of historical yields for 1999–2009. The first set of projections contains baseline BBRKC harvest levels generated without OA (Scenario 1). The first set is associated with a particular steady state for the population dynamics that is reached in the limit (i.e., as $t \rightarrow \infty$), which implies stationary yields over time if OA effects are absent (Fig. 3). In addition to a baseline without OA effects, two bioeconomic projections with OA effects were applied in the regional CGE model. These projections were derived from results for the linear and nonlinear survival models presented in Punt *et al.* (2014). These results indicated the nonlinear model is more likely than the linear model based on survival data for juvenile red king crab from OA exposure experiments described in Long *et al.* (2013).²¹ The second set of projections contains the harvest levels generated with OA based on a linear regression of survival data for juvenile red king crab (Scenario 2). The third set of projections contains the harvest levels generated with OA based on a nonlinear (i.e., power-law) regression using the survival data from OA exposure experiments (Scenario 3). A comparison of these scenarios shows a high degree of uncertainty in the effects of OA on the survival of juvenile crab (Fig. 4).

Here, we use only the first 90 years of each projection because OA effects imply MSY for BBRKC has essentially collapsed to zero by then. We first solve the CGE model for each of the 90 periods (years) with each of the 90 baseline BBRKC harvest levels (corresponding to each year) *without* OA and with capital and labor updated each period, and calculate the benchmark sequence of the values of endogenous variables (e.g., output, welfare change, and resource rent). Next, we solve the CGE model for each of the 90 periods with each of 90 BBRKC harvest levels *with* OA and with capital

²¹See Fig. 3 in Punt *et al.* (2014) for a comparison of fits for the linear and nonlinear regression models applied to survival data from OA exposure experiments described in Long *et al.* (2013). In these experiments, pH = 8.0 was the control. Both models were tuned so that fits to the data for pH = 8.0 were identical. According to Punt *et al.* (2014) both survival models fit the data for pH = 7.5 reasonably well. However for pH = 7.8, the nonlinear model produced a much better fit than the linear model which substantially underpredicts survival in this case.

Figure 4. Bioeconomic Yield Projections for BBRKC fishery with OA based on a baseline without OA effects, linear, and nonlinear relationships between pH and survival of juvenile crab

and labor updated each period, and calculate the counterfactual sequence of the values of endogenous variables. We then compare the values of endogenous variables from the benchmark and counterfactual sequences of solutions to calculate the effects of OA.²²

Because of its regional income effects, the world price for king crab is an important variable in our welfare analysis of OA effects. The changes in the world price of BBRKC are from two sources — (i) supply side (i.e., the OA-induced reduction in BBRKC harvest)²³ and (ii) demand side (i.e., potential increase in the world demand for Alaska’s exports of BBRKC).

To specify the BBRKC export demand, we use a price elasticity of demand less than infinity, represented by a downward sloping demand curve, which implies an endogenous increase in world price of BBRKC with falling yields under OA. This endogenous price increase for BBRKC partially offsets the loss in income (i.e., the revenue received by the BBRKC harvesters) from falling yields. We estimate that the demand for BBRKC is elastic,²⁴ and therefore, the effects of this price increase may not be large at first, but because yields are driven to zero with OA in Scenarios 2 and 3,

²²The effects (in percentage terms) of OA for a variable of interest (VAR) is calculated as follows: Effects of OA = $100 * \frac{\sum_{t=1}^T (VAR_t^1 - VAR_t^0)}{\sum_{t=1}^T VAR_t^0}$ where t = time period; T = terminal period (= 90); VAR = variable of interest; 1 = counterfactual path; and 0 = benchmark path.

²³OA could also affect Russian red king crab stocks and harvest. However, we have not explicitly incorporated that effect into the change in the supply of the red king crab in the world market and therefore in the world price.

²⁴We used an elasticity of 5 in the present study. Herrmann and Greenberg (2006) estimated an elasticity of 4.55 for Japanese demand for Alaska snow crab. The study also estimated an elasticity of 9.09 for Japanese demand for Alaska red king crab. These numbers are reported as “mean-level elasticity”; that is, the point estimates at the ratio of sample means. In our study, however, we used the elasticity estimate at the 2010 data point which is consistent with our assumption of an elasticity of 5 for king crab.

this price increase becomes more important over time in both scenarios, though the timing for each is different.

