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SOCIO-ECONOMIC CAUSES AND CONSEQUENCES OF FUTURE ENVIRONMENTAL CHANGES WORKSHOP

A WORKSHOP SPONSORED BY THE U.S. ENVIRONMENTAL PROTECTION AGENCY'S NATIONAL CENTER FOR ENVIRONMENTAL ECONOMICS (NCEE), NATIONAL CENTER FOR ENVIRONMENTAL RESEARCH (NCER)

November 16, 2005

EPA Region 9 Building

75 Hawthorne Street 1st Floor Conference Room San Francisco, CA

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ACKNOWLEDGEMENTS

This report has been prepared by Alpha-Gamma Technologies, Inc. with funding from the National Center for Environmental Economics (NCEE). Alpha-Gamma wishes to thank NCEE's Cynthia Morgan and Jennifer Bowen and the Project Officer, Cheryl R. Brown, for their guidance and assistance throughout this project.

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U.S. Environmental Protection Agency
Socio-Economic Causes and Consequences of Future Environmental Changes Workshop

November 16, 2005
EPA Region 9
75 Hawthorne Street
1St Floor Conference Room
San Francisco, CA

8:45-9:15	**Registration**	
9:15 -9:30	**Introductory Remarks – Tom Huetteman, Deputy Assistant Regional Administrator, USEPA Pacific Southwest Region 9**	
9:30-11:30	**Session I:**	**Trends in Housing, Land Use, and Land Cover Change** Session Moderator: Jan Baxter, US EPA, Region 9, Senior Science Policy Advisor
	9:30 – 10:00	Determinants of Land Use Conversion on the Southern Cumberland Plateau **Robert Gottfried (presenter)**, Jonathan Evans, David Haskell, and Douglass Williams, University of the South
	10:00– 10:30	Integrating Economic and Physical Data to Forecast Land Use Change and Environmental Consequences for California's Coastal Watersheds Kathleen Lohse, David Newburn, and **Adina Merenlender (presenter)**, University of California at Berkeley
	10:30 – 10:45	**Break**
	10:45 – 11:00	Discussant: Steve Newbold, US EPA, National Center for Environmental Economics
	11:00 – 11:15	Discussant: Heidi Albers, Oregon State University
	11:15 – 11:30	Questions and Discussions
11:30 – 12:30	**Lunch**	
12:30 –2:30	**Session II:**	**The Economic and Demographic Drivers of Aquaculture and Greenhouse Gas Emissions Growth** Session Moderator: Bobbye Smith, U.S. EPA Region 9
	12:30 – 1:00	Future Growth of the U.S. Aquaculture Industry and Associated Environmental Quality Issues **Di Jin (presenter)**, Porter Hoagland, and Hauke Kite Powell, Woods Hole Oceanographic Institution

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	1:00 – 1:30	Households, Consumption, and Energy Use: The Role of Demographic Change in Future U.S. Greenhouse Gas Emissions Brian O'Neill, Brown University, **Michael Dalton (presenter)**, California State University – Monterey Bay, John Pitkin, Alexia Prskawetz, Max Planck Institute for Demographic Research
	1:30 – 1:45	Discussant: Tim Eichenberg, The Ocean Conservancy
	1:45 – 2:00	Discussant: Charles Kolstad, University of California at Santa Barbara
	2:00 – 2:30	Questions and Discussion
2:30 – 2:45	**Break**	
2:45 - 4:55	**Session III:**	**New Research: Land Use, Transportation, and Air Quality** Session Moderator: Kathleen Dadey, US EPA, Region 9, Co-chair of the Regional Science Council
	2:45 - 3:10	Transforming Office Parks Into Transit Villages: Pleasanton's Hacienda Business Park **Steve Raney (presenter)**, Cities21
	3:10 – 3:35	Methodology for Assessing the Effects of Technological and Economic Changes on the Location, Timing and Ambient Air Quality Impacts of Power Sector Emissions Joseph Ellis and **Benjamin Hobbs (presenter)**, Johns Hopkins University, Dallas Burtaw and Karen Palmer, Resources for the Future
	3:35 - 4:00	Integrating Land Use, Transportation and Air Quality Modeling **Paul Waddell (presenter)**, University of Washington
	4:00- 4:25	Regional Development, Population Trend, and Technology Change Impacts on Future Air Pollution Emissions in the San Joaquin Valley Michael Kleeman, Deb Niemeier, **Susan Handy (presenter)**, Jay Lund, Song Bai, Sangho Choo, Julie Ogilvie, Shengyi Gao, University of California at Davis
	4:25 – 4:55	Questions and Discussion
4:55 – 5:00	**Wrap-Up and Closing Comments**	

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[DRAFT]

Future Growth of the U.S. Aquaculture Industry and Associated Environmental Quality Issues*

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October 26 2005

* Prepared for the US Environmental Protection Agency Workshop on Socio-Economic Causes and Consequences of Future Environmental Changes, San Francisco, CA, November 16, 2005.

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Acknowledgements: We would like to thank Eric Thunberg for providing helpful insights and suggestions and for supplying projections of groundfish landings in New England. This study has been supported by the US Environmental Protection Agency STAR Grant Program (Agreement Number: R82980401) and the Marine Policy Center of the Woods Hole Oceanographic Institution. The results and conclusions of this paper do not necessarily represent the views of the funding agencies. The usual disclaimers apply.

Abstract

Aquaculture is an important and growing source of the supply of protein from seafood. The potential expansion of the aquaculture industry into marine environments has become a subject of concern to other ocean users, conservationists, and pollution regulators. In forecasting the future expansion of aquaculture in coastal-ocean environments, most studies focus only on the constraint posed by the local environmental assimilative capacity. We develop an alternative market-oriented approach for projecting the growth of the industry. We evaluate equilibria in the market for seafood, where the product may be supplied either by a wild-harvest fishery or open-ocean aquaculture or both. In our framework, the net demand for farmed fish determines the size of the aquaculture industry and, in turn, the levels of pollution discharges. Analogous to studies of assimilative capacity, the socially optimal industry size may be constrained by environmental damages resulting from pollution. In open-ocean environments where the assimilative capacity is unlikely to be a serious constraint, however, the market-oriented approach is a much better method for projecting industry growth. We illustrate our approach with a case study of a groundfish fishery and the proposed open-ocean aquaculture of Atlantic cod in New England. We find that, for a range of competitive production costs for aquaculture, the optimal industry structure would comprise both a wild-harvest fishery and aquaculture. For example, with a rebuilt groundfish stock yielding 156 thousand mt annually, the optimal marine aquaculture industry would comprise 11 farms producing 23 thousand mt of cod each year. The aquaculture industry would be smaller if the industry is held to account for any damages to the environment through a pollution tax. Alternatively, the industry would be larger if effective pollution control measures can be implemented or if there is a significant expansion in the demand for seafood.

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1. Introduction

The production of seafood by aquaculture is growing rapidly in many parts of the world. According to the United Nations Food and Agriculture Organization, one-quarter of the world's total seafood production of 130 million mt per year is now produced by aquaculture. Of world total aquaculture production, the marine aquaculture industry produces 15 million mt. Although the lion's share of this production occurs in other countries, especially in China and southeast Asia, many observers suggest that aquaculture has the potential to grow significantly in US marine waters. Here, we analyze the potential for the future expansion of open-ocean aquaculture in the United States, and we consider how this potential might be constrained by pollution.

A marine aquaculture industry is unlikely to realize its full potential in the United States if operators ignore several types of external effects. First, aquaculture facilities, such as netpens for growing finfish, are sources of macronutrients (nitrogen [N] and phosphorus [P]) and sediment loads. Feces and unused food diminish water quality, increasing biochemical oxygen demand and enhancing the potential for eutrophication (Folke, Kautsky, and Troell; Smearman, D'Souza, and Norton). Second, the application of therapeutants and pesticides can lead to chemical pollution. Third, in some circumstances, fish diseases can be introduced or spread more readily by aquaculture into healthy environments (Folke and Kautsky; Brennan). Finally, the farming of carnivorous species requires large inputs of forage fish for feed, potentially stressing ecosystems with which the forage fish are associated (Naylor *et al*.).[1] The destruction of mangrove forests and coastal wetlands for pond farming is another problem associated with the expansion

[1] This type of impact is a consequence of the over-exploitation of the fisheries for forage fish.

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of aquaculture in coastal areas (Barbier and Cox). Table 1 summarizes key economic and ecological effects associated with marine aquaculture development. A preliminary qualitative assessment of environmental effects is presented in Figure 1.

Whether the culturing of fish causes marine pollution depends to a large extent on the assimilative capacity of the receiving environment. A water body's assimilative capacity is a function of its physical, chemical, and biological characteristics (Silvert; Brennan). Estimates of assimilative capacity using specialized water quality assessment models are the most common way to project limits to the future expansion of marine aquaculture (Gillibrand and Turrell). Typically, a water quality assessment model simulates both water flows and waste transport. Waste transport is influenced by water depth, current velocity, and the settling velocity of waste particles. For a specific pollutant, such as nitrogen (N), the model starts with the total quantity of N in feed and calculates the shares of N consumed by fish, dissolved in water, settled in the sediments, and flushed out of the system. The difference in water quality with aquaculture and without it can then be used to estimate the maximum acceptable N loading from aquaculture expansion. Finally, the maximum loading then is used to calculate the maximum "allowable" aquaculture production level (Midlen and Redding).

As an example of the water quality assessment approach, Norway has implemented a nationwide assessment of the suitability of its coastal zones and rivers for aquaculture (Ibrekk, Kryvi, and Elvestad). This assessment involves a determination of the maximum acceptable organic loading for each water body.[2] In this way, the residual capacity of a water body to handle aquaculture development can be evaluated. Under the

[2] Maximum organic loading is estimated by subtracting the existing organic loads and nutrients from an estimate of the natural capacity of the area to tolerate these inputs.

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Norwegian assessment, nine percent of Norway's coastal areas have been found suitable for aquaculture. The full utilization of these areas for aquaculture would result in an annual production of 600,000 mt of salmon and trout.

In the case of open-ocean aquaculture, however, the water quality assessment approach is inappropriate for anticipating aquaculture development, because effluents disperse quickly. Further, changes in nutrient levels are difficult to gauge in an open-ocean environment. In this article, we develop a market-oriented approach for projecting the growth of an aquaculture industry in the open ocean. We evaluate equilibria in the market for seafood, where the product may be supplied either by a wild-harvest fishery or open-ocean aquaculture or both. In our framework, the net demand for farmed fish determines the size of the aquaculture industry and, in turn, the level of pollution discharges. Analogous to studies of environmental assimilative capacity, the socially optimal industry size may be constrained by environmental damages resulting from pollution. In open-ocean environments, where the assimilative capacity is unlikely to be a serious constraint, however, the market-oriented approach is a superior method for projecting industry growth. We illustrate our approach with a case study of a groundfish fishery and the proposed open-ocean aquaculture of Atlantic cod in New England.

The remainder of this article is organized as follows. Section 2 presents a review of the literature concerning pollution control and the measurement of environmental costs in marine aquaculture. Section 3 describes our analytical framework and the data used for simulations. Section 4 summarizes the results of a set of simulations. Section 5 presents some conclusions.

2. Literature Review

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2.1. Marine Aquaculture and Pollution Control

Nutrient pollution (*e.g.*, excessive levels of N and P) in aquatic and marine ecosystems has been the focus of many recent studies (Beveridge; Smearman, D'Souza, and Norton; Midlen and Redding). Folke, Kautsky, and Troell conclude that salmon farming, as undertaken in Swedish coastal waters in the early 1990s, is not only ecologically but also economically unsustainable. Although there are a number of environmental impacts contributing to external costs, nutrient releases and their causal relationships to eutrophication and toxic algal blooms lead to the most significant impacts. The authors calculate that nutrient releases from a fish farm producing 100 mt of salmon each year correspond to those of a human settlement of 850-3,200 persons.

Normally, in the absence of regulation, we expect firms to disregard environmental costs. In some cases, such as netpen operations for salmon, discharges from aquaculture production facilities can be monitored and measured. Effluents from these facilities could then be regulated as point sources. One approach is to charge fish farmers a tax equal to the marginal external costs imposed by their farms on the environment at the socially optimal externality level (Smearman, D'Souza, and Norton). For example, Sylvia, Anderson, and Cai develop a procedure for calculating the optimal tax on effluent discharges from salmon netpen operations.

Waste discharges from other types of aquaculture operations, such as large-scale coastal shrimp ponds, cannot be measured so easily. Consequently, the regulation of these operations as point sources generally is not feasible. Mathis and Baker argue that in the face of uncertainty about effluent releases, the power of traditional economic instruments such as taxes and tradable permit systems to internalize environmental costs

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is greatly reduced. Broadly speaking, because of the complexity of production processes and pollutant releases, combinations of market-based and command-and-control instruments may be required (Stanley). Studies by GESAMP and by Brennan describe the key factors affecting environmental management in aquaculture, highlighting a range of potentially useful policy instruments, such as pollution standards, taxes, legal liability measures, and best management practices (BMPs).

Stanley suggests that wastewater discharges from coastal shrimp farms are non-point source pollution, because the wastewater may be released at irregular times and levels from large numbers of farms covering large geographic areas. The nature of non-point pollution implies that the direct regulation of aquaculture operations is not feasible. The shrimp farming industry apparently favors the implementation of BMPs, which would involve the adoption of voluntary pollution controls that are not easily observed or enforced.

Brennan provides an overview of pollution control options currently practiced in the marine aquaculture industry. First, pollution may be managed through siting decisions that involve a review of the current levels of nutrient loadings at a specific location. Typically, densely populated areas may be eutrophic already, implying that only more remote locations would be available for aquaculture. Second, depending upon the conditions at a particular location, nutrient controls may involve restrictions on the total number and size of individual farms, as well as limits on stocking densities.[3] Further, various technologies may be used to improve the efficiency by which cultured fish convert feed into biomass (*i.e.*, to lower the feed conversion ratio [FCR]), thereby

[3] Reducing stocking densities can lead to other benefits, such as reduced risks of disease and increased harvest sizes.

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reducing the quantity of unused food in the aquaculture operation. The U.S. Environmental Protection Agency recently has proposed regulations to monitor feed rates and to reduce feed inputs (USEPA). Lastly, different biocontrol techniques have been considered. For example, Neori *et al*. report that seaweed can be effective as a biofilter in an integrated fish-seaweed culture operation. Similarly, Folke and Kautsky propose a method for the polyculture of seaweeds, mussels, and salmon.

The effectiveness of technology-based pollution control measures in Norwegian salmon aquaculture has been examined by Asche, Guttormsen, and Tveteras and by Tveteras independently. Data from Norway between 1980 and 2000 exhibited a declining trend in FCR[4] and in the applications of antibiotics and chemicals,[5] even as production was expanding. Because feed often is the most costly input, constituting around 50 percent of production costs, gains in feed efficiency lead to both increased productivity and reduced effluents. Tveteras argues that industry growth can be achieved together with pollution reductions by encouraging technological innovations in industry-specific, pollution-reducing inputs. In the case of the salmon aquaculture industry, growth in supply has been associated with reduced environmental problems in both relative and absolute senses.

2.2. Measurement of Environmental Cost

The worldwide expansion of aquaculture production has been matched by growing concerns about its environmental impacts. Public pressure is mounting now for the aquaculture industry to account for its use of public resources and to demonstrate its

[4] The FCR has declined for salmon from nearly 3:1 in 1980 to just over 1:1 in 2000. In laboratory experiments, it has been possible to achieve FCRs as low as 0.6:1.

[5] Vaccines have been found to reduce substantially the incidence of fish diseases. Antibiotic applications can be minimized through a shift from curative to preventative disease treatment.

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environmental sustainability (Muir *et al*.). Economic assessments of social and environmental costs and benefits might provide different and possibly more critical guidance for aquaculture development. Typically, total external costs are calculated as the sum of costs arising from specific externalities, such as impacts on water quality, local fisheries, and neighboring mariculture operations (Brennan; Stanley). Existing studies of the economic benefits of water quality improvements may provide insights for aquaculture management (Freeman 1979, 1995; Lyon and Farrow). The interactions between aquaculture and commercial fisheries in the market have been examined by Anderson (1985a, 1985b), who considers the implications for fishery management and for ocean ranching of salmonids. Hoagland, Jin, and Kite-Powell examine interactions between aquaculture and fisheries in both the seafood market and in the allocation of ocean areas.

It can be difficult to construct an accurate cost measure of environmental damages from pollution discharges, because marine resources provide a variety of tangible and intangible goods and services to the public. Although most economists would argue that marine resources generate both use and non-use values, there is little consensus among specialists about which damage assessment methodologies are appropriate in any given situation (*viz.*, Kahneman and Knetsch; Smith; Arrow *et al*.). Muir *et al*. review the relevant issues and propose ways in which valuation techniques may be applied more effectively in strategic and local decision-making for aquaculture development. For example, in the case of salmon farming in Scottish sea lochs, these authors suggest that contingent valuation ought to be used to value an environmental amenity (e.g., the habitat characteristics of the loch), the travel cost approach ought to be used to capture the value

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of recreation at a specific location, and hedonic pricing ought to be used to estimate changes in property values due to the negative impacts of aquaculture facilities or the positive impacts of a well-managed development.

Smearman, D'Souza, and Norton estimate the external costs of aquaculture production in West Virginia. The authors suggest that total external costs may be measured as the sum of pollution prevention (*e.g.*, the costs of pollution control technologies), pollution avoidance (*e.g.*, the costs associated with activities taken by parties affected by pollution), and pollution damages. The first two components typically are engineering costs, and they can be relatively easy to quantify. Pollution damages are more difficult to measure, and they must be quantified using willingness to pay estimates based upon expressions of contingent values or calculations of travel costs. The authors estimate that, for the open type production system used in trout farming, pollution control costs are six percent and pollution damages are 25 percent, respectively, of private production costs.

Using survey results, Tran, Le, and Brennan estimate external costs in the shrimp farming industry located in the rice-growing regions of the Mekong Delta. In their study, external costs are defined to include sedimentation and salinization of fresh waters, leading to losses in rice production, the taking of preventative measures (*e.g.*, dike construction), delays in rice planting, and long term losses of farm land. Kitabatake models production losses caused by eutrophication in the farming of carp in Japan's Lake Kasumigaura, using a framework that integrates production, damage, and cost functions. Empirical results are developed using data from aquaculture producers, showing that about

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four percent of annual carp production in the lake is lost due to eutrophication. Pollution-related losses are primarily of fish cultured with an automatic feeding technology.

3. Methods

3.1. Framework

Our general analytical framework is depicted as a flow chart in figure 2. The chart illustrates the interactions among the key components of the framework, and it serves as a blueprint for our model of aquaculture environmental policy analysis. The future scale of aquaculture operations is influenced by the supply and demand for seafood. In turn, aggregate seafood demand is a function of population, income, and protein substitutes. Income levels are affected by changes in economic conditions. Aggregate seafood supply comes from three sources: fisheries, net imports (wild-harvest and cultured seafood), and aquaculture. The future supply from fisheries depends upon future stock sizes, which are influenced by current and future fisheries management efforts to allocate quotas and to protect and rebuild fish stocks. The level of imports is affected by supply and demand in international markets and by relevant trade policies.

For given levels of seafood supplies from fisheries and imports, we can estimate the demand (*i.e.*, price and quantity) for aquaculture products. Together, the demand for aquaculture products and its production technologies (and costs) determine the size of the aquaculture industry, which in turn determines the potential level of pollution.

3.2. Model

We assume that aquaculture produces the same species as a commercial fishery and that the product is undifferentiated in the market. We consider a linear demand function for fish:

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$$p = (p_0 - kh)e^{\theta t} \quad (1)$$

where p_0 is the choke price, k is the slope, h is the landings of fish or production from aquaculture supplied to the market, and θ is an exogenous parameter. The price is increasing in θ. In the analytical model, we do not explicitly model fish imports, and equation (1) is the net demand for domestic fish supplies. With this demand, we can compute the social benefit (B) at a given level of supply, h, to be:

$$B(h) = e^{\theta t}\int_0^h (p_0 - k\eta)d\eta = e^{\theta t}(p_0 h - kh^2/2) \quad (2)$$

The production function for the wild harvest fishery is:

$$h_f = qxE \quad (3)$$

where h_f is the level of landings from the harvest fishery, q is a catchability coefficient, x is the size of the natural fish stock, and E is an aggregate variable that represents fishing effort.

A variety of models of aquaculture production are extant in the literature (Hatch and Kinnucan; Bjorndal; Allen *et al*.; Shang). We assume that one type of unchanging aquaculture technology is used. As a consequence, capital and labor are proportional to acreage. A production function for aquaculture takes the following form:

$$h_a = ws \quad (4)$$

where h_a is the total farmgate output, w is the output per farm, and s is the total number of farms. According to this model, a larger number of farms are needed if aquaculture is to increase its supply to the market.

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Total benefits from the supply of fish are the sum of the revenues from the harvest of fish from a wild stock and the production of fish by aquaculture. From equations (3) and (4), benefits are a function of *E*, *x* and *s*:

$$B(E,x,s) = B(h_f + h_a) \qquad (5)$$

The cost of fishing, C_f, is modeled as a function of fishing effort:

$$\frac{\partial C_f}{\partial E} > 0 \qquad (6)$$

The cost of aquaculture, C_a, also is a function of the total number of farms *s*; and the cost of investment in new farms (*I*) is a function of the increment, *z*, to the total *s*.

$$\frac{\partial C_a}{\partial s} > 0, \qquad \frac{\partial I}{\partial z} > 0 \qquad (7)$$

The environmental damage from aquaculture is a function of the scale of production:

$$\frac{\partial D}{\partial s} > 0 \qquad (8)$$

A hypothetical regional manager chooses a level of investment in aquaculture, *z*, and a level of fishing effort, *E*, to maximize the net benefits of fish production from both the wild harvest fishery and aquaculture:

$$max \int_0^\infty \{ B(E,x,s) - C_f(E) - C_a(s) - I(z) - D(s) \} e^{-\delta t} dt \qquad (9)$$

subject to

$$\dot{x} = f(x) - qxE \qquad (10)$$

$$\dot{s} = z \qquad (11)$$

The two constraints describe the growth of the wild stock and changes in the scale of aquaculture production. The current-value Hamiltonian is:

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$$H = B(E,x,s) - C_f(E) - C_a(s) - I(z) - D(s) + \lambda[f(x) - qxE] + \beta z \quad (12)$$

The marginal conditions for an interior solution include:

$$\frac{\partial H}{\partial E} = \frac{\partial B}{\partial E} - \frac{\partial C_f}{\partial E} - \lambda qx = 0 \quad (13)$$

$$\frac{\partial H}{\partial z} = -\frac{\partial I}{\partial z} + \beta = 0 \quad (14)$$

$$\dot{\lambda} - \delta\lambda = -\frac{\partial H}{\partial x} = -\frac{\partial B}{\partial x} - \lambda\frac{\partial f}{\partial x} + \lambda qE \quad (15)$$

$$\dot{\beta} - \delta\beta = -\frac{\partial H}{\partial s} = -\frac{\partial B}{\partial s} + \frac{\partial C_a}{\partial s} + \frac{\partial D}{\partial s} \quad (16)$$

Substituting (3) and (4) into (5), the benefit function becomes:

$$B = e^{\theta t}[p_0(qxE + ws) - k(qxE + ws)^2/2] \quad (17)$$

We employ a surplus production model to describe the growth, *f*, of the wild stock:

$$f(x) = rx - \frac{rx^2}{K} \quad (18)$$

where *r* is an intrinsic growth rate, and *K* represents the ecosystem's carrying capacity.

We specify the cost and investment functions as

$$C_f = cE \quad (19)$$

$$C_a = vs \quad (20)$$

$$I = bz \quad (21)$$

$$D = ms \quad (22)$$

Equations (13) through (16) become

$$\lambda = e^{\theta t}[p_0 - k(qxE + ws)] - c/(qx) \quad (23)$$

$$\beta = b \quad (24)$$

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$$\dot{\lambda} - \lambda(\delta - r + qE + 2rx/K) + e^{\theta t} qE[p_0 - k(qxE + ws)] = 0 \qquad (25)$$

$$\dot{\beta} - \delta\beta + e^{\theta t} w[p_0 - k(qxE + ws)] - v - m = 0 \qquad (26)$$

From (24) and (26), we can solve for the optimal steady-state production scale of aquaculture:

$$s^* = \frac{p_0 - kh_f - e^{-\theta t}(\delta b + v + m)/w}{kw} \qquad (27)$$

The number of aquaculture farms is positively related to fish price (p_0) and the growth in demand over time and is negatively related to production cost (v), the cost of investment in farms (z), environmental damages (m), average farm productivity (w), and landings from the harvest fishery (h_f).

Assuming that the price of fish is not appreciating over time ($\theta = 0$) and a steady-state equilibrium is feasible, we use equations (23) through (26) to derive the following expressions for the marginal benefit (MB), the marginal cost of aquaculture with respect to fish yield (MC_a), and the marginal cost of fishing with respect to yield (MC_f)[6]:

$$MB = p_0 - k(qxE + ws) \qquad (28)$$

$$MC_a = \frac{\delta b + v + m}{w} \qquad (29)$$

$$MC_f = mc_f\left[1 + \left(\frac{qE}{\delta - \frac{df}{dx}}\right)\right] \qquad (30)$$

[6] We substitute for λ using equation (23) and β using equation (24). Then we solve both (25) and (26) for MB.

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where we define $mc_f = c/(qx)$ to be the marginal cost of fishing with respect to yield, h_f, for the current period.[7] The market-clearing quantity is $h_f + h_a$ and the price is MB. Equations (25) and (26) indicate that, at market equilibrium, the marginal cost of production from both activities must equal MB (= $MC_a = MC_f$).

In our problem, the regional manager maximizes the benefits of fish production from both (either) the wild harvest fishery and (or) aquaculture. As shown in figure 3, this is the area below the demand curve and above the supply (*i.e.*, marginal cost) curve(s). When $MC_a < MC_f$ is always true over the entire range of aquaculture production levels (MC_a is always below MC_f in figure 3), we have a corner solution in which the entire market is supplied by aquaculture. In contrast, when $MC_a > MC_f$ is always true, the fishing industry is the sole supplier. In an interior solution (see figure 3), the wild harvest fishery is more competitive than aquaculture ($MC_f < MC_a$) within a certain range of production (h_f), and when market demand is greater than h_f, aquaculture becomes less costly ($MC_f > MC_a$). In this case, the rest of the market is supplied by aquaculture (h_a).

With $\theta = 0$, we can solve the steady-state fish stock (x^*), using equations (10), (18), (23) through (26).

$$x^* = \frac{cr/(qK) + (r-\delta)MC_a \pm \sqrt{[cr/(qK) + (r-\delta)MC_a]^2 + 8\delta crMC_a/(qK)}}{4rMC_a/K} \quad (31)$$

The corresponding aquaculture production scale (s^*) is

$$s^* = \frac{p_0 - kf(x^*) - (\delta b + v + m)/w}{kw} \quad (32)$$

The amount of pollution produced at an aquaculture facility is a function of the fish species, the production system, and the type and quality of feed. How much a

[7] Because $h_f = qxE$, we can write the total cost of fishing as $cE = c[h_f/(qx)]$.

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facility is actually polluting, in turn, depends on factors such as location, whether or not a pollution control system is used, the characteristics of the water flow, and water temperature (Beveridge; Midlen and Redding). Using farm-level pollution estimates described in the Appendix, we can calculate the total annual pollution from the aquaculture industry (N_i):

$$N_i = s^* Q_i \qquad (33)$$

where Q_i with i = [*BOD, TN, TP, TSS*] are farm-level annual pollution quantities (see (A24)).

3.3. Data

In order to project future growth in open-ocean aquaculture and the interactions between aquaculture and a commercial fishery, we consider the New England groundfish fishery and the potential aquaculture of Atlantic cod (*Gadus morhua*). The growout of cod in floating netpens (on the surface or submerged) has been proposed as a potential aquaculture activity along the New England coast. Open-ocean operations can be stocked with juvenile cod produced at an onshore hatchery. We assume that the cost of juveniles from the hatchery is part of the operating costs of the aquaculture operation. The product would be sold in the market for whitefish.

We employ published estimates of parameters for the groundfish fishery and the market (table 2). Edwards and Murawski develop a surplus production model for New England groundfish. Using their model coefficients, we estimate an intrinsic growth rate (r) of 0.3715 year^{-1} for our logistic growth function. Similarly, we calculate a carrying capacity for all groundfish species of 1.681 million metric tons. We use an estimate of the catchability (q) of cod at 0.000007 days^{-1}, also published in the same study.

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We employ the groundfish demand function estimates from Edwards and Murawski, and we calculate a choke price (p_0) of $2,546 per mt and a slope (k) of 3.82 $/10^{-3} mt. We employ an average estimate of unit fishing costs (c) of $3,300 day^{-1} for two intermediate size trawlers, based upon unpublished data compiled by the NOAA Northeast Fisheries Science Center.

To describe aquaculture production in the model, we develop a firm-level submodel of the operations of an open-ocean aquaculture facility for growing cod (this model is described in detail in the Appendix).

The firm-level model can be used to evaluate the effects of the implementation of pollution-control measures. The pollution-control measures are designed to reduce feed inputs, which leads to a lower FCR. A lower FCR is reflected in the submodel by an increase in an adjustment factor ψ (A11). The pollution control measures include feed management and BMPs for the control of solids. Feed management involves variable costs, and BMPs involve both fixed and variable costs. Although the implementation of these measures is costly, they result in a savings in feed costs, thereby lowering annual production costs.

We do not have specific estimates for ψ. Instead, we consider three sets of parameter results in table 3 to illustrate three different levels of the effectiveness of pollution control measures. In the baseline case, feed cost = $0.50/kg, ψ = 1.00, and *FCR* = 1.365, the farm level annual yield (w) is 2,115 mt, annual aquaculture production cost (v) is $3.62 million, the cost of new investment (b) is $7.51 million, and the total N input is 83 mt per year. If the pollution control measures are effective, *FCR* is lowered to 1.239 and the annual production cost falls to $3.49 million. Pollution loading declines as

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well, as reflected in total N releases of 76 mt per year. Note that production and investment costs are very sensitive to feed costs. For a feed price of $0.60/kg, the production costs (in parentheses) are significantly higher than the baseline values, thereby affecting the competitiveness of cod aquaculture.

4. Simulations and Results

Our model is an extension of the classical fishery bioeconomic model (Clark). It can be used to assess a number of important policy variables. We examine first the steady-state (long-run equilibrium) level of aquaculture with respect to different levels of environmental damages, using the baseline parameter values described in the last section.

When waste discharges do not cause measurable environmental damage ($m = 0$),[8] the optimal scale of the aquaculture industry includes 11 farms[9] producing a total of 23.18 thousand mt of cod. The harvest fishery lands 156.11 thousand mt of groundfish, slightly below MSY (156.123 thousand MT). The total fish supply is 179 thousand mt per year (see figure 3). The aquaculture industry releases 910 mt of total N (see table 4).

To simulate the effects of a greater social cost of aquaculture, we arbitrarily set the farm-level environmental damage (m) to $100 thousand per year; the socially optimal number of farms is then reduced to four. Although there is a slight increase in the supply from the traditional fishery,[10] the total fish supply declines to 165 thousand mt. As a result, the total N input is lowered to 344 mt per year.