We allow the downward sloping demand curve for BBRKC to shift upward slightly²⁵ every year to reflect the assumption that world prices may be higher in the future because world demand for BBRKC could increase as time passes because of rising incomes, for example. In this study, we focus on the case where the downward sloping demand curve shifts upward, and calculate the economic and welfare effects of OA with shifts in the downward sloping demand curve. Although we focus on this case, we also calculated the effects (i) when the downward sloping demand curve does not shift, (ii) when the demand for BBRKC is perfectly elastic that does not shift, and (iii) when the perfectly elastic demand shifts exogenously. We did this to examine how sensitive the effects are to different assumptions regarding the demand for BBRKC. The results from this sensitivity analysis and their discussion are provided in [Appendix B](#).

6. Data

An Alaska social accounting matrix (SAM) was generated using 2004 data and software from IMPLAN. The 509 industry sectors in IMPLAN were aggregated into 14 nonseafood production industries. Because of the unreliability of the fish harvesting and processing data in IMPLAN, we did not use the data. For fish harvesting and processing industries, we instead used data from the Commercial Fisheries Entry Commission (CFEC), Alaska Fisheries Information Network (AKFIN), Pacific Fisheries Information Network (PacFIN), and National Marine Fisheries Service (NMFS), the Alaska Fisheries Economic Assessment Model (FEAM), and interviews of key industry informants. More detailed information about the procedures used to develop the seafood industries' dataset can be found in [The Research Group \(2007\)](#) and [Seung and Waters \(2010\)](#).

The resulting state of Alaska SAM has a total of 32 aggregated production industries producing 32 commodities; three value-added sectors (labor, capital, and indirect business taxes); two government expenditure sectors (combined state and local government, and federal government); three household categories (classified by income level); a savings investment account; and an account for imports and exports to the ROW. The 32 production industries include nine fish harvesting industries (depending on the species caught), nine fish processing industries, and 14 nonseafood industries.

We specified the values of certain parameters (such as elasticities) in the model equations based on previous studies. See [Seung and Waters \(2010, Table A.3\)](#) for some elasticity values (e.g., elasticity of substitution in production and elasticity of substitution in Armington function) and their sources used for the present study. This

²⁵We assumed that the demand curve shifts to the right slightly such that the quantity demanded given a BBRKC price increases by 1.5% every year.

study needed to specify the values of additional parameters and elasticities to implement our dynamic CGE model. Population growth rate (0.97%) and labor force participation rate (0.65) were based on Alaska Department of Labor and Workforce Development (2012) and Alaska Department of Labor and Workforce Development (2013), respectively. Rate of growth of capital in the nonseafood sector is assumed to be 1.4%, which is the annual average growth rate of real gross domestic product for Alaska from 1997 to 2011 (Bureau of Economic Analysis). Factor migration elasticity is set at 0.137 (Plaut, 1981).

7. Results

We calculated the impacts of OA for the three yield projections, a baseline without effects of OA, with linear OA effects, and with nonlinear OA effects in the pre-recruit survival model. Each projection forms a scenario. Scenario 1 is the baseline and there are no impacts of OA on BBRKC yields. Therefore, we do not report the results from Scenario 1. Figure 4 shows the BBRKC yield projection for each scenario. The BBRKC yield projection without OA (Scenario 1) is rather stable. In Scenario 2, with linear effects of OA in the pre-recruit survival model, the BBRKC catch with OA decreases rather fast as time passes. In Scenario 3, with nonlinear effects of OA in the pre-recruit survival model, the BBRKC catches decreases as time passes, but not as fast as in Scenario 2 (Fig. 4). While it takes about 15 years for the yield to go down to half of the base-year (2010) level [3500 metric tons (t)] in Scenario 2, it takes as long as about 55 years, in Scenario 3, for the yield level to decrease to half of the base-year level. Therefore, it is expected that the regional economic impacts from Scenarios 2 and 3 will be significantly different.

Table 2 presents the cumulative impacts of OA on industry output (in quantity and value) and employment for Scenarios 2 and 3. The results in Table 2 are obtained by running the CGE model for each of 90 years without and with OA under the assumption that the BBRKC export demand is downward sloping and shifts over time. In Scenario 2, the cumulative output in BBRKC harvesting industry decreases exogenously by about 61% with OA over the 90-year period compared to the industry's cumulative output without OA. The change in output in the BBRKC industry represents *direct* impacts caused by OA. The output in the BBRKC processing industry decreases by a similar percentage (61%). While the quantity of output decreases by about 61% for both the BBRKC harvesting and processing industries, changes in the value of output for the two industries are much smaller (33% for harvesting and 35% for processing) due to (i) the endogenous increase in the price of the BBRKC along the downward sloping demand curve and (ii) the exogenous shift of the curve. This price increase partially offsets the loss of fishery income for BBRKC from falling yields under OA. The total output in the region decreases by about 0.3%. Employment in BBRKC harvesting and processing industries decrease roughly by the same percentage as decrease in the output in the industries (61%).