To examine the impact of rising imports on the steady-state results, we change the slope parameter (k) to 3.608, representing a 10% increase in imports (decline in demand

[8] This is possible in offshore waters where currents disperse effluents quickly.

[9] This is calculated from Equation (32).

[10] This is because the supply curve of traditional fishery is nearly vertical when it approaches MSY.

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for local fish). The result suggests that, in this case, imports will displace farmed fish (only three farms needed) and landings from the harvest fishery will not change.

If the feed conversion ratio (FCR) is lowered from our baseline estimate (1.365), the optimal size of the aquaculture industry will be significantly larger. As shown in figure 4, at $m = 0$, the number of farms increases from 11 to 20 and 23, when *FCR* is lowered from 1.365 to 1.286 and 1.239, respectively. In all cases, the number of farms declines as the environmental damage per farm (m) rises.

To link environmental damage to effluent quantity, we express unit environmental damage in terms of dollars per mt of feed. Remember that in our firm-level model, quantities of different effluents (e.g., TN and TP) from each farm are all proportional to feed quantity. The optimal industry size for different levels of unit environmental damage is depicted in figure 5. Unlike figure 4, the number of farms declines with respect to unit damage more rapidly and in a nonlinear fashion. This result may be explained as follows. In figure 4, the number of farms grows as the damage per farm declines (*i.e.*, moving from right to left). As the number of farms grows, the total feed quantity also rises. For a constant damage value per unit feed quantity, the number of farms grows more slowly initially as we move from right to left in figure 5.

Next, we examine the optimal scale of open-ocean aquaculture with expanding demand. The industry size is calculated using Equation (27). Although we do not have an analytical solution for landings from the harvest fishery (h_f), our steady-state estimate of 156.10 thousand MT is quite close to MSY and cannot be increased significantly (see figure 3). In order to consider a range of projections of population and income growth, we simulate the increase in the number of farms over a 30-year period with three

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different demand growth schedules. According to the U.S. Bureau of Census, the population growth rate in New England will be about 0.5% per year from 2005 to 2025 (Campbell). From 2002-2012, the projected personal consumption expenditures in the United States are increasing at a rate of 2.8 percent per year (BLS). As shown in figure 6, if demand rises at one, two, and three percent per year over 30 years, the industry size will expand respectively from 11 to 84, 138, and 178 farms.

Using the cod production and cost data, we show that the optimal level of landings from the traditional fishery is 156 thousand mt. Currently, the total groundfish landings in New England are only about 60 thousand mt, after two decades of decline due to overfishing (figure 7). During the 1990s, a wide variety of effort control measures were implemented in this fishery. Groundfish stocks are now beginning to recover. According to projections (figure 7), New England groundfish landings will reach 106, 136, and 146 thousand mt in 2012, 2015, and 2026, respectively. Nevertheless, prior to 2015, landings from the harvest fishery will still be significantly below 156 thousand mt. In order to bridge this supply gap, and in the absence of increasing levels of imports, additional aquaculture farms might enter the market. For example, an additional 20 farms could supply over 40 thousand mt of cod.

5. Conclusions

Existing studies project the future expansion of the marine aquaculture industry based on the assimilative capacity of the coastal environment, using water quality assessment models. In this article, we present a market-oriented approach for projecting future industrial expansion based upon equilibria in the seafood market. We consider supplies from both wild-harvest fisheries and open-ocean aquaculture. In our framework,

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the net demand for farmed fish determines the size of the aquaculture industry and, in turn, its level of pollution discharges. The socially optimal industry size is constrained by the environmental damages associated with effluent discharges. We illustrate our analytical approach using a case study of the New England groundfish fishery and proposed open-ocean aquaculture of Atlantic cod. Our results suggest that, in the case of New England groundfish market, the socially optimal solution involves a combination of the wild-harvest fishery and aquaculture. Aquaculture and the fishery are not mutually exclusive. It makes economic sense to rebuild and protect the groundfish stock, while also pursuing the industrial development of aquaculture.

The future size of the open-ocean aquaculture industry depends upon its costs and productivity. We use a detailed simulation model of firm-level investment and production to develop cost and production estimates for open-ocean aquaculture of cod. Based on these cost estimates, our analysis indicates that the optimal industry size implies 11 farms producing 23 thousand mt per year, after the groundfish stock has been rebuilt to yield annual landings of 156 thousand mt. The industry size will be much smaller (fewer than ten farms) if effluent discharges cause significant damage to the marine environment (see figure 5). Indeed, at present, the cost of cod farming is relatively high with respect to the harvest fishery. If the actual production costs (e.g., feed cost) are higher than our baseline estimates, cod aquaculture may not yet be economically feasible, given the projected growth in future landings from the groundfish fishery (figure 7).

Although the present analysis suggests that proposed cod aquaculture in New England is likely to remain secondary to harvest fishery production in terms of volume, the scale of the industry may be significant if pollution control measures can be shown to

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be effective (figure 4) or if there is significant growth in fish demand in the future (figure 6). Because there will be regulatory limits to landings from the wild-harvest fishery, future growth in demand is likely to be met only with contributions to supply from imports and from aquaculture operations.

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Appendix: A Model of Firm-Level Investment and Production

Our firm-level model assumes that a growout operation produces a fixed amount of fish each month, following pre-determined stocking and harvesting schedules (*cf*., Kite-Powell *et al*.; Jin *et al*.). The model simulates fish growth and projects costs for each month in a 15-year period. It calculates the amount of up-front investment required, annual operating cost, and fish production. Several biological and environmental variables (*e.g*., mortality and water temperature) may be specified as stochastic variables to capture random effects in fish growth.

Fish Growth

To ensure a year-round fish yield, a certain number of fingerlings are stocked each month. Generally, for a particular cohort, fish growth may be modeled in continuous time as (see Arnason):

$$\frac{dx(\tau)}{d\tau} = G[\, f_d(\tau), x(\tau), \tau\,] \qquad \text{(A1)}$$

where x is the fish biomass at time τ, τ denotes time within a growout period [$\tau = 0$ (stocking), …, T (harvesting)], $G(\bullet)$ is the growth function, and f_d is the quantity of feed at τ. To control density, we model G following the Beverton-Holt approach (Ricker) and specify

$$x(\tau) = n(\tau)\omega(\tau) \qquad \text{(A2)}$$

where n is the number of fish in thousand and ω is the weight of a fish in grams. Without intervention,

$$n(\tau) = n(0)e^{-\alpha\tau} \qquad \text{(A3)}$$

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where α is the mortality rate (Allen *et al.*). This relationship says that the number of fish will decrease while the weight grows. In discrete time (τ = month), (A3) becomes

$$n(\tau) = n(\tau - 1)(1 - \alpha) \qquad \text{(A4)}$$

For cod, we model mortality as:

$$\alpha(\tau) = 0.01 - 0.000001\omega(\tau) \qquad \text{(A5)}$$

The growth rate of individual fish weight (ω) in continuous time is

$$\frac{d\omega(\tau)}{d\tau} = g(\tau) \qquad \text{(A6)}$$

In discrete time, (A6) may be rewritten as:

$$\omega(\tau) = \omega(\tau - 1) + g(\tau - 1) \qquad \text{(A7)}$$

where $g(\cdot)$ is the weight growth function of an individual fish. For cod, we specify the monthly growth as a function of fish weight and water temperature (Jobling):

$$g(\tau) = 0.37223\omega(\tau)^{0.559} e^{0.297\gamma - 0.000538\gamma^3} \qquad \text{(A8)}$$

where g is in grams per month, ω is weight in grams, and γ is the temperature in degrees Celsius. The feed conversion ratio (*FCR*) is defined as:

$$FCR(\tau) = \frac{f_0(\tau)}{g(\tau)} \qquad \text{(A9)}$$

where f_0 is the quantity of feed per fish. Thus, the total feed quantity in kg at τ is:

$$f_d(\tau) = f_0(\tau)n(\tau) = FCR(\tau)g(\tau)n(\tau) \qquad \text{(A10)}$$

For cod, we have *FCR* as a function of fish weight:

$$FCR(\tau) = [1.5 - 0.00035\omega(\tau)] / \psi \qquad \text{(A11)}$$

where $1 \leq \psi \leq 1.1$ is an adjustment factor that allows us to reduce the baseline FCR to reflect the effect of pollution control measures (discussed below).

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Fish Production

For specific stocking and harvesting schedules, the model calculates the factor inputs, associated costs, and fish production month-by-month over 15 years [t = 1, 2, …, 180 (month)]. For cod, the growout period is two years. There are 24 cohorts. Cohort 1 is initially stocked at t = 1 (τ = 1), harvested at t = 24 ($\tau = T$), and restocked at t = 25 (τ = 1). Total fish biomass at harvest time $x(T=24)$ in kg can be calculated from (A2). Note that $x(T)$ = 0 for t = 1 – 23.

Costs of Investment and Production

For open-ocean aquaculture, the total cost includes expenditures on cages, a boat, fingerlings, feed, and shore-based operations (e.g., administration and marketing). In the model, we assume a sequential cage installation schedule. For each of the first 24 months, there is one new cage added to the farm. The cost of each cage is

$$c_k(t) = \mu(acq + inst) + efix \qquad t=1,2,\ldots,24 \qquad \text{(A12)}$$

where c_k is the cost of each cage in \$, μ is the cage volume in m^3, *acq* is the cage acquisition cost in \$/m^3, *inst* is the cage mooring and installation cost[11] in \$/m^3, and *efix* is the fixed cost associated with environmental compliance in \$/cage. For cage maintenance in subsequent months, the cost is

$$c_m(t) = \mu \cdot cn(t) \cdot cm(t) + evar(t) \qquad t=25, 26,\ldots,180 \qquad \text{(A13)}$$

where *cn* is the number of cages in the farm, *cm* is the cage operating and maintenance cost in \$/m^3/year, and *evar* is the variable cost of environmental compliance in \$/month.

[11] This parameter may be modeled as a function of water depth.

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Each month, feed and fingerlings are transported to the farm and harvest is transported back to shore by boat. Aggregating cage-level feed quantity [$f_d(\tau)$ from (A10)], we have the farm-level monthly feed quantity (*fq*) in kg:

$$fq(t) = \sum_{\tau=1}^{cn(t)} f_d(\tau) \qquad \text{(A14)}$$

For each month, the quantity of fingerlings and water transported for stocking (*sq*) in kg is:

$$sq(t) = stock \cdot sg \cdot \varphi \qquad \text{(A15)}$$

where *stock* [= *n(0)*] is the number of fingerlings in thousands, *sg* is the fingerling weight in gram/fish, and φ is ratio of water weight to fingerling weight during transport to farm. For each month, the number of boat days (*bd*) is calculated as either the number of days necessary for transporting harvest from the farm or the number of days needed for transporting feed and fingerlings to the farm, whichever is greater.

$$bd(t) = max\{ x(T)/ld, [fq(t) + sq(t)]/ld \}/trip \qquad \text{(A16)}$$

where *x(T)* is the fish harvest in kg, *ld* is the boat payload in kg, *fq* is the feed quantity in kg, *sq* is the quantity of fingerlings in kg, and *trip* is the number of round-trips per day.[12]

For each month, boat cost (c_b) is

$$c_b(t) = bfix/12 + bvar \cdot bd(t) \qquad \text{(A17)}$$

where *bfix* is the vessel fixed cost in \$/year, and *bvar* is the variable and crew cost in \$/day. Fingerling cost (c_r) is

$$c_r(t) = 1000 \cdot stock \cdot sp \qquad \text{(A18)}$$

where *sp* is the fingerling cost in \$/fish. Feed cost (c_f) is

[12] This parameter may be modeled as a function of distance to shore.

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$$c_f(t) = fq(t) \cdot fp \qquad \text{(A19)}$$

where *fp* is the feed cost in \$/kg. Shore cost (c_s) is

$$c_s(t) = (sh + ins)/12 \qquad \text{(A20)}$$

where *sh* is the on shore cost (e.g., dock, facilities, management administration, marketing and distribution) in \$/year and *ins* is the insurance cost in \$/year.

From Equations (14), (15), and (19) through (22), we can calculate the total cost (*C*) in each month

$$C(t) = \sum_i c_i(t) \qquad \text{(A21)}$$

Note that $i = [k, m, b, r, f, s]$. We define the total investment in the first three years as:[13]

$$Inv = \sum_{t=1}^{24} C(t) \qquad \text{(A22)}$$

The average annual operating cost over the next 13 years is:

$$C_{op} = \sum_{t=25}^{180} C(t)/13 \qquad \text{(A23)}$$

As noted, several key economic and biological variables in the model may be specified as stochastic. We attach a normally distributed random element, $\xi_j \sim (0, \sigma_j^2)$, to each of the four variables: mortality rate ($\alpha + \xi_\alpha$), fish weight growth ($g + \xi_g$), and water temperature ($\gamma + \xi_\gamma$). We run the stochastic version of the firm model by setting the variances as: $\sigma_m^2 = \sigma_g^2 = 0.05$ and $\sigma_\gamma^2 = 0.5$).

Pollution

Using the monthly farm-level feed quantity (*fd*) from (A14) we can estimate the average yearly feed quantity and associated pollutant quantity (Q_i):

[1313] Discounting is not included here, because it has been incorporated into the general model.

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$$Q_i = \Phi_i \cdot 12 \cdot E(fq) \qquad \text{(A24)}$$

where Φ_i with i = [*BOD, TN, TP, TSS*] are the feed-to-pollutant factors.

We apply the models to Atlantic cod. Cod can be stocked and harvested year-round in southern New England waters. The growout site is assumed to be located 6 km from the shore station or dock used by the support vessel. The water depth is 50 m. Monthly water temperatures are shown in table A1. Table A2 summarizes other model input parameters describing cage system, stocking, feed cost, boat, etc. We use a set of biological parameters for cod published by Best.

As shown in table A2, the cage capacity per cohort is 5000 m^3. The fixed cost for the growout support vessel, which stocks the cages, carries feed to the cages, supports maintenance, and carries out harvesting, is $100,000/year. Operating costs are $1,500/day for fuel and other consumables, and personnel costs are another $1,500/day. The vessel has an operating speed of 15 km/h and a payload capacity of 30 metric tons. On a typical round trip carrying feed, it spends 3 hours on site. The maximum length of a work day is 12 hours; and due to weather constraints and maintenance requirements, the vessel is at sea a maximum of 25 days per month. Onshore costs include $30,000/year for dock use and other onshore facilities, $70,000/year for management and administrative costs, and $50,000/year for marketing and distribution.

Environmental compliance costs are also included in the lower portion of table A2. These cost data are based on EPA (USEPA) estimates for four pollution control measures for offshore cage aquaculture: (1) Feed Management (*fmv* is the cost associated with extra time for record keeping); (2) Solid Control BMP Plan (*scf* covers the cost associated with developing three 5-year plans and *scv* is the cost for monthly review of

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the plans); (3) Drug and Chemical Control BMP Plan (*dcf* is the cost to develop three 5-year plans and *dcv* is the cost for monthly review of the plans); and (4) Active Feed Monitoring (*aff* is the cost of one set of underwater cameras and *afv* is the cost associated with feeding control). These pollution controls measures are cumulative and designed to lower feed and drug inputs. Note that *efix* in (A12) is calculated using *scf*, *dcf*, and *aff*, and *evar* in (A13) is based on *fmv*, *scv*, *dcv*, and *afv*. Feed-to-pollutant factors are in table A3. They are also from EPA (USEPA).