Table 2. Impacts of OA on output and employment over a 90-year period: with downward sloping export demand of BBRKC which shifts up every year to reflect world demand increase.

Industry/Sector	Quantity of output ^a		Value of output ^b		Employment
	Without OA	% Change	Without OA	% Change	% Change
Scenario 2					
BBRKC harvesting	7853.0	−60.90	3078.1	−32.99	−60.97
Other fish harvesting	103,054.7	0.00	32,485.8	0.04	−0.38
BBRKC processing	17,880.9	−60.64	6478.5	−35.37	−60.65
Other seafood processing	233,564.8	0.01	78,006.8	0.01	−0.11
All nonseafood industries	6,823,751.1	−0.11	1,829,345.4	−0.09	−0.13
Total (all industries)	7,186,104.5	−0.32	1,949,394.6	−0.26	−0.26
Scenario 3					
BBRKC harvesting	7853.0	−30.46	3078.1	−11.12	−30.60
Other fish harvesting	103,054.7	0.00	32,485.8	0.03	−0.38
BBRKC processing	17,880.9	−30.40	6478.5	−11.62	−30.42
Other seafood processing	233,564.8	0.06	78,006.8	0.02	−0.05
All non-seafood industries	6,823,751.1	−0.04	1,829,345.4	−0.03	−0.04
Total (all industries)	7,186,104.5	−0.15	1,949,394.6	−0.08	−0.11

^aThe unit of output is calibrated such that one unit of output is sold at \$1 million in the base year.

^bThe value of output is in present discounted value.

Wage rates decrease with OA (not shown in the table) for two major reasons. First, labor is released from BBRKC harvesting and processing industries due to reduction in the two industries’ output. The released labor is added to the supply in the regional labor market. Second, the reduction in output of BBRKC harvesting and processing industries implies a reduced demand by these industries for goods and services from nonseafood industries, which in turn reduces production in the nonseafood industries. The reduction in production by nonseafood industries will further lower the wage rate. Lower wage rates cause some labor to out-migrate to ROW, resulting in a decrease of about 0.3% (Table 2) in total regional labor. Since in this study labor is perfectly mobile among all the industries within the region and partially mobile between regions, labor discharged from BBRKC harvesting and processing industries can flow either to other industries in the region or to ROW. The results in Table 3 indicate that the out-migration of the labor to ROW is larger than the flow of labor from the BBRKC industries to other industries within the region. Compared with Scenario 2, Scenario 3 produces significantly smaller impacts. Outputs in BBRKC harvesting and processing industries are reduced by only about half (about 30%) of the reductions in Scenario 2. Total regional output decreases by about 0.2% in Scenario 3.

Table 3 presents our main results concerning welfare losses from falling yields under OA. With exogenous shifts in the downward sloping demand curve for BBRKC, the welfare losses are \$69.8 million, \$511.5 million, and \$636.5 million, respectively, for low, medium, and high income households (or an aggregate household welfare loss

Table 3. Present discounted value of welfare loss (\$ million) with downward sloping export demand of BBRKC that shifts.

Scenario \ Household type	Low income household	Medium income household	High income household	All households
Scenario 2	69.8	511.5	636.5	1217.8
Scenario 3	32.5	229.0	281.6	543.1

of \$1,217.8 million), in Scenario 2. Welfare losses in Scenario 3 are much smaller, as expected, than those from Scenario 2; the aggregate household welfare loss in Scenario 3 is \$543.1 million.

Figure 5 shows resource rents with exogenous shifts of the export demand curve. In Fig. 5, resource rents in Scenario 1 increase at a relatively constant rate because ex-vessel prices of BBRKC go up over time, which is caused by the exogenous increase in the world price of the processed BBRKC, while BBRKC yields stay relatively stable over time. The resource rent in Scenario 2 decreases in a rather monotonic way. That is, the effects of decrease in BBRKC yields on the resource rent outweigh the effects of the increase in the BBRKC price. In Scenario 3, where the reductions in BBRKC yields are much smaller than in Scenario 2, however, the resource rent increases up to a point (year 2050), and decreases after that point. This critical point occurs because the effects of an increase in the BBRKC price on the resource rent are stronger than those of reductions in the yields before 2053, while the opposite is true after.