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Table 1. Typology of Economic and Ecological Effects

	Positive	**Negative**	**Indeterminate**
Direct Economic Effects	• Increase in seafood output • Decrease in seafood price • Increase in demands for factors from other industries • R&D and technology investments	• Administrative costs of providing access • Ineffective regulations • Industry concentration (if monopolistic)	• Employment for currently unemployed workers • Increase in seafood quality
External Effects	• Organic nutrient inputs (up to a threshold) • Nutrient removal (shellfish)	• Displacement of more productive ocean uses • Eutrophication • Chemical pollution • Pharmaceutical pollution • Escapement • Ecosystem disruption • Protected species takings • Growth overfishing of ranched stocks	• Bioaccumulation of carcinogens in fish • Overexploitation of forage fish stocks
Distributional Effects	• Employment opportunities in a new industry • Redeployment of unused capital from the fishing industry • Rents accrue to the public as the owner of “ocean space”	• Local communities left out of industry • Reorganization of local market structure • Loss of access to local seafood protein (forage fish)	• Reduction of trade deficit

Table 2. Parameters for the Market and the Fishery

Variable	Description	Unit	Value
p_0	intercept of fish demand function	\$/MT	2,546
k	slope of fish demand function	$\$10^{-3}/MT^2$	3.28
r	Intrinsic growth rate	$time^{-1}$	0.3715
K	carrying capacity	10^3 MT	1,681
q	catchability coefficient	day^{-1}	0.000007
c	unit cost of fishing effort (E)	10^3\$/day	3.3
δ	discount rate		0.07

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Table 3. Parameters for Open-Ocean Aquaculture

Variable	Description	Unit	Value		
			$\psi = 1.00$	$\psi = 1.05$	$\psi = 1.10$
FCR	average feed conversion ratio		1.365	1.286	1.239
w	aquaculture production output per farm	MT/farm	2,115	2,158	2,143
v	aquaculture production operating cost [a]	10^3 \$/year/farm	3,615 (3,913)	3,556 (3,842)	3,487 (3,760)
b	investment cost [a]	10^3 \$/farm	7,514 (7,792)	7,464 (7,732)	7,442 (7,706)
$12 \cdot E(fq)$	feed quantity	MT/year/farm	2,765	2,660	2,544
Q_{BOD}	biochemical oxygen demand (BOD)	MT/year/farm	968	931	890
Q_{TN}	total nitrogen (TN)	MT/year/farm	83	80	76
Q_{TP}	total phosphorus (TP)	MT/year/farm	14	13	13
Q_{TSS}	total suspended solids (TSS)	MT/year/farm	830	798	763

Notes:
a. Values are associated with feed cost (*fp*) = \$0.50/kg and \$0.60/kg (in parentheses), respectively.

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Table 4. Simulation Results

Output Variables	Description	Unit	Without Damage[a]	With Damage[b]	Rising Imports[c]
x	fish stock	10^3MT	847.51	843.81	847.51
E	fishing effort	10^6 days	26.314	26.431	26.314
h_f	fishing landings	10^3MT	156.11	156.12	156.11
s	aquaculture industry size	farms	10.96	4.14	3.25
h_a	aquaculture production	10^3MT	23.18	8.76	6.88
h	total fish supply	10^3MT	179.30	164.88	163.00
N_{BOD}	total BOD[d]	MT	10,609	4,008	3,146
N_{TN}	total TN	MT	910	344	270
N_{TP}	total TN	MT	153	58	46
N_{TSS}	total TSS	MT	9,097	3,436	2,698

Notes:
a. $m = 0$.
b. m = $100,000 per farm per year.
c. Imports account for 10% of total fish supply and $m = 0$.
d. All total pollutant estimates (N_i) are based on baseline values ($\psi = 1.00$ in table 3).

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Table A1: Monthly Average Temperatures

Month	Water Temperature
	C^0
Jan	2
Feb	2
Mar	3
Apr	5
May	10
Jun	17
Jul	21
Aug	22
Sept	22
Oct	18
Nov	10
Dec	5

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Table A2: Firm Model Input Parameters.

Parameter	Description	Unit	Value
μ	cage volume per cohort	m^3	5,000
acq	cage purchase cost	$\$/m^3$	15.00
inst	cage mooring and installation cost	$\$/m^3$	3.00
cm	cage operating and maintenance cost	$\$/m^3$/year	1.00
stock	number of fingerlings stocked per cohort	1,000 fish	150
sg	stocking weight	gram/fish	50
φ	ratio of water weight to fingerling weight during transport to farm		5
sp	fingerling cost	$/fish	0.85
fp	feed cost	$/kg	0.50
bfix	vessel fixed cost	$/year	100,000
bvar	vessel variable and crew cost	$day	3,000
ld	vessel payload	MT	30
trip	round trips per day		3
sh	on shore cost	$/year	150,000
ins	insurance cost	$/year	50,000
fmv	feed management variable cost	$/cohort/month	33.32
scf	solid control BMP plan fixed cost	$/farm	1615.20
scv	solid control BMP plan variable cost	$/month	21.15
dcf	drug and chemical control BMP plan fixed cost	$/farm	1615.20
dcv	drug and chemical control BMP plan variable cost	$/month	21.15
aff	active feed monitoring fixed cost	$/farm	10,000
afv	active feed monitoring fixed cost	$/cohort/month	33.32

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Table A3: Feed-to-Pollutant Conversion Factors

Parameter	Pollutant	Conversion Factor
Φ_{BOD}	biochemical oxygen demand (BOD)	0.35
Φ_{TN}	total nitrogen (TN)	0.03
Φ_{TP}	total phosphorus (TP)	0.005
Φ_{TSS}	total suspended solids (TSS)	0.3

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Note: all effects are negative unless preceded by "+". "Z" = zero, "M" = moderate, "S" = significant.	Offshore Finfish	NearshoreFinfish	Land Based Finfish	Nearshore Mollusks	Offshore Mollusks	Offshore Fish Ranching	Nearshore Fish Ranching	Coastal Marine Shrimp	Polyculture
Organic Pollution and Eutrophication	M	S	M	Z	Z	Z	M	S	M
Chemical and Pharmaceutical Pollution	Z	M	M	Z	Z	Z	Z	S	Z
Habitat Modification	Z	Z	Z	Z	Z	Z	Z	S	Z
Disease Transmission to Wild Stocks	S	S	Z	M	M	Z	Z	Z	M
Escapements and Interbreeding	S	S	Z	M	M	Z	Z	Z	M
Exploitation of Forage Fish Stock	S	S	S	Z	Z	S	S	Z	Z
Takings of Protected Species	M	M	Z	Z	M	M	M	Z	M
Direct Depletion of Natural Stocks	Z	Z	Z	Z	Z	S	S	Z	Z
Bioaccumulation of Carcinogens	S	S	S	Z	Z	M	M	Z	Z
Increased Productivity from Nutrient Input	+M	+S	Z	Z	Z	Z	Z	Z	+M
Nutrient Removal	Z	Z	Z	+S	+M	Z	Z	Z	+M

Significant negative effect (S)
Significant positive effect (+S)
Moderate negative effect (M)
Moderate positive effect (+M)
Neutral or No effect (Z)

Figure 1. Preliminary qualitative assessment of environmental effects

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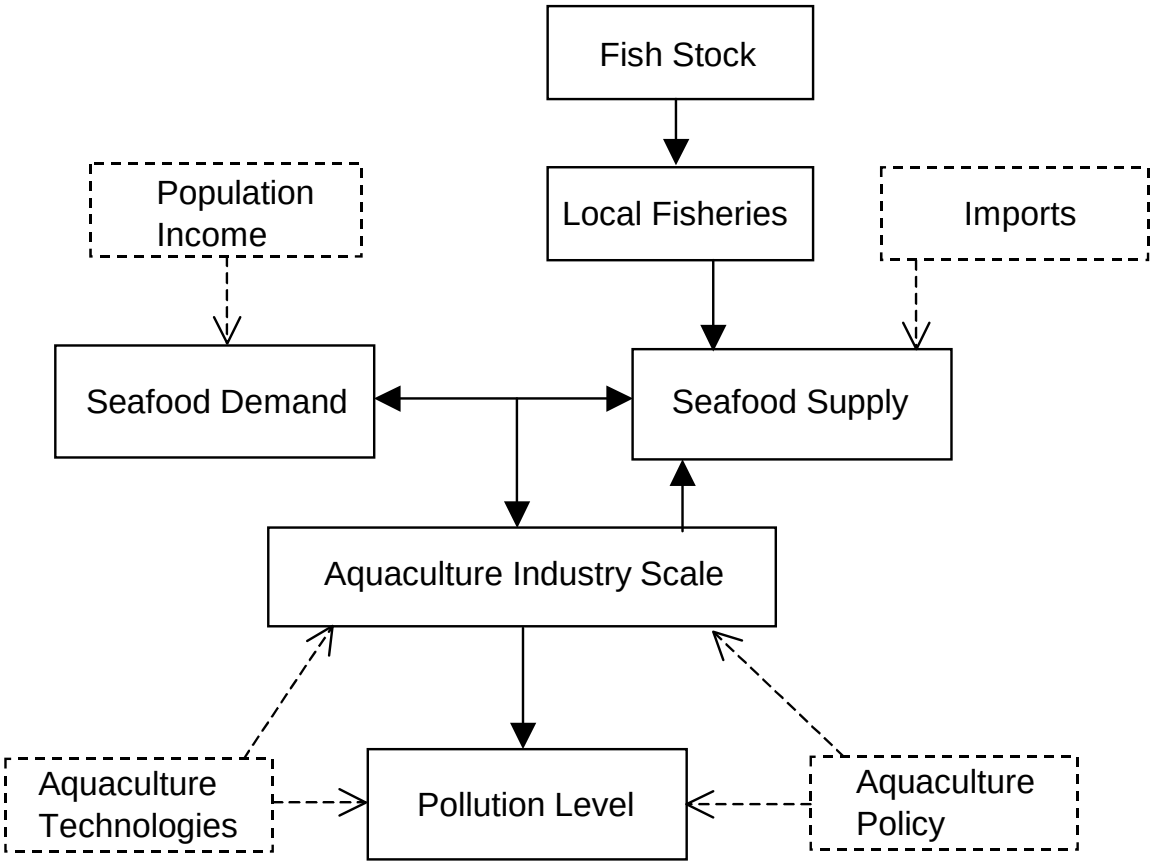

Figure 2: Environmental quality and aquaculture growth

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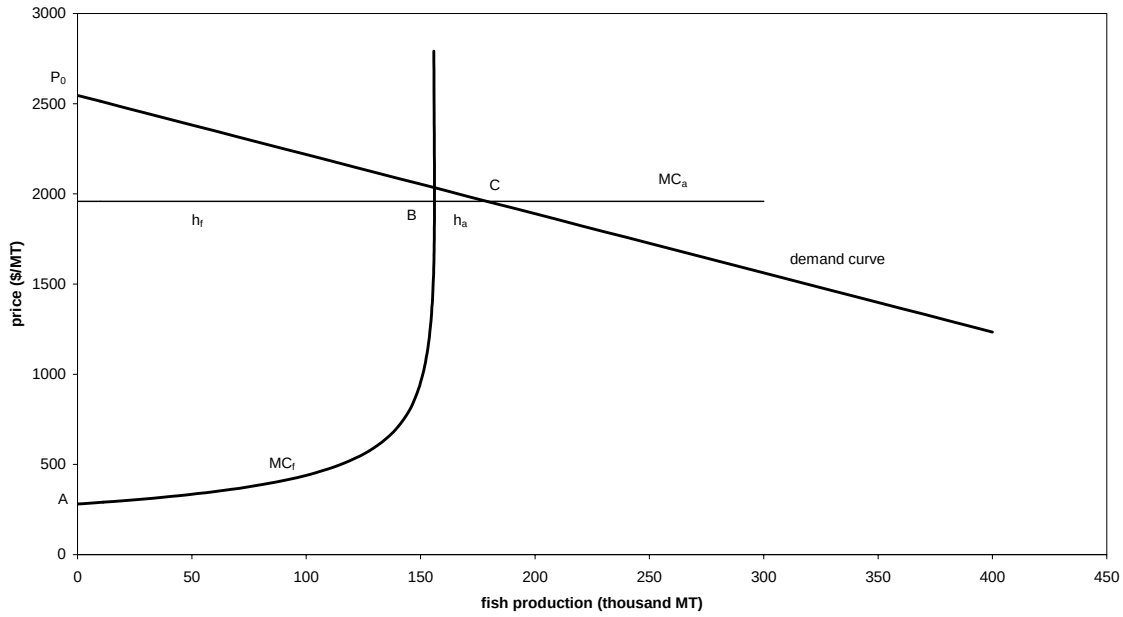

Figure 3: Market demand and supply

The marginal costs of fishing (MC_f), the marginal costs of aquaculture (MC_a), and the demand curve. Total fish production equals the sum of supplies from the wild fishery, h_f, and aquaculture, h_a. A regional manager's objective is to maximize net surpluses, represented by the area $ABCP_0$.

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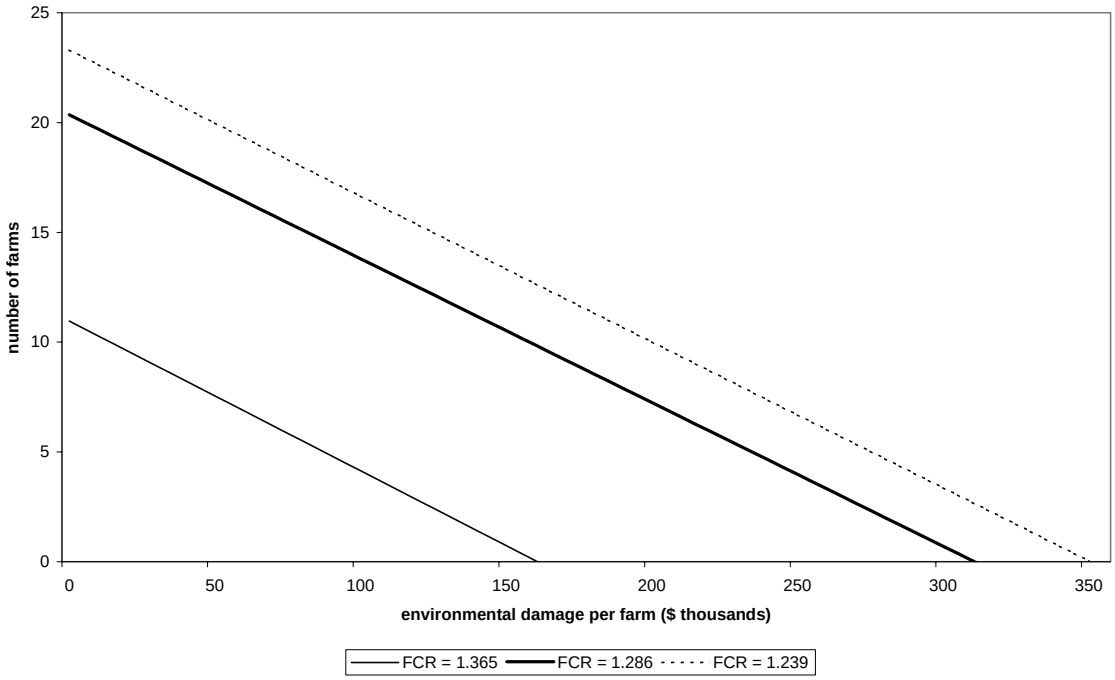

Figure 4: Farm-level environmental damage and aquaculture industry size

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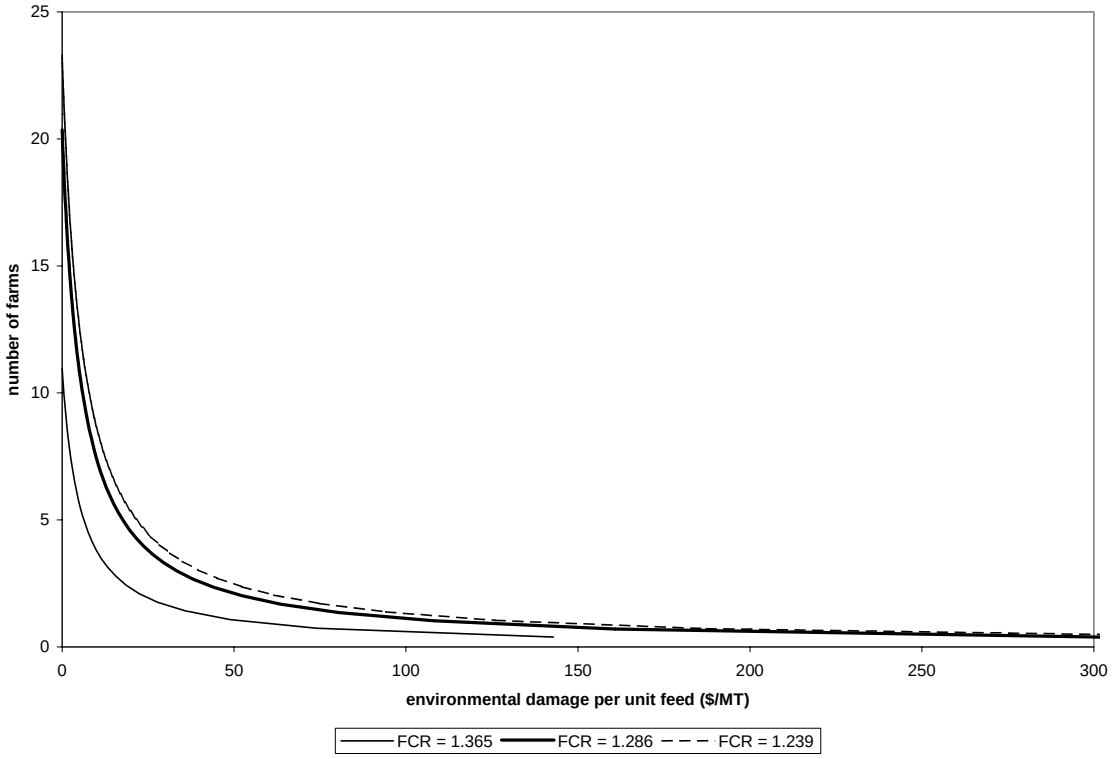

Figure 5: Unit environmental damage and aquaculture industry size

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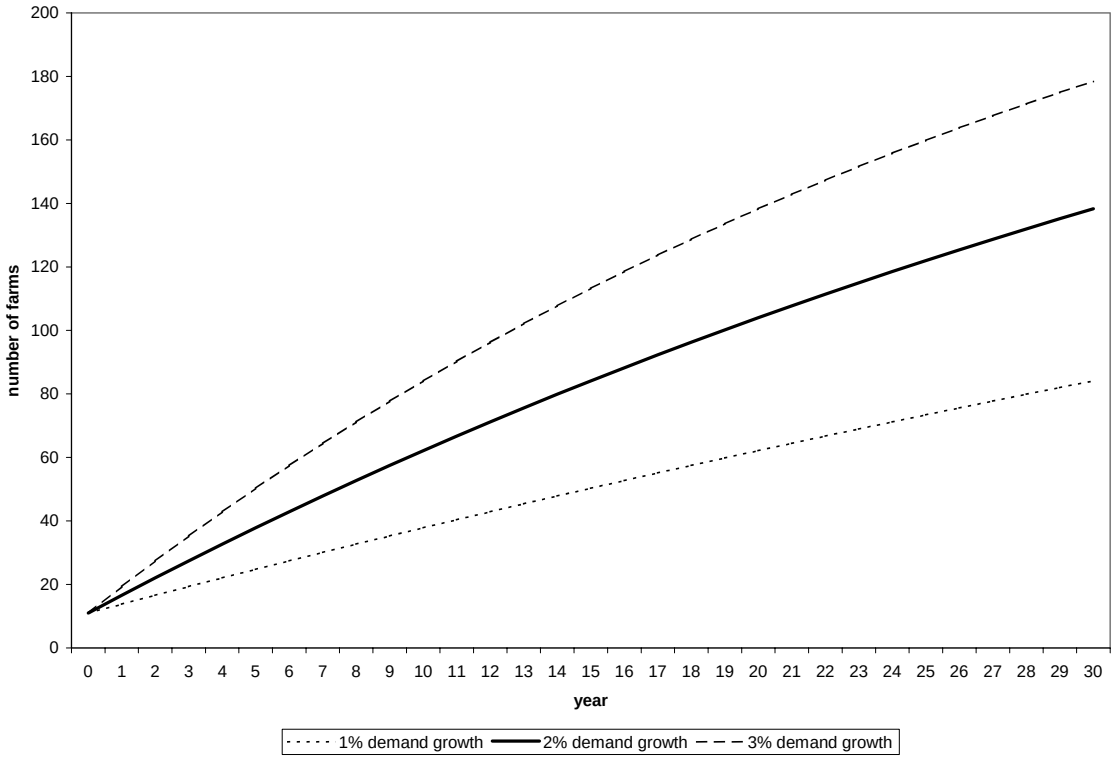

Figure 6: Future expansion of the open-ocean aquaculture industry

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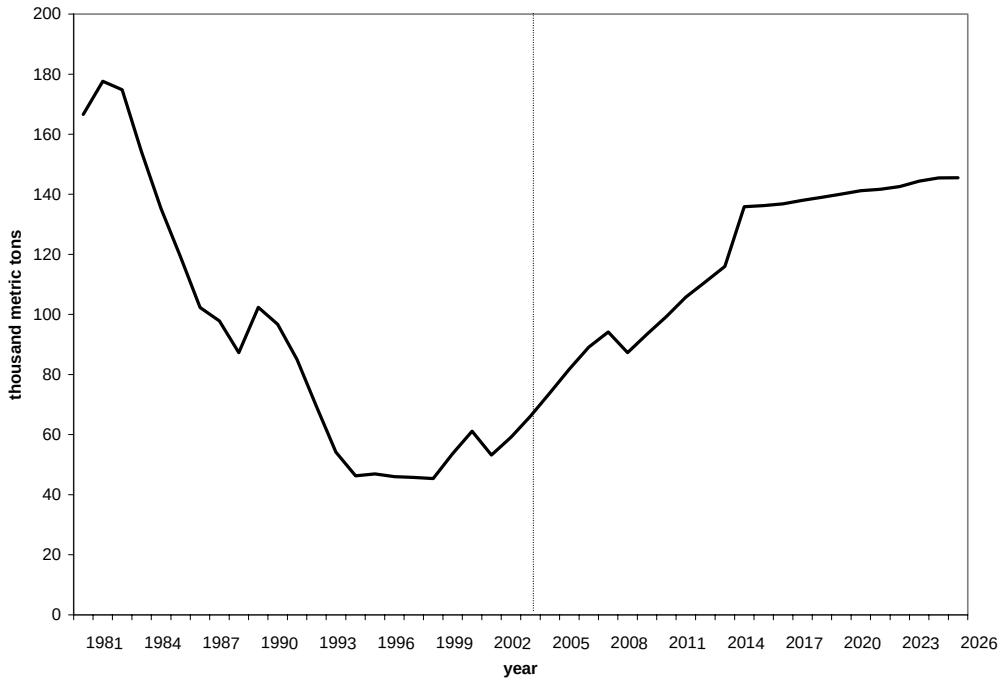

Figure 7: New England groundfish landings and projection

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Interim Report **IR-05-025**

Population Aging and Future Carbon Emissions in the United States

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April 25, 2005

Interim Reports on work of the International Institute for Applied Systems Analysis receive only limited review. Views or opinions expressed herein do not necessarily represent those of the Institute, its National Member Organizations, or other organizations supporting the work.

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Abstract

Changes in the age composition of U.S. households over the next several decades could affect energy use and carbon dioxide emissions. This article incorporates population age structure into an energy-economic growth model with multiple dynasties of heterogeneous households. The model is used to estimate and compare effects of population aging and technical change on baseline paths of U.S. energy use and emissions. Results show that population aging reduces long-term carbon dioxide emissions, by almost 40% in a low population scenario, and effects of aging on emissions can be as large, or larger than effects of technical change in some cases.

Acknowledgments

The PET model was developed at Stanford University, with support from the U.S. Department of Energy, under the direction of Larry Goulder, Paul Ehrlich, Steve Schneider, and Don Kennedy. We are grateful to Jae Edmonds, Son Kim, and Ron Sands for providing production data for the United States. We thank Warren Sanderson, Ross Guest, and others at the Symposium on Population Ageing and Economic Productivity, Vienna Institute for Demography, December 2004 for helpful comments and suggestions. Work described in this article was supported in part by the U.S. Environmental Protection Agency (EPA) through grant/cooperative agreement # R-82980101, and the Office of Science (BER), U.S. Department of Energy, Grant No. DE-FG02-01ER63216, both to Brown University. This research has not been subjected to the EPA's required peer and policy review and therefore does not necessarily reflect the views of the Agency and no official endorsement should be inferred.

This paper was submitted to Energy Economics in April 2005.

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Population Aging and Future Carbon Emissions in the United States

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Introduction

Population growth and technical change are among the most important factors to consider in projections of future carbon dioxide (CO_2) emissions and other greenhouse gases (Schelling, 1992). These emissions, primarily from burning fossil fuels for energy but also other sources such as land use, contribute to the trend of global warming that could cause earth's climate to change in unpredictable and potentially dangerous ways (O'Neill and Oppenheimer, 2002; Mastrandrea and Schneider, 2004). The role of technical change has been the focus of several studies that estimate baselines for future emissions (e.g. Weyant, 2004). The treatment of population in these projections has been limited mainly to direct scale effects from changes in population size alone. However, other demographic factors may be important. Indirect scale effects can arise through compositional changes in the population due to aging, urbanization, or other determinants of economic growth (Birdsall et al., 2001). In addition, population composition can affect consumption patterns, which vary in their indirect energy requirements because of the energy embodied in different consumer goods (Schipper, 1996; Bin and Dowlatabadi, 2005). Compositional changes in population will occur over the next several decades in many parts of the world, and effects of these changes on energy demand and emissions are currently unknown.

This article estimates potential effects of population aging on energy use and CO_2 emissions for the United States (U.S.). Our approach differs in two important ways from existing energy and emissions projections: First, we use households, rather than individuals, as the demographic unit of analysis, and second, we incorporate demographic heterogeneity by introducing the age structure of households into an energy-economic growth model. The empirical energy studies literature has identified household characteristics, such as size and age structure, as key determinants of direct residential energy demand (Schipper, 1996), and has shown that changes in the composition of U.S. households could have substantial effects on national energy demand (O'Neill and Chen, 2002). A few studies have included household characteristics in projections of future energy demand, but these have been limited to short time horizons and simple household projections (Lareau and Darmstadter, 1983; Weber and Perrels, 2000). Household characteristics have not been incorporated into energy-economic growth models, which are among the most widely used tools for

making long-term CO_2 projections and analyzing climate change policies (Weyant and Hill, 1999). To frame the development of our own methodology, we give an overview of the two families of models, infinitely lived agent (ILA) and overlapping generations (OLG), which have been used for long-term emissions projections and climate change policy analysis. We focus on the treatment of savings decisions, and assumptions implicit in solution methods, two key issues for judging a model's applicability to introducing heterogeneity in households.

Infinitely lived agent models

Most energy-economic growth models used for climate change policy analysis have a dynamic structure that is based on a variant of the infinitely lived agent in Ramsey's (1928) savings model, and are the typical approach for comparing costs and benefits of alternative emissions abatement strategies (Manne, 1999; Cline, 1992; Peck and Teisberg, 1992; Nordhaus, 1994; Manne, Mendelsohn, and Richels, 1995; Nordhaus and Yang, 1996). In such models, population is treated as a single representative household that is infinitely lived. The economy is analyzed as though there were a benevolent planner acting as a trustee on behalf of both present and future generations. Schelling (1995) and others (e.g., Azar and Sterner, 1996) have criticized the strong welfare assumptions implicit in the representative agent, planner-based ILA approach. Nonetheless, ILA models have been developed with detailed production sectors for energy and other intermediate goods, have a transparent dynamic structure to describe capital accumulation, and can be calibrated to historical data. In other words, ILA models are broadly consistent with economic theory, and currently provide the most detailed empirical tools for evaluating the costs, and perhaps benefits, of controlling greenhouse gas emissions.

While these models have many similarities, they also exhibit important differences. Many models adopt a recursive, or backwards-looking, formulation of investment decisions, and are based on a variation of the Solow (1956) growth model that assumes some type of fixed savings rule, usually a constant fraction of income in each period. Fixed savings rules are usually a simplification that avoids solving a dynamic optimization problem. Nonetheless, models with fixed savings rules often compensate for this simplification with detailed energy sectors, and other realistic features such as land-use and demographic change (e.g., MacCracken, et al., 1999).

Other models in the energy economics literature adopt a forward-looking approach to capital accumulation that assumes perfect foresight about the future productivity of capital, prices, and other variables (e.g., Goulder, 1995). The properties of a dynamic competitive equilibrium with forward-looking behavior are substantially different from models based on fixed savings rules. In fact, a dynamic equilibrium with fixed savings rules is not an authentic competitive equilibrium because households are not, strictly speaking, utility maximizers. While the assumption of perfect foresight may not be realistic, it does incorporate information about the future into current decisions, and is thus an improvement over fixed savings rules from the point of view of economic theory. Moreover, perfect foresight can be interpreted as a first-order approximation to rational expectations (Fair and Taylor, 1983). Some economic growth models mix different types of savings behavior by assuming a proportion of the population solves a

dynamic optimization problem, while others follow a fixed savings rule (McKibbin and Vines, 2000).

Overlapping generations models

Overlapping generations (OLG) models provide an alternative to ILA models for dealing with sustainability and other intergenerational welfare issues (Howarth and Norgaard, 1992; Farmer and Randall, 1997). The OLG models have an explicit demographic structure to describe key life-cycle stages. Like their ILA counterparts, OLG models come with a variety of structural assumptions and solution techniques. In general, OLG models have dynamic properties that are different from ILA models (Auerbach and Kotlikoff, 1987; Geanakoplos and Polemarchakis, 1991; Kehoe, 1991). However, these differences depend critically on the assumption that savers in OLG models plan only for their own retirement, and do not care about future generations. For example if parents care about the welfare of their children, a bequest motive exists that influences savings behavior, and leads to an OLG model that is similar to ILA models in terms of discounting (Barro, 1974).

The Blanchard-Yaari-Weil model of perpetual youth provides a set of conditions under which OLG and ILA approaches are equivalent (Blanchard, 1985, Blanchard and Fischer, 1987). Marini and Scaramozzino (1995) use a version of this model to show that solving a social planner's problem with overlapping generations collapses to the representative agent framework as a special case only when there is an absence of heterogeneity among generations. In other words, the suitability of the planner-based ILA approach to environmental policy analysis reduces to an empirical issue of whether there is significant heterogeneity in the savings and consumption decisions of different generations.

Recently, several OLG models have been used to re-examine the climate change policy implications derived from the planner-based ILA models cited above. In some cases, OLG models yield results that are similar to corresponding ILA models (Stephan, et al., 1997; Manne, 1999). However, other studies find substantial differences between results with OLG and ILA models. Howarth (1996, 1998) matches a two-period OLG model to assumptions in Nordhaus (1994), and finds that modest to aggressive reductions in greenhouse gas emissions are justifiable in terms of economic efficiency. Howarth shows that, in general, ILA models can be represented as reduced-form OLG models without qualitatively important demographic features. He concludes that Nordhaus' (1994) model, in particular, is strongly sensitive to changes in the intergenerational weights used in the social welfare function. Gerlagh and van der Zwaan (2000, 2001) reach stronger conclusions, and question whether ILA models are appropriate for analysis of climate change policies. Differences in their results from other OLG models, notably Stephan et al. (1997) and Manne (1999), are attributed to an explicit representation of longer life expectancy and population aging in their three-period OLG model.