Figure 6 shows the change in QSLR calculated with the effects of exogenous shift of the downward sloping demand for BBRKC. It is seen from Fig. 6 that the QSLRs in all scenarios are increasing over most of the simulation periods. The steady increase in QSLRs in Scenario 1, where the quantity of BBRKC is stable, is caused by the exogenous price increases due to shifts in the export demand curve.

Figure 5. Resource rent (with downward sloping export demand of BBRKC which shifts up every year to reflect world demand increase)

Figure 6. QSLR (with downward sloping export demand of BBRKC which shifts up every year to reflect world demand increase)

8. Conclusion

We used yield projections from a bioeconomic model with effects of OA on the survival of juvenile crab in a CGE model for the state of Alaska to compute regional economic impacts of falling yields under OA. We used a yield projection without effects of OA as a baseline (Scenario 1), a yield projection based on a linear relationship (Scenario 2), and a nonlinear (i.e., power law) relationship (Scenario 3) between survival of juvenile crab and pH.

As expected, compared with Scenario 2, Scenario 3 produces significantly smaller impacts on output and employment over the next few decades, which is the most likely case according to [Punt et al. \(2014\)](#), though yields collapse in both scenarios by 2100. The reductions in the value of output of BBRKC harvesting and processing industries are much smaller than the reductions in the quantity, because of the endogenous increase in the price of the BBRKC along the downward sloping demand curve. This price increase partially offsets the loss of fishery income for BBRKC from falling yields under OA.

Because of its regional income effects, the world price for king crab is an important variable in our welfare analysis of OA effects. We considered two types of changes in this world price. The first type was endogenous changes from movement along a downward sloping world export demand curve associated with falling yields for BBRKC under OA. The second type was exogenous growth in world prices of king crab, represented by exogenous shifts of a downward sloping export demand curve. Alternatively, we assumed that export demand for BBRKC is perfectly elastic. Welfare losses from OA are found out to be larger with exogenous growth in the world price for king crab caused by an exogenous shift-up of the demand than without the exogenous growth whether or not the demand is infinitely elastic. This result suggests that

economic and welfare effects of OA depend not only on the magnitude of OA-induced changes in yields (i.e., supply) but also on the elasticity of world demand, and changes in world demand for BBRKC.

Sensitivity to OA varies substantially across species (e.g., [Ries et al., 2009](#)). Our original research plan was based on single-species assessments for the Bering Sea ([Sigler et al., 2008](#)). Red king crab was among the first species considered because of its commercial importance, and based on biology, it was hypothesized to be among the most vulnerable species to effects of OA. In comparison, related research on walleye pollock, which supports the largest fishery in the Bering Sea, showed no significant effects of OA ([Hurst et al., 2013](#)). If significant effects for other commercially important species in the Bering Sea are found, an immediate extension of this study is to use methods similar to those used in the present study to calculate the economic effects of OA-induced changes in yields of other commercially important species. In particular, an assessment of economic impacts of OA on the Eastern Bering Sea snow crab fishery is warranted. This fishery generated \$270 million in 2012, compared to \$76 million for the BBRKC fishery, and a total for all BSAI crab fisheries of \$387 million ([Garber-Yonts and Lee, 2013](#)). In addition, the snow crab fishery is responsible for bycatch in the Tanner crab fishery which is also vulnerable to effects of OA. Currently, future yield projections with OA effects on these species are being made. When these projections are complete, we will investigate the economic effects of the OA-induced changes in yields of these species.

Some caveats are in order. First, we calculated the economic impacts assuming that the OA affects only BBRKC. However, in reality, OA will perturb the whole BSAI marine ecosystem. This may result in the changes in the yields of various different species, not just BBRKC. However, since there is no previous study yet that provides how the yields of different species will change due to OA, the present study limited the analysis to BBRKC. There are some studies that examine the fishery ecosystem-wide impacts of changes in fish harvesting. For example, [Finnoff and Tschirhart \(2008\)](#) uses multi-species ecological model, called General Equilibrium Ecosystem Model (GEEM), to track the changes in the species in response to changes in fish harvesting, embedded in a CGE framework. However, the study uses a highly simplified multi-species food web as a simple ecosystem model based on myopic expectations. Although the study is novel, it is inapplicable to our system for two fundamental reasons. First, their CGE-GEEM model lacks age/stage structured population dynamics which is the most important detail of our system. Second, our bioeconomic model is based on rational expectations (i.e., forward-looking behavior), which is generally accepted over myopic expectations in economic models. In particular, we are unwilling to accept myopic expectations in our bioeconomic model.