Multiple dynasty approach

We develop an energy-economic growth model that shares features of ILA and OLG approaches. We introduce demographic dynamics into the Population-Environment-Technology (PET) model, a computable general equilibrium model of the economy with detail in the energy sector, by using household projections to construct "cohorts" of households, where household age is defined by the age of the household head (Deaton, 1997). These projections, carried out with the ProFamy model (Zeng et al., 1998), represent a substantial improvement over previous household projection models, which have typically relied on simple headship rate methods that have several serious shortcomings (Jiang and O'Neill, 2004). Household cohorts from the ProFamy model are grouped into three infinitely lived dynasties in the PET model. Each dynasty contains households separated in age by the average length of a generation, taken to be thirty-years. For example, eighty-year-old, fifty-year-old, and twenty-year-old households are grouped in a single dynasty, based on the assumption that the younger households are, on average, descendents of the older households. Note that by increasing the length of a generation, the number of dynasties increases and our approach converges to the simplest OLG framework, with each dynasty represented by only one cohort, excluding any altruistic behavior. Conversely, a shorter generational length reduces the number of dynasties and is closer to a typical ILA framework. Therefore, heterogeneity in dynasties increases with generational length.

To calibrate the PET model, estimates of consumption expenditures, savings, asset accumulation, labor supply, and other variables for households in each age group were derived from the U.S. Consumer Expenditure Survey (CES). The PET model has seventeen consumer goods, including energy intensive goods like utilities and fuels, and less intensive goods such as education or health (Goulder, 1995). Households in different age groups are associated with distinct income and consumption levels, based on the CES data. Differences among age groups imply that each dynasty is associated with a specific pattern of income and consumption, based on its age distribution at each point in time. These differences have implications for energy demand, both directly and indirectly.

In our results, the most important effects are caused by differentials in labor income across age groups that create complex dynamics for consumption and savings. These dynamics, and other relationships implied by the household projections and CES data, create interacting effects that influence each dynasty's current and future consumption and savings decisions. A dynamic general equilibrium model is required to analyze these interacting effects on behavior, including how price changes for individual consumer goods affect tradeoffs between consumption and savings at the level of individual households.

Using the PET model, we are able to decompose and analyze these general equilibrium effects. We use the model to analyze how household-level variables respond to plausible changes in the age composition of U.S. households over the next several decades. We also use the model to estimate how changes in household-level variables affect the whole economy, and whether projected changes in the age composition of U.S. households could have a substantial influence on total energy demand and CO_2 emissions. Our results show that combining ILA and OLG approaches creates complicated dynamics for the age structure of each dynasty, which cause cycles

in labor income that affect savings and consumption directly, and also have indirect effects on energy demand. We find that including heterogeneity among U.S. households reduces long-term emissions, by almost 40% in our low population scenario. Effects of heterogeneity are less extreme in other scenarios, and our results estimate that emissions are around 15% lower. We also find that effects of aging on emissions can be as large, or larger than effects of technical change in some cases.

The following section describes the PET model and household economic data. The population and household projections are described in the third section, and results of simulations with the PET model are presented afterwards. We conclude with a discussion of our analysis, results, and directions for future research.

Population-Environment-Technology Model

The PET model is a global-scale dynamic computable general equilibrium model designed to analyze economic tradeoffs associated with production and use of fossil fuels, and carbon dioxide emissions. A separate document, available from the authors, gives mathematical descriptions and data sources of the PET model (Dalton and Goulder, 2001). An overview is given here, and schematic diagram of the model is provided in Figure 1. The production component of the PET model has industries with many perfectly competitive firms that produce intermediate goods, including energy and materials, and final goods. Consumption and investment are final goods, and a government sector produces a final good. Production functions for each industry in the model have a capital-labor-energy-materials (KLEM) structure, with a nested constant elasticity of substitution form. There is a separate nest for energy inputs with oil and gas, coal, refined petroleum, and electricity. Other intermediate goods are aggregated, and produced by a single materials industry. Exogenous technical change is included in the PET model using separate productivity coefficients that change over time for each input of each production function in the model. Growth in the productivity coefficients for different inputs include patterns of labor, capital, and energy augmenting technical change.

Each production function in the PET model has a substitution parameter for energy inputs that is assumed to be greater than the substitution parameter for KLEM inputs, implying that energy inputs are more substitutable in production with one another, than energy is with other inputs. Estimating or assigning appropriate values for substitution parameters is an important topic in applied general equilibrium analysis, and has been the subject of past work with the PET model. We assign values here based on a standard configuration of the model, with the substitution elasticity for energy inputs set equal to 2.0 for all industries, implying modest substitutability of energy inputs, and an elasticity for KLEM inputs of 0.4, so that demand for these inputs is relatively inelastic. Different assumptions regarding the structure of production functions and substitution elasticities appear in the energy and climate change literature (e.g. Weyant and Hill, 1999). The substitution elasticities given above are consistent with this literature. Because oil and gas, and coal industries produce primary energy from fossil fuels, outputs of these industries account for CO_2 emissions in the model.

The consumption component of the PET model is based on a population with many households that take prices as given. Each consumer good in the model is produced by a different industry, and one industry produces investment goods.

Households demand consumer goods, and receive income by supplying capital and labor to producers. Households save by purchasing investment goods, and in the model, savings behavior is determined by solving an infinite horizon dynamic optimization problem for the dynasty to which the household belongs. Consumption and savings are described in more detail below.

The following sections present parts of the PET model related to household consumption and savings, and the data used to calibrate the household component of the model. These parts of the model are central to our general equilibrium analysis of demographic factors that affect energy use and CO_2 emissions. The PET model includes international trade, and can analyze different countries and world regions, but currently we have household economic data and projections for the U.S. only. Therefore, we are primarily interested in interactions between household consumption and factor supply within the U.S. economy. We have omitted trade from work in this article to simplify the model, and isolate effects of demographic factors. We recognize that results are likely to be affected by this omission, but an initial assessment without effects of trade provides a useful benchmark against which further work can be compared, and still allows an informative comparison of results with demographic heterogeneity.

Household consumption and savings

Using age of the household head, we classify individual households in the population into three separate dynasties, indexed by i. Each dynasty consists of a large number of identical households, extending a standard assumption in neoclassical growth models that the population consists of a large number of identical households. Our extension to multiple dynasties is consistent with neoclassical growth theory, and from the point of view of general equilibrium analysis, is more natural and interesting than assuming all households are the same.

Let n_{it} denote the total number of people living in each household type at time $t \geq 0$. Each household is endowed with labor l_{it}, and an initial stock of assets $\overline{k}_i$, which are expressed in average per capita terms. Likewise, other variables are expressed in per capita terms, except where noted. Capital owned by different households is homogeneous, and perfectly substitutable in production. Households save by purchasing investment goods x_{it}, at price q_t. Investment is added to a stock of household assets, or capital k_{it}, which depreciates at rate $\delta > 0$ that is the same for all households, according to the law-of-motion

$$k_{it+1} = (1-\delta)k_{it} + x_{it}. \tag{1}$$

Household capital income is determined by the rental rate of capital, r_t, which is the same for all households. Labor's wage rate, w_t, is also assumed to be equal across households, so that differences in labor income are from variations in per capita labor supply or productivity. Labor is assumed, without loss of generality, to be the numeraire good in our analysis, and $w_t = 1$ for all t.

The PET model has 17 consumer goods, indexed by j. Per capita consumption for households of type i, of good j, at date t is denoted by c_{ijt}. The price of each consumer good is denoted by p_{jt}. Households have a common discount factor $0 < \beta < 1$, and intertemporal substitution parameter $-\infty < \rho < 1$. Preferences for different consumer goods are characterized by a substitution parameter $-\infty < \sigma < 1$ that is also assumed to be the same for all households. The expenditure share parameters μ_{ijt} are differentiated for households, and can vary over time.

This article evaluates the importance of demographic factors during a transition period of one hundred years, and does not address possible effects on the long run equilibrium. Therefore, we assume that households are identical in the long run. The rationale for this assumption is to establish consistency for comparing results in cases with and without demographic heterogeneity. In cases with demographic heterogeneity, values for per capita labor supply, l_{it}, and expenditure shares, μ_{ijt}, tend over time to equal values for all i. These long run conditions imply the terminal or long run balanced growth path equilibrium with demographic heterogeneity is the same as the reference case with representative households.

Simulations with the PET model start at 2000. The transition period in the model is one hundred years, the time span of the demographic projections described below. Simulations continue for another hundred years, during which we assume that demographic heterogeneity gradually disappears so that all households are identical at 2200. Even without these long run restrictions on l_{it} and μ_{ijt}, if capital income tax rates ϕ_{it} are the same for each i, then other assumptions in the model, described below, imply that asset stocks of each dynasty, k_{it}, expressed in per capita terms, converge endogenously to equal values. In other words, per capita asset holdings are the same across dynasties in the long run, even if labor income or consumption patterns are different. This result depends on the tax rates for capital income being the same for each dynasty, but is not directly affected by the tax rate on labor income θ_{it}.

In the model, households receive per capita lump-sum transfers from the government, g_{it}, which is a net value so that negative values represent net payments by households. Private transfers, among households, are represented in the model, but are not distinguished here to save notation. The budget constraint for a household in dynasty i at date t is

$$\sum_{j=1}^{17} p_{jt} c_{ijt} + q_t x_{it} = (1-\theta_{it}) w_t l_{it} + (1-\phi_{it}) r_t k_{it} + g_{it}. \qquad (2)$$

Demand for consumption goods is influenced by tradeoffs across goods at each t, and by dynamic factors related to savings and investment. Households take prices as given, are rational with forward-looking behavior, and in particular have perfect foresight of future values for all variables that affect their investment decisions. These variables include relevant prices, such as q_t and r_t, and future asset holdings by other households. Forward-looking behavior implies that equilibrium conditions in the model are dynamically consistent. Although the assumption of perfect foresight is restrictive in terms of the information structure of the model, this approach is preferable to an even

more restrictive information structure, such as ignoring the value of future information altogether, which is true of models that use fixed savings rules to drive investment. Perfect foresight may be justified either by appealing to some type of certainty equivalence, or as the first step in an algorithm that converges to a rational expectations equilibrium (Fair and Taylor, 1983).

Tradeoffs across goods are described with a constant elasticity of substitution expenditure function, and over time by a constant elasticity of substitution intertemporal utility function. The PET model does not include leisure in household utility functions. Therefore, labor supply is inelastic, and given by each household's labor endowment, l_{it}, which is determined by the CES data described below.

Given prices, and subject to constraints (1) and (2), each household of type i chooses sequences of consumption $\{c^*_{ijt}\}$, for all j, and investment $\{x^*_{it}\}$, to maximize

$$\frac{1}{\rho}\sum_{t=1}^{\infty}\beta^t n_{it}\left(\sum_{j=1}^{17}\mu_{ijt}c_{ijt}^{\sigma}\right)^{\frac{\rho}{\sigma}}. \tag{3}$$

We describe two steps in the solution algorithm for each household's optimization problem to aid explanation of results below. Other parts of the dynamic algorithm are described in detail in the PET model's technical document (Dalton and Goulder, 2001). In the first step, demand for each consumer good is determined from prevailing prices by minimizing total expenditures, subject to a given level of utility, at each date t. A dual price index is used to calculate the marginal cost of consumption for each household, which varies across households because of heterogeneity in expenditure shares. The price index dual to the expenditure function in (3) has a closed-form expression for each household type,

$$\overline{p}_{it}=\left(\sum_{j=1}^{17}\mu_{ijt}^{\frac{1}{1-\sigma}}p_{jt}^{\frac{\sigma}{\sigma-1}}\right)^{\frac{\sigma-1}{\sigma}}. \tag{4}$$

Each price index includes a weighted sum that depends on expenditure shares for each household, and the prices of consumer goods faced by all households. In the general equilibrium PET model, prices of consumer goods are influenced in complex ways by changes in factor supply, including effects on labor of an aging population. The dual price index (4) summarizes price changes across goods to indicate overall effects on the marginal cost of consumption for each household. The marginal cost of consumption $\overline{p}_{it}$ is compared to the price of investment goods q_t to determine optimizing tradeoffs for households between consumption and savings at each t.

The second step in each household's problem is solving for paths of consumption expenditures and investment, for all t, that maximize (3). While price changes for consumer goods have static effects on the pattern of consumption, the tradeoff between consumption and savings affects model dynamics. The model's solution algorithm uses the Euler equations that are first-order conditions from maximizing (3), subject to (1) and (2), which after manipulation imply

$$\frac{q_t}{\overline{p}_{it}}\left(\sum_{j=1}^{17}\mu_{ijt}c_{ijt}^{\sigma}\right)^{\frac{\sigma-1}{\sigma}}=\beta\left(\frac{r_{t+1}+(1-\delta)q_{t+1}}{\overline{p}_{it+1}}\right)\left(\sum_{j=1}^{17}\mu_{ijt+1}c_{ijt+1}^{\sigma}\right)^{\frac{\sigma-1}{\sigma}}. \tag{5}$$

The Euler equations (5), capital law-of-motion (1), budget constraint (2), and transversality conditions

$$\lim_{t\to\infty}\lambda_{it}k_{it}=0 \tag{6}$$

are necessary and sufficient for maximizing (3). Moreover, a solution to (3) is unique (Stokey and Lucas, 1989). The transversality conditions ensure that each household's sequence of capital stocks is bounded. We use this fact to compute a steady state level of the capital stock that is the same for all households, k^*, which satisfies conditions assumed above.

The PET model allows labor augmenting and other types of technical change. Let γ denote the long run rate of labor augmenting technical change. The long run condition used to compute the steady state level of the capital stock is given by the steady state, or balanced growth path, ratio of the return on capital to the price of investment goods

$$(1-\phi_{it})\frac{r_t}{q_t}=\frac{1}{\beta}(1+\gamma)^{1-\rho}-(1-\delta). \tag{7}$$

By assumptions above, parameters on the right-hand side of (7) do not depend on time, and are the same across household types. Because households face the same prices on capital and investment, if capital income tax rates are the same across households, then per capita asset accumulation is equal in the long run, which was mentioned above in the description of long run conditions. The PET model uses the Euler equations (5), and a variation of the Fair-Taylor algorithm (Fair and Taylor, 1983), to compute the dynamic transition from $\overline{k}_i$ to k^* for each household.

Production, consumption, and income data

The pattern of expenditure shares on energy and other inputs varies across industries. Brenkert et al. (2004) describes the benchmark input-output data that are used in the PET model. These data are used to calibrate the PET model's production functions, and are derived from the U.S. National Income and Product Accounts (NIPA), and other sources. To calibrate the model's household demand system, we use data from the U.S. Consumer Expenditure Survey (CES). The CES is a nationally representative survey composed of two parts: An Interview survey, and a Diary survey. In some cases, CES survey results are different from NIPA data. To resolve differences in the consumption and production data, we use CES data to determine aggregate expenditure shares of each consumer good at the economy-wide level, and apply these economy-wide shares to total consumption expenditures in order to determine the output of each consumer good industry. Conditional on the CES-determined output levels, demands for energy and other inputs of each industry are determined using input-output ratios derived from NIPA data. Additional details on the calibration procedure are described in Dalton and Goulder (2001).