Second, we used relatively simple dynamics in the CGE model with myopic expectations of the future events whereas the bioeconomic model is based on an industry (i.e., partial) equilibrium under rational expectations. Typically, industries in CGE models exhibit constant returns to scale production functions, are competitive,

and maximize profits or minimize costs. With these assumptions, industry decisions are static and dynamic optimization is not necessary which is convenient for computing a general equilibrium. However, fishing sectors that are represented by bio-economic models exhibit externalities based on stock dynamics, which involve dynamic optimization. A future study will use a fully dynamic CGE model where the future expectations are explicitly considered in current period decision making by economic agents.

Third, the CGE model used in this study is for a single region, Alaska. However, the Alaska red king crab fishery, as other Alaska fisheries, has strong economic ties with other states (especially the state of Washington). Many vessel owners and crew members in the BBRKC crab fishery do not live in Alaska, and therefore, much of their income leaks out of Alaska. This means that our single-region CGE model does not capture much of the impacts from OA that occur in the non-Alaska states. A future study will develop a multi-regional CGE model to capture these interregional effects.

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Appendix A. Population Dynamics and MSY

Computing dynamic MEY subject to MSY requires numerical values for all the parameters of the bioeconomic model in the dynamic optimization above and a numerical value for MSY. The biological parameters for recruitment and population dynamics are the most important for analyzing effects of OA on MSY. To derive equilibrium yield curves, we begin with an alternative, but equivalent, formulation of population dynamics from the one above. The alternative form identifies the structural biological parameters in population dynamics which are represented in a reduced-form in the dynamic optimization above. The population dynamics model on which the dynamic optimization is based is male-only because only males may be landed and the biological status of the population is based on MMB at the time of mating. The simplified model is reduced to five size-classes and does not divide the population by shell condition. Previous analyses have shown that the estimates of abundance and trends in males is robust to this simplification.

Let $\mathbf{G}$ denote a lower triangular growth matrix, and $\mathbf{S}(F^D)$ is a survival matrix that is a function of the fishing mortality rate in the directed fishery $F^D \geq 0$. The basic dynamics are

$$N_{t+1} = \mathbf{GS}(F^D)N_t + R_{t+1}. \quad (\text{A.1})$$

The main diagonal of the growth matrix is defined by a vector of rates that represent the fractions of surviving crab that do not grow to the next size-class in the following time-period:

$$G = (0.0000345257, 0.401269, 0.220713, 0.310889, 1)'$$

Then, the rate $1 - G_i$ is the fraction of surviving crab that grow from size-class i to size-class $i + 1$, and explicitly, the growth matrix is

$$\mathbf{G} = \begin{bmatrix} G_1 & 0 & 0 & 0 & 0 \\ 1 - G_1 & G_2 & 0 & 0 & 0 \\ 0 & 1 - G_2 & G_3 & 0 & 0 \\ 0 & 0 & 1 - G_3 & G_4 & 0 \\ 0 & 0 & 0 & 1 - G_4 & G_5 \end{bmatrix}.$$

The matrix $\mathbf{S}(F^D)$ is diagonal with entries

$$S_{i,i} = e^{-m}(1 - Q_i^T F^T)(1 - Q_i^D F^D), \quad (\text{A.2})$$

where m is the instantaneous rate of natural mortality, which is estimated to be 0.18 per year. In addition, Q_i^D is selectivity for the directed fishery for size-class i , and F^D is the exploitation rate, in the directed fishery. Finally, Q_i^T is selectivity for the groundfish trawl fishery for size-class i , and $F^T = 0.00444298$ is the exploitation rate, due to bycatch in the groundfish trawl fishery.

The estimated selectivity vectors for the directed fishery, and for bycatch in the groundfish trawl fishery, respectively, are

$$Q^D = (0, 0.0610595, 0.278191, 0.886012, 1)' \quad \text{and} \\ Q^T = (0.0406715, 0.0636642, 0.280257, 0.8216, 1)'.$$

Let U_i denote the product of the proportion mature-at-length and the weight-at-length for animals in size-class i which form the fecundity vector to calculate spawners-per-recruit (SPR)

$$U = (0, 0, 0.352814, 1.94595, 3.04285)'.$$

Let V_i denote the proportion of the catch of animals in size-class i that are retained which form the retained-catch vector to calculate yield-per-recruit (YPR)

$$V = (0.36075, 0.00000334292, 0.0030868, 0.376191, 0.720584)'.$$

Let W_i denote the average weight of an animal in size-class i , which form the weight-at-size vector to calculate YPR

$$W = (0.326549, 0.648298, 1.17945, 1.94595, 3.04285)'.$$

In addition, we define a unit vector $\mathbf{u} = (1, 0, 0, 0, 0)'$ and let $\mathbf{I}$ denote the identity matrix.