The CES Interview survey has a sample size of approximately 5,500 households and is based on recall of expenditures over the past three months and income over the past year. It is aimed at capturing relatively large expenditures and those that occur on a regular basis. The Interview survey has a rotating panel design: Each panel is interviewed for five consecutive calendar quarters and then dropped from the survey. A new panel is then introduced. Therefore, about 20% of the addresses are new to the survey each quarter. The Diary survey is based on a written account of expenditures over the past two weeks, and is aimed at better capturing small, frequent purchases.

The CES data are used for economic analyses of consumption (e.g., Paulin, 2000; Schmitt, 2004). Details of our work with the CES data are described in a separate document (O'Neill, 2005). In brief, data are integrated by choosing for each consumption category whether the Interview or Diary data are more reliable according to the Bureau of Labor Statistics. The CES categories are then aggregated into the 17 consumer good categories used in the PET model (Goulder, 1995). Mean annual per capita expenditures for these goods are calculated by household type. Household types are defined by characteristics of the "reference person" in the household, defined in the CES data as the first member mentioned by the respondent when asked to "Start with the name of the person or one of the persons who owns or rents the home." We use the reference person as our "householder" or "household head".

Values in Table 1 show how consumption of the 17 consumer goods varies across age groups using expenditure shares, or fraction of total expenditures, for each good. We use these expenditure shares as benchmark data for the PET model, which are converted to share parameters μ_{ijt} that calibrate the model's household demand system. To summarize key differences in expenditure patterns, we distinguish between younger versus older households. As discussed below, the household projections show that future compositional changes are driven by shares of the population at opposite ends of the age range in Table 1. As seen in the table, older households spend a substantially larger share of income than younger households on utilities, services, and health care, and a substantially smaller share on clothing, motor vehicles, and education.

Since the most energy intensive goods are utilities and fuels, expenditure patterns in Table 1 imply that aggregated consumption in older households is more energy intensive than consumption in younger households. The utilities category is about two-thirds electricity, with the remaining third split between natural gas, and payments for water and sewer services. Electricity demand is driven principally by appliance use, and natural gas consumption by space conditioning (EIA, 2004). Although older households spend a larger fraction of income on utilities, absolute levels of expenditures on utilities are roughly the same across the younger and older households when income differences are taken into account, which is consistent with previous work on patterns in residential energy use (Bin and Dowlatabadi, 2005). The fuels category is 80-90% gasoline, and is therefore influenced mainly by car use. The remainder is split primarily between fuel oil and natural gas. While old households spend a larger share of per capita income on fuels than young households, income differences imply the absolute level of fuel use is substantially smaller, which is consistent with other work (O'Neill and Chen, 2002).

Government transfers in Table 2 include social security, workers compensation, unemployment benefits, and other kinds of public assistance, and these favor older

households in per capita terms by a wide margin. Savings includes retirement contributions, down payments on purchases of property, mortgage payments, capital improvements, and investments in own businesses or farms. Assets include the value of financial accounts and securities plus the equity share of property.

Household Projections and Dynasties

In Table 3, we present population and household projections from the ProFamy model for three scenarios. The ProFamy projections run from 2000 to 2100. For simplicity, population is assumed to stay constant after 2100 in our analysis. Values in the table give total population in each year of the projection, followed by percentage shares of the population living in households of different ages, in order to more clearly distinguish differences in both scale and composition across scenarios. Work with the ProFamy model, which jointly projects population and households, and methods for developing the U.S. household projections, are described in a separate paper (Jiang and O'Neill, 2005), and an overview is given here.

The scenarios we use are based on a set of plausible demographic assumptions for fertility, mortality, migration, and union formation and dissolution rates that span a wide range of outcomes in terms of population size, age structure, and household size. Assumptions for demographic rates, and how to combine them in each scenario, were chosen in order to produce one scenario with relatively small, old households (our low scenario), one scenario with relatively large, young households (our high scenario), and one scenario with moderate outcomes (our medium scenario). Population size varies among the three scenarios by more than a factor of four at 2100. An important property of the projections is that the age composition of households in the low scenario is markedly different from the pattern in high and medium scenarios, with people living in older households making up a much greater percentage of the population under conditions of low fertility and mortality.

We use the population distribution by household age to construct dynasties that consist of a series of cohorts of households of different ages at each point in time. The procedure for constructing cohorts and dynasties from the ProFamy projections is outlined in Figure 2. This procedure implies that each dynasty has a specific household age distribution at each point in time, based on the population size of each cohort.

We use benchmark data from the CES for households of different ages to derive weighted-mean per capita labor supply and expenditure shares for consumer goods for each dynasty over time. Per capita labor supply for each age group is derived from the CES data, and multiplied by the population living in households of different ages. The sum of these products determines total labor supply of each dynasty. Then for each dynasty, the ratio of total labor supply over the dynasty's total population size determines the mean per capita labor supply. Expenditure shares are translated into share parameters for the PET model's demand system during model calibration. In this way, the ProFamy projections are used to determine the changing composition of the population across household types within each dynasty. The CES data are used to calculate average per capita labor supply, and household expenditure shares within each dynasty that change over time to reflect the changing demographic composition.

Results

We conducted two sets of simulations with the PET model to analyze the effects on emissions of population aging in the United States over the next hundred years. To isolate effects of demographic factors, the first set does not include technical change. The second set includes technical change, and is organized in the same way as the first set of simulations, which is divided into three groups. The first group uses a configuration of the PET model with a single representative household and no aging. This group is considered the starting point for our analysis, and is similar to the typical approach used currently for many models in the climate change literature. The second group uses a configuration of the model with heterogeneous households that includes three dynasties with age-specific demographic heterogeneity in consumption patterns, initial capital, and labor supply. A comparison of results from the second group of simulations with those in the first group provides the basis for our main conclusions on whether the introduction of demographic heterogeneity can substantially affect emissions.

The third group of simulations also uses a representative household configuration of the PET model with a single dynasty, but aggregate labor supply changes over time to be consistent with a changing age structure. This "representative households with aging" configuration has the same total labor supply as the heterogeneous household configuration, and this comparison tests whether results obtained with heterogeneous households can be approximated using a simpler model, with a single dynasty. Each of the three groups consists of 12 simulations, based on the low, medium, and high household projections described above, and stratified by four combinations of household substitution parameters for sensitivity analysis. We use low, medium, and high household projections to test the effects of aging under alternative, but plausible, population scenarios of future demographic changes.

Heterogeneous versus representative households

The model configuration with heterogeneous households has three dynasties that follow the dynamics in Figure 2. For each dynasty, age-specific weights for consumption expenditures are derived from values in Table 1. Initial capital and weights for labor supply are derived from Table 2. The model configuration for representative households without aging has per capita expenditure shares that are equal to the mean values in Table 1. Labor supply, consumption expenditures, and other variables are equal in per capita terms, and are derived from mean values in Table 2. Benchmark values for transfers and income tax rates are set to zero to simplify the interpretation of results.

The multiple dynasty structure of the model configuration with heterogeneous households has interesting implications for the dynamics of labor income and capital. Graphs in Figure 3 show these dynamics. The top graph in Figure 3 shows per capita labor income for the three dynasties. Population aging causes the downward trends in per capita labor income for the dynasties, and the effects of aging are strongest in the low population scenario. In contrast, per capita labor income for a representative household is a flat line at $20,000 per year. The dynasties can be identified from their supply of labor in 2000. For example in 2000, dynasty 1 has a cohort in the 45-55

group, which has the largest per capita labor income. Thus, dynasty 1 has the largest labor income in 2000.

Labor income directly affects the dynamics of savings and capital, which are presented in the bottom graph of Figure 3. Capital for a representative household is illustrated with a flat line at about $70,000 per person. In Figure 3, the variation across dynasties in each year exceeds the variation across population scenarios within each dynasty until about 2050, after which variation across scenarios is larger. An implication is that age structure is important in the short run, but because of population momentum, effects of aging in the short run are similar across population scenarios. However in the long run, aging and the population scenario have differential effects.

The graphs in Figure 4 compare results for total CO_2 emissions, and per capita CO_2 emissions, over time for heterogeneous and representative households. Total emissions with heterogeneous households are driven by changes in age composition of the population. Results show that total emissions with heterogeneous households range from 0.9 to 5.1 billion metric tons per year at 2100. For representative households, changes in emissions over time are due to changes in the size of the population, and emissions range from 1.4 to 5.9 billion metric tons per year by 2100 in the three population scenarios.

The top graph in Figure 4 shows that heterogeneity leads to lower emissions in each population scenario. Differences between emissions in simulations with heterogeneous and representative households are a combination of direct effects from changes in labor supply due to aging, and indirect or general equilibrium effects from changes in capital accumulation, prices, or other factors. Aging implies fewer young workers, whose per capita labor contribution tends to be greater than the population mean. Hence, aging implies a reduction in aggregate labor supply for a given population size.

The bottom graph in Figure 4 shows per capita emissions for heterogeneous and representative households in each population scenario with no technical change. Because total population within each scenario is the same, differences in per capita emissions are caused exclusively by changes in total emissions. Per capita growth in output, measured by gross domestic product (GDP) per person, is essentially zero with representative households, and changes in carbon intensity, represented by CO_2 emissions per dollar of GDP, are also minor. Consequently, per capita emissions with representative households are essentially constant over time and across population scenarios, around 5.3 tons per person.

The bottom graph in Figure 4 shows that demographic heterogeneity in the low population scenario reduces per capita emissions by about two metric tons per person by 2100. Per capita labor supply, which is a weighted average over different age groups, is similar in medium and high population scenarios, which is why per capita emissions are relatively close. The scarcity of young workers drives results in the low population scenario, which has substantial effects on per capita emissions. The range of per capita emissions between low and high population scenarios is about one ton per person by 2100, but because of population momentum, these effects are not apparent until after 2050.

Population aging and representative households

A model configuration with identical households is used to evaluate whether the main effects of population aging can be incorporated into the model simply by scaling the labor supply of representative households. This representative household configuration with aging has the same level of aggregate labor as the model with heterogeneous households. In comparison to the model with representative households and no aging, the long-term emissions reductions for representative households with aging are about 85% of those associated with heterogeneous households for our reference values of the household substitution parameters. Thus, much of the effect of population aging in our reference case can be captured in a representative household model with dynamic labor supply. However, whether a representative household model is adequate in other cases is unclear. For example in simulations with alternative values of the household substitution parameters, described next, the direction of these effects changes.

Sensitivity analysis of household substitution parameters

The substitution parameters ρ and σ in each household's utility function from (3) directly affect results. Our reference value for households' intertemporal substitution parameter is $\rho = 0.5$, or an elasticity of $1/(1-\rho) = 2.0$. This value is taken from Goulder (1995), who reports it is in the range of estimates obtained by Hall (1988), and Lawrance (1991). Our reference value for the substitution elasticity of consumer goods is also 2.0, or $\sigma = 0.5$. We conduct a sensitivity analysis to examine how results with inelastic values for ρ and σ differ.

Values for the intertemporal substitution elasticity are important in macroeconomic models (Guvenen, 2003), and obtaining reliable and consistent estimates has been a problem. Beudry and van Wincoop (1996) use panel data for U.S. states, and report estimates close to a value of one, and significantly different from zero. Note that an elasticity of one implies a ρ of zero, which is equivalent in the limit to the natural log utility function. An elasticity of zero implies $\rho \to -\infty$, which is the Leontief case of perfect complements. A recent study, using a new econometric approach, estimates intertemporal substitution elasticities less than one, but not significantly different from zero (Yogo, 2004). Therefore, negative values for ρ seem plausible. Inelastic values for σ are also plausible. To represent inelastic demand for different consumption goods, we use an alternative value for the consumption substitution parameter of $\sigma = -3.0$, or an elasticity of 0.25. To represent inelastic consumption over time, we use an alternative value for the intertemporal substitution parameter of $\rho = -3.0$. The reference and alternative values for these parameters are intended to span a plausible range that includes both substitutes and complements in consumption.

Values in Table 4 summarize comparisons among the model configurations, substitution parameters, and population scenarios. Our primary comparison is between the two model configurations that consider population aging. Values in the table for the reference case with $\rho = 0.5$ and $\sigma = 0.5$ are taken from the simulations shown in Figure 4. In this case, for the low population scenario, emissions are about 37% less in 2100 with heterogeneous households relative to the representative household configuration without aging. Most of this difference is due directly to scale effects from

changes in labor supply associated with population aging because emissions at 2100 for the representative household configuration with aging are about 31% less than for representative households without aging. The remaining difference occurs through capital dynamics and general equilibrium effects. The effects of population aging on emissions are smaller for medium and high population scenarios, about 18% and 13% respectively, because the effects of population aging are not as strong.

For each population scenario, values in Table 4 for the representative household configuration with aging do not vary much for different substitution parameters. The reason is that variation in exogenous labor supply alone has neutral scale effects on the PET model, which is a standard property of neoclassical growth models. Therefore, baseline emissions for the single dynasty cases are scaled by the size of the labor force, but are not sensitive to the choice of household substitution parameters. Results in Table 4 for heterogeneous households are also insensitive to the consumption substitution parameter σ for cases with the reference value of $\rho = 0.5$ for the intertemporal substitution parameter.

However, most energy-economic growth models include only a single consumer good, and this type of aggregation is equivalent to assuming perfect complements, $\sigma \to -\infty$, for different consumer goods. In Table 4, reductions in baseline emissions with the inelastic value of $\rho = -3.0$ are smaller than for the reference case. In this case, compared to representative households with no aging, reductions in baseline emissions for heterogeneous households are smaller than representative households with aging in corresponding population scenarios. As noted above, the implication is that simply scaling the labor supply of a single, representative dynasty to account for future aging gives ambiguous results that either underestimates or overestimates, depending on true values of household substitution parameters, the emissions reductions associated with an aging population.

According to Table 4, emissions reductions for heterogeneous and representative households with aging are similar for cases with the inelastic value of $\sigma = -3.0$ for the consumption substitution parameter. However, substitutability of different consumer goods seems plausible in a developed country like the U.S. With $\sigma = 0.5$ and $\rho = -3.0$, differences in emissions reductions between heterogeneous and representative households with aging are substantial in early years of the simulations, for each population scenario, and differences remain large, throughout the simulation horizon, for the low scenario.

Demography and technical change

Technical change is expected to be an important factor in future CO_2 emissions, and is a prominent feature of current energy-economic growth models (Weyant, 2004). The flexible production structure of the PET model can simulate different patterns of technical change. For comparison, the SRES scenarios provide a logical framework for organizing alternative assumptions about future technical change (IPCC, 2000). Our second set of simulations uses the SRES A1 scenario to compare emissions with representative and heterogeneous households in the presence of a plausible pattern of future technical change according to the SRES methodology. The simulations with technical change are based on the representative household configuration of the PET

model, with our medium population projection to be consistent with the A1 scenario, and our reference values of 0.5 for both household substitution parameters. Productivity growth rates for labor and energy were selected so that variables related to GDP and CO_2 emissions in the PET model match averages for different models used in the SRES A1 scenario for the OECD region, as seen in Figure 5.

The SRES A1 scenario uses medium population projections for the OECD countries, but on average, these differ in growth rates by about 0.5% per year from our medium projection for the U.S. Therefore, we match the PET model to average growth rates for per capita GDP from SRES. To match these growth rates in the PET model, labor productivity measured in efficiency units is assumed to grow at 1.6% per year through 2160, and then gradually falls to zero at 2200. Growth in labor productivity increases the scale or size of the economy, but does not affect the carbon intensity of output, which is measured by the ratio of CO_2 emissions over GDP. To match average rates of decline in carbon intensity for OECD countries in A1, we assume productivity growth rates of 2.9% per year through 2160 in the use of refined petroleum and electricity by the energy and materials producing industries in the PET model. After 2160, we assume these growth rates gradually fall to zero at 2200, and the economy reaches a steady state. The top graph in Figure 5 shows the relative growth rate over time of per capita U.S. GDP from the PET model under these assumptions, compared to the SRES models for this scenario in the OECD region. The bottom graph in Figure 5 shows the relative annual rate of change over time in carbon intensity. Note the PET model resembles the AIM model in both graphs, which is the "marker" for the A1 emissions scenario.