From Eq. (A.1), the steady state equilibrium population vector, in numbers of crab, for unit recruitment with fishing mortality rate F in the directed fishery is defined by a function

$$n(F) = (\mathbf{I} - \mathbf{GS}(F))^{-1} \mathbf{u}.$$

Under the assumption that spawning occurs after the directed fishery, SPR for a population dynamics equilibrium depends on the fecundity vector U , the selectivity vector for the directed fishery Q^D , and is defined such that

$$\text{SPR}(F) = e^{-m(\frac{1}{2} + \frac{2}{12})} \sum_{i=1}^5 n_i(F)(1 - FQ_i^D) U_i \iff \text{SPR}(F) = e^{-m(\frac{1}{2} + \frac{2}{12})} U'(\mathbf{I} - F\mathbf{Q}^D)n(F). \quad (\text{A.3})$$

The fraction $2/12$ in the SPR mortality term is based on an assumption that spawning occurs in February of each year and the year starts on 1 July. In addition, the equilibrium YPR variable is defined using the retained-catch vector V , its diagonal matrix version $\mathbf{V}$, and the weight-at-size vector W , by

$$\text{YPR}(F) = e^{-\frac{m}{2}} \sum_{i=1}^5 n_i(F)F Q_i^D V_i W_i \iff \text{YPR}(F) = e^{-\frac{m}{2}} W' \mathbf{V} \mathbf{Q}^D n(F)F.$$

From these relationships, both SPR and YPR are functions of the fishing mortality rate F . By definition, equilibrium yield is the product of YPR times recruitment, and recruitment itself is a function of SPR. Therefore, the equilibrium yield curve is also a function of F .

The MSY proxy used for management is established at $F_{35\%}$ (from Amendment 24 to the Fishery Management Plan for BSAI King and Tanner Crabs) which solves

$$\frac{\text{SPR}(F)}{\text{SPR}(0)} = 0.35.$$

In particular, $F_{35\%}$ does not depend on the form of the spawner–recruit function, and for consistency, should be the same whichever functional form is assumed (e.g., BH, Ricker).

To derive yield curves, let $q = rs$ denote the spawning stock biomass, which is the product of a recruitment variable, r , and a SPR variable, s . A (nonlinear) BH spawner–recruit curve with parameters c and d is $r = cq/(1 + dq)$. These parameters are defined in terms of a steepness parameter $\sigma = 0.759856$ which in the absence of OA arises from the assumption that MSY occurs at a F_{MSY} proxy of 0.35, and is the expected fraction of unfished recruitment ($r_0 = 16136.4$ [thousands]) when spawning stock biomass is 20% of its unfished level, and initial values at the unfished equilibrium for SPR, $s_0 = 7.60785$. Parameters in the BH function are $c = 4\sigma/((1 - \sigma)s_0)$,

$d = (5\sigma - 1)/((1 - \sigma)r_0s_0)$, and then,

$$r = \frac{cq}{1 + dq} \Rightarrow r = \frac{c}{d} - \frac{1}{ds} \Rightarrow r = \left(\frac{4\sigma r_0}{5\sigma - 1} \right) - \left(\frac{(1 - \sigma)r_0s_0}{5\sigma - 1} \right) \frac{1}{s}. \quad (\text{A.4})$$

From Eq. (A.4), recruitment is a function of SPR, which itself is a function of fishing, mortality, and that closes the population dynamics model and leads to the yield curve

$$y_{\text{BH}}(F) = \text{YPR}(F) \times r_{\text{BH}}(\text{SPR}(F)).$$

However, the nonlinear BH function is incompatible with the linear-quadratic structure of the bioeconomic model. Instead, we formulated an ASR function and calibrated it to numbers from the BH version at the MSY proxy. This function is specified with parameters a and b such that $r = aq + b$ with equilibrium recruitment of

$$r = a(rs) + b \Rightarrow r = \frac{b}{1 - as}. \quad (\text{A.5})$$

From Eq. (A.5), the yield curve associated with an ASR function is

$$y_{\text{ASR}}(F) = \text{YPR}(F) \times r_{\text{ASR}}(\text{SPR}(F)).$$

Figures A.1 and A.2 show results for the calibrated ASR function. This calibration procedure solved for numerical values of parameters in Eq. (A.5),

$$a = 0.0794922 \quad \text{and} \quad b = 10694.2. \quad (\text{A.6})$$

An ASR function with numerical values in Eq. (A.6) satisfies two conditions. First, $F_{35\%}$ maximizes $y_{\text{LINE}}(F)$, and second, $y_{\text{LINE}}(F_{35\%}) = y_{\text{BH}}(F_{35\%})$. The second condition is associated with initial recruitment $r_0 = 20452.9$ (thousands) for an ASR function to satisfy $b = r_0(1 - as_0)$ with numerical values in Eq. (A.6).

Equations (A.1) and (A.2) relate directly to population dynamics and recruitment in the constraint set of the dynamic optimization presented above. From Eq. (A.2), let M

Figure A.1. MMB relative to that in an unfished state, and the yield curve, versus fishing mortality rate (F) under the assumption of a BH spawner–recruit function. The MSY proxy is 5490 metric tons and $F_{35\%} = 0.214193$

Figure A.2. Yield curve, and recruitment, versus MMB with an ASR function calibrated to BH at the MSY proxy

denote a diagonal matrix with entries

$$M_{i,i} = e^{-m}(1 - Q_i^T F^T).$$

Thus, $\mathbf{h}_1 = \mathbf{GM}$ and $\mathbf{h}_2 = -\mathbf{GM}$ for population dynamics in the constraint set for dynamic optimization. Let $\mathbf{U}$ denote the fecundity matrix with first row entries taken from the fecundity vector U and zeros elsewhere. The definition in Eq. (A.3) implies recruitment takes the form

$$R_t = ae^{-m(\frac{1}{2} + \frac{2}{12})} \mathbf{U}(\mathbf{I} - F\mathbf{Q}^D)N_{t-k} + b\mathbf{u} \iff R_t = ae^{-m(\frac{1}{2} + \frac{2}{12})} \mathbf{U}(N_{t-k} - Y_{t-k}) + b\mathbf{u}.$$

Therefore, $\mathbf{H}_0 = ae^{-m(\frac{1}{2} + \frac{2}{12})} \mathbf{U}$ and $\mathbf{h}_0 = b\mathbf{u}$ for recruitment, with numerical values from Eq. (A.6), in the dynamic optimization presented above.

Appendix B. Sensitivity Analysis for World Demand for BBRKC

We conducted sensitivity analysis to examine how sensitive the CGE results are to different assumptions about the world demand for BBRKC. First, we calculated the economic impacts when the downward sloping demand curve does not shift in our CGE model. Results are shown in Tables B.1 and B.2 and Figs. B.1 and B.2 below. Second, we also developed two additional CGE model versions. In the first of these additional versions, world demand for king crab is assumed to be perfectly elastic and does not change over time. Consequently, the world price for king crab does not respond to falling yields from OA, for example, which is an extreme assumption. In the second version, we assume that this perfectly elastic demand curve shifts up exogenously every year to simulate an exogenous growth of the world price of BBRKC. The results from these additional model versions are reported in Table B.2 where the welfare changes from different model versions are compared.

With the downward sloping export demand curve not shifting during the simulation period, the total regional output decreases by about 0.3% owing to OA in Scenario 2 (Table B.1). The decrease in the “value” of output is again much smaller. In

Table B.1. Impacts of OA on output and employment over a 90-year period: with downward sloping export demand of BBRKC.

Industry/Sector	Quantity of output ^a		Value of output ^b		Employment
	Without OA	% Change	Without OA	% Change	% Change
Scenario 2					
BBRKC harvesting	7853.0	−60.90	2572.9	−28.21	−60.97
Other fish harvesting	103,054.7	0.00	32477.2	0.06	−0.38
BBRKC processing	17,530.9	−60.22	5905.1	−33.17	−60.23
Other seafood processing	233,524.1	0.03	77,989.9	0.02	−0.09
All nonseafood industries	6,822,274.2	−0.10	1,828,978.7	−0.08	−0.11
Total (all industries)	7,184,236.9	−0.30	1,947,923.7	−0.21	−0.23
Scenario 3					
BBRKC harvesting	7853.0	−30.46	2572.9	−8.41	−30.60
Other fish harvesting	103,054.7	0.00	32,477.2	0.03	−0.38
BBRKC processing	17,530.9	−29.98	5905.1	−10.29	−30.00
Other seafood processing	233,524.1	0.07	77,989.9	0.02	−0.04
All nonseafood industries	6,822,274.2	−0.03	1,828,978.7	−0.02	−0.03
Total (all industries)	7,184,236.9	−0.14	1,947,923.7	−0.06	−0.10

^aThe unit of output is calibrated such that one unit of output is sold at \$1 million in the base year.

^bThe value of output is in present discounted value.

Table B.2. Present discounted value of welfare loss (\$ million) with alternative assumptions about demand for BBRKC.

Scenario \ Household type	Low income household	Medium income household	High income household	All households
With downward sloping export demand of BBRKC that does not shift				
Scenario 2	57.5	423.0	529.0	1009.5
Scenario 3	25.6	180.8	224.7	431.1
With perfectly elastic export demand of BBRKC				
<i>No exogenous shift of demand curve</i>				
Scenario 2	66.4	482.6	629.1	1178.1
Scenario 3	32.9	230.2	307.6	570.7
<i>Demand curve shifts up to reflect increase in world demand increase</i>				
Scenario 2	118.5	873.7	1112.0	2104.2
Scenario 3	63.9	465.3	591.9	1121.1

Scenario 3, the total regional output decreases by about 0.1%. Results in Table B.1 show that economic impacts of OA in both Scenarios 2 and 3 with no exogenous shifts of the BBRKC export demand curve are close in percentage terms to those obtained in the case where there is shift in the demand curve (Table 2), except for the percentage changes in the value of output in the two scenarios.

Figure B.1. Resource rent (with downward sloping export demand of BBRKC)

However, results for welfare changes from economic impacts of OA without exogenous growth in world demand for BBRKC are different as shown in Tables 3 and B.2. The welfare results obtained with no shift of the BBRKC demand curve (Table B.2) contrast with the welfare results obtained with exogenous shifts of the BBRKC export demand curve both in the continuous benchmark and in the continuous counterfactual paths (Table 3). When we do not allow the demand curve to shift up, the values of output (and therefore, fishery income) for the BBRKC industries and the value of the total regional output decrease by smaller amounts and percentages (Table B.1) than when the demand curve shifts shift (Table 2). Therefore, the welfare losses from OA with no shift in the BBRKC export demand curve are smaller than those calculated with exogenous shifts in the demand curve.

We also calculated the welfare changes assuming that the export demand for BBRKC is perfectly elastic. The implicit assumption is that Alaska's production of BBRKC does not have enough market power in the world red king crab market to influence the world price of the product (small country assumption). Results in

Figure B.2. QSLR (with downward sloping export demand of BBRKC)

Table B.2 show that welfare losses with perfectly elastic export demand for BBRKC (bottom two panes in Table B.2) are larger than those with downward sloping demand curve (Table 3 and top pane in Table B.2) whether or not the demand curve shifts up or not.

Figure B.1 shows resource rents for the BBRKC harvesting industry calculated with a downward sloping export demand curve for BBRKC which does not shift. With the demand for BBRKC not shifting, the resource rent curves for the three scenarios in Fig. B.1 look quite different from those in Fig. 5. In Fig. B.1, resource rents appear stable in Scenario 1 because yields are stable over time in that scenario. Resource rents decrease faster in Scenario 2 than in Scenario 3, primarily because yields in Scenario 2 decrease faster than in Scenario 3. Figure B.1 indicates that in Scenarios 2 and 3, the effects on resource rent of the price change (i.e., the endogenous increase in the ex-vessel price of BBRKC along the downward sloping export demand curve caused by reductions in harvests of the fish) are not as strong in most periods as the effects of the quantity change (i.e., reductions in the harvests), leading to the result that the resource rent decreases after a point (year 2010 in Scenario 2 and year 2020 in Scenario 3) on the time path for each of the two scenarios.

Figure B.2 shows the change in QSLR calculated without the effects of exogenous shift of the downward sloping demand for BBRKC. Figure B.2 indicates that the QSLR in Scenario 1 is relatively stable because of stable levels of BBRKC yields. In Scenarios 2 and 3, however, the effects of the endogenous increase in the world price of BBRKC from reduced harvests are stronger than those of the quantity reductions, increasing QSLRs over the simulation periods. The QSLRs in Scenarios 2 and 3 without the effects of the exogenous shift of the demand curve (Fig. B.2) increase less steeply than when the effects of the demand shift are considered (Fig. 6) because the price effects without the demand shift are much weaker than those with the shift.

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