The graphs in Figure 6 compare results for U.S. GDP and CO_2 emissions with and without technical change for representative and heterogeneous households. The top graph shows the effects of population aging on U.S. GDP as the difference between curves for representative and heterogeneous households. The upward trend in the pair of curves without technical change is attributed to population growth in our medium household projection. For the upper pair of curves, the scale of the economy grows with technical change, and the absolute difference in GDP with representative and heterogeneous households is close to $20 trillion by 2100, expressed in year 2000 dollars, compared to about $4 trillion without technical change. However, the relative difference in GDP is about the same in both cases, around 16% less with heterogeneous households.

The bottom graph in Figure 6 shows the effects of demographic heterogeneity and technical change on CO_2 emissions. The results of these comparisons are interesting. As also seen in Figure 4, CO_2 emissions exhibit a roughly linear increase over time with the medium household projection and representative households. Changes in the composition of the population with heterogeneous households affect emissions relatively soon in the simulation horizon, reducing emissions almost 10% by 2030, compared to the corresponding case with representative households. In contrast, differences in emissions between representative households with and without technical change are relatively minor before 2060, and the effects of technical change on emissions do not catch up to the effects of population aging until 2086. The explanation for this result derives from the fact that both population growth and economic growth have scale and composition effects.

In the medium household projection, the composition effect from population aging is relatively strong compared to the scale effect from population growth. The scale effect for technical change is due primarily to increases in labor productivity. The composition effect for technical change comes from productivity improvements in the use of refined fuels and electricity, relative to the use of more carbon intensive energy sources such as oil and coal. The process of fuel switching induced by this type of technical change causes a steady decline over time in the carbon intensity of output. Other things being equal, the decline in carbon intensity would reduce emissions. However in Figure 6, emissions reductions induced by the composition effect of declining carbon intensities are neutralized for several decades by the contemporaneous increase in emissions caused by the scale effects of labor augmenting technical change.

While the comparison of effects on emissions from technical versus demographic change is interesting, Figure 6 shows the combined effects are also important, and close to additive in the long run for this particular group of simulations. The population composition effect in the absence of technical change reduces emissions by about 18% by 2100. Effects of energy and labor augmenting technical change reduce emissions by another 24%, relative to emissions with heterogeneous households and no technical change. In comparison, effects of both aging and technical change in the bottom curve on the graph reduce emissions by 38% relative to the top curve with representative households and no technical change.

Results in Figure 6 are derived from a single group of simulations, and are not conclusive. Simulations using the SRES A1 scenario are intended to illustrate the interesting possibilities of combining effects of demography and technical change in the PET model. The results of sensitivity testing in Table 4 imply the relative strengths of scale and composition effects depend on the parameter values, population scenario, and model configuration used for analysis. For example in other groups of simulations with our low household projection and reference values for the household substitution parameters, the effects of technical change in A1 do not catch up to the effects of aging on emissions before 2100. This case is interesting because the average population growth rate for OECD countries in the A1 scenario, 0.2%, is in fact closer to the average population growth rate in our low projection, -0.1%, than to the average growth rate in our medium projection, 0.7%. On the other hand, emissions are much closer with our inelastic value for the consumption substitution parameter, and effects of technical change on emissions surpass the effects of aging at 2045, instead of 2086 with the reference value for this parameter. Of course, these results will vary across SRES scenarios, which is a topic for future research.

Discussion

Demographic factors are usually treated implicitly in energy-economic growth models. This article describes a modeling framework, household projections, and economic data to estimate the effects of population aging on U.S. energy use and CO_2 emissions. Our framework is based on the Population-Environment-Technology (PET) model, a standard neoclassical growth model with detail in energy inputs and consumer goods that is extended to incorporate population age structure and other demographic features. The PET model is decentralized, there is no social planner, and the dynamic competitive

equilibrium in each simulation is solved directly from market clearing conditions, and the maximizing behavior of households and firms.

For the model to be consistent with the interpretation of decentralized forward-looking households over an infinite planning horizon, we assume intergenerational altruism in the form of parents caring about the welfare of their children. While this form of altruism is implicit in the dynastic structure of neoclassical growth models, we developed an explicit procedure for linking cohorts into three heterogeneous infinitely lived dynasties. Each dynasty contains households separated in age by the average length of a generation, which is about thirty-years, so that on average, younger households are descendents of the older households. Taken together, the three dynasties combine features of existing infinitely lived agent (ILA) and overlapping generations (OLG) models, and this approach offers several advantages.

To populate the three dynasties, we use household projections from the ProFamy model, which is a major improvement over previous household projection methods. We develop low, medium, and high population scenarios with the ProFamy model. The influence of population aging is strongest in our low scenario, which exhibits large compositional changes in the age structure of the population over time. Compositional changes due to aging are present in the medium and high scenarios, too, but to a lesser degree. We developed age profiles of expenditure patterns, labor income, asset holdings, and other economic variables for each dynasty from the U.S. Consumer Expenditure Survey (CES). These age profiles have measurable differences across age groups both in the levels and composition of labor and capital income, and expenditure shares for the seventeen consumer goods in the PET model. Age-specific heterogeneity in factor incomes, consumption patterns, and population composition create interacting effects that flow back and forward through the economy. A decentralized general equilibrium framework, such as the PET model, is needed to decompose and analyze these interacting micro and macroeconomic effects. Scarcity of labor and capital at a point in time, as well as expected future changes in these factors, are signaled by market prices that are observed by households. These price signals are incorporated directly into consumption and savings decisions of households in the PET model.

The OLG structure of household cohorts in the PET model implies that per capita labor income and capital accumulation within each dynasty are cyclical, with a general downward trend from the effects of aging on per capita labor supply. Labor income for each dynasty follows the same thirty-year pattern, increasing for ten-years after a young cohort enters the workforce, followed by a steady twenty-year decline that is caused by other cohorts aging. Capital accumulation of each dynasty is influenced by labor income, but the general pattern is qualitatively different. Capital is accumulated by each dynasty for the ten-year period that labor income rises, but then is relatively stable for a decade, followed by a ten-year decline. This general pattern implies that dynasties save during periods of high labor income when there are many young or middle-age households, and spend down their capital stocks when households are older and labor income is lower. This general pattern is consistent with the life-cycle savings behavior found in OLG models.

We use the PET model to estimate effects of population aging by comparing emissions baselines from simulations with age-specific heterogeneity to baselines without aging and representative households. To isolate demographic effects, the first

set of simulations does not include technical change. Our results compare two types of heterogeneous households to representative households. The first type has heterogeneity only in expenditure shares for different consumer goods that depends on age of the household head. The second type has heterogeneity in expenditure shares, and also in sources of household income, including capital and labor.

The first type of heterogeneity affects only the composition of demand, but our results show these effects are negligible. In contrast, age-specific heterogeneity in labor income reduces CO_2 emissions by 11%, 18%, and 37% per year by 2100 in the high, medium, and low population scenarios, respectively. In our reference case, a labor scale effect accounts for about 85% of these reductions, and the other 15% is from capital dynamics and general equilibrium effects. However, sensitivity analysis indicates that simply scaling labor supply of a single representative dynasty to account for population aging has ambiguous effects that either underestimate or overestimate emissions reductions from population aging, depending on values of household substitution parameters, about which we are uncertain.

A second set of simulations compares emissions baselines with population aging to representative households in the presence of technical change. Assumptions about technical change are based on the SRES A1 Scenario for OECD countries. For our reference values of household substitution elasticities, effects on emissions from aging and decreases in carbon intensity from technical change are additive in the long run. The most interesting result is that effects of aging on emissions are as large, or larger, than effects of technology in some cases.

Results in this article support further consideration of demographic factors in emissions projections, and suggest these factors may be critical to the development of new emissions scenarios, particularly those based on low population projections for the U.S., because effects of aging are most important in this scenario. However, our model and current approach are based on several simplifying assumptions that ignore feedbacks, which could dampen, or deepen, economic effects of an aging population. For example, this article considers population age structure, but changes in household size, the proportion of immigrant households, or other demographic factors are probably also important. In addition, labor participation by older households has been increasing over the past decade, and this trend seems likely to continue, particularly if wages rise in response to changes in aggregate labor supply. We have ignored these effects by treating labor supply as an exogenous variable.

Resolving these issues is beyond the scope of this article, the aim of which is to present a new method for isolating effects of population heterogeneity for age, the most widely recognized demographic factor, in a dynamic general equilibrium setting, and establish an initial set of empirical bounds on these effects. This initial assessment provides an informative comparison of results with and without demographic heterogeneity, in the absence of some potentially confounding factors such as international trade, and thus provides a useful benchmark against which further work can be compared. Results in this article suggest that demographic factors have the potential to substantially affect long-term emissions for the U.S., and motivate further study of relationships between demographic change, economic growth, and energy use.

Future work could address some limitations of the work described in this article. First, our analysis of technical change could be extended to other SRES scenarios.

Second, household size and nativity could be included as additional demographic factors. Third, empirical estimates are needed for the household substitution elasticities used in this article. These values are associated with the substitutability of consumption over time, and across different goods, including energy intensive goods like utilities and fuels, and less intensive goods such as education or health. Some results in this article are sensitive to these values. Data from the U.S. Consumer Expenditure Survey (CES) could be used to estimate substitution elasticities for consumer goods, and test hypotheses about whether these vary among age groups and other demographic categories.

An important limitation of our current approach is that labor supply is inelastic, and does not respond to changes in real wages or other variables. Clearly, increasing labor supply is a plausible response by older age groups to changes in real wages, policy, life expectancy, or other factors that provide an incentive to delay retirement, or otherwise continue working. A thorough analysis of household economic data should be done to infer a reasonable range of alternatives for age profiles of labor supply, and to develop a set of scenarios for future labor force participation by different demographic groups.

Another important restriction is that results in this article are for the U.S. only, under assumptions of a closed economy. Several models, including the PET model, have the structure to include multiple countries or regions, and international trade, but demographic projections for other countries to support the type of analysis in this article do not currently exist. The data required for future work on these countries are extensive, including household projections, household survey data, and production data for different consumer good industries. Results with international trade are difficult to predict *a priori*, and will depend on the countries being compared. Countries that differ in age distribution will gain from trade, since labor intensive goods can be exported by the country with the younger population. International trade might be expected to diminish the effects of aging on energy use and CO_2 emissions, relative to an autarky situation without trade. However, population aging is a global event (O'Neill, MacKellar, and Lutz, 2001). Extrapolating results in this article suggests there may be a general upward bias in current global emissions projections, which should provide additional motivation for research in this area.

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Figure 1: Overview of the PET model. Households demand consumption and investment goods (C and I), and supply capital and labor (K and L). Final good producers supply C, I, and a government good (G). Intermediate goods producers supply energy and materials (E and M). The primary energy producers, which are coal, oil and gas industries, create CO_2 emissions.

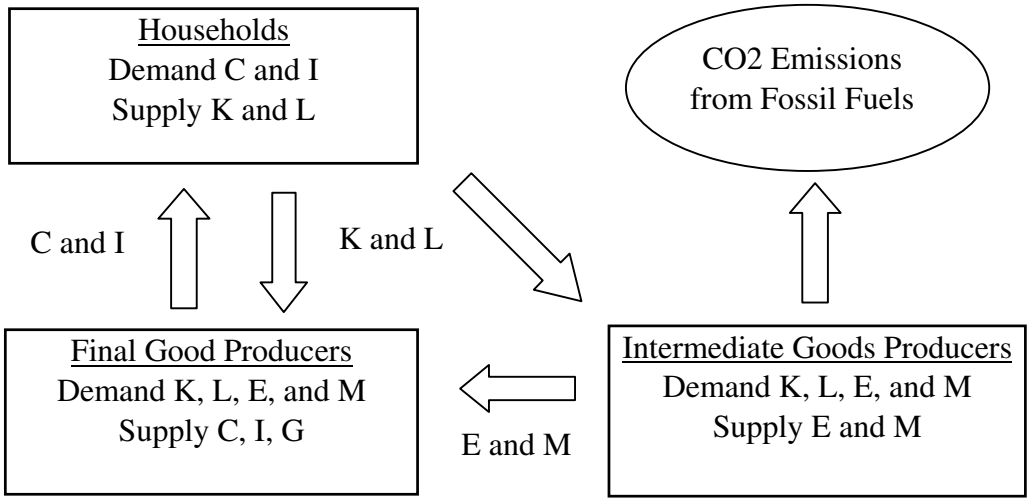


Figure 2: Cohort structure of dynasties in the PET model. Dynasty 1 consists of cohorts 1a-f (boxes). Dynasty 2 consists of cohorts 2a-f (circles). Dynasty 3 consists of cohorts 3a-e (triangles).

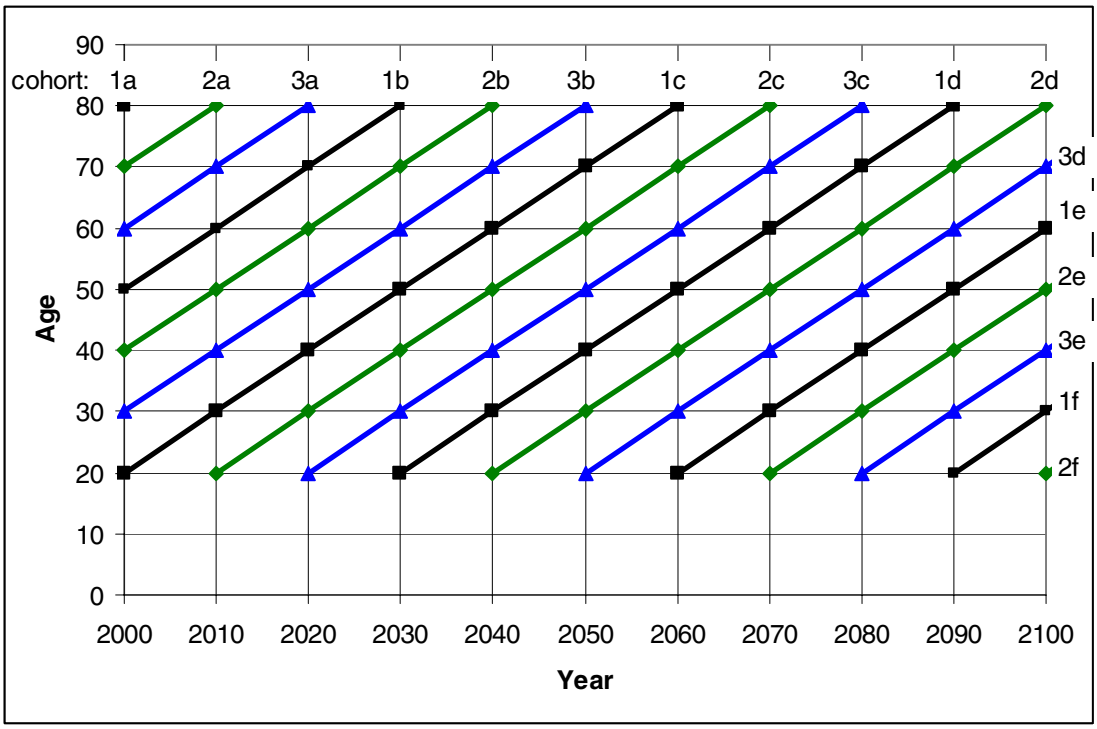


Fig. 3: Per capita dynamics for labor income (top) and capital stock (bottom) in thousands of year 2000 dollars for the 3 dynasties in the low (hatched), medium (light solid), and high (dark solid) population scenarios.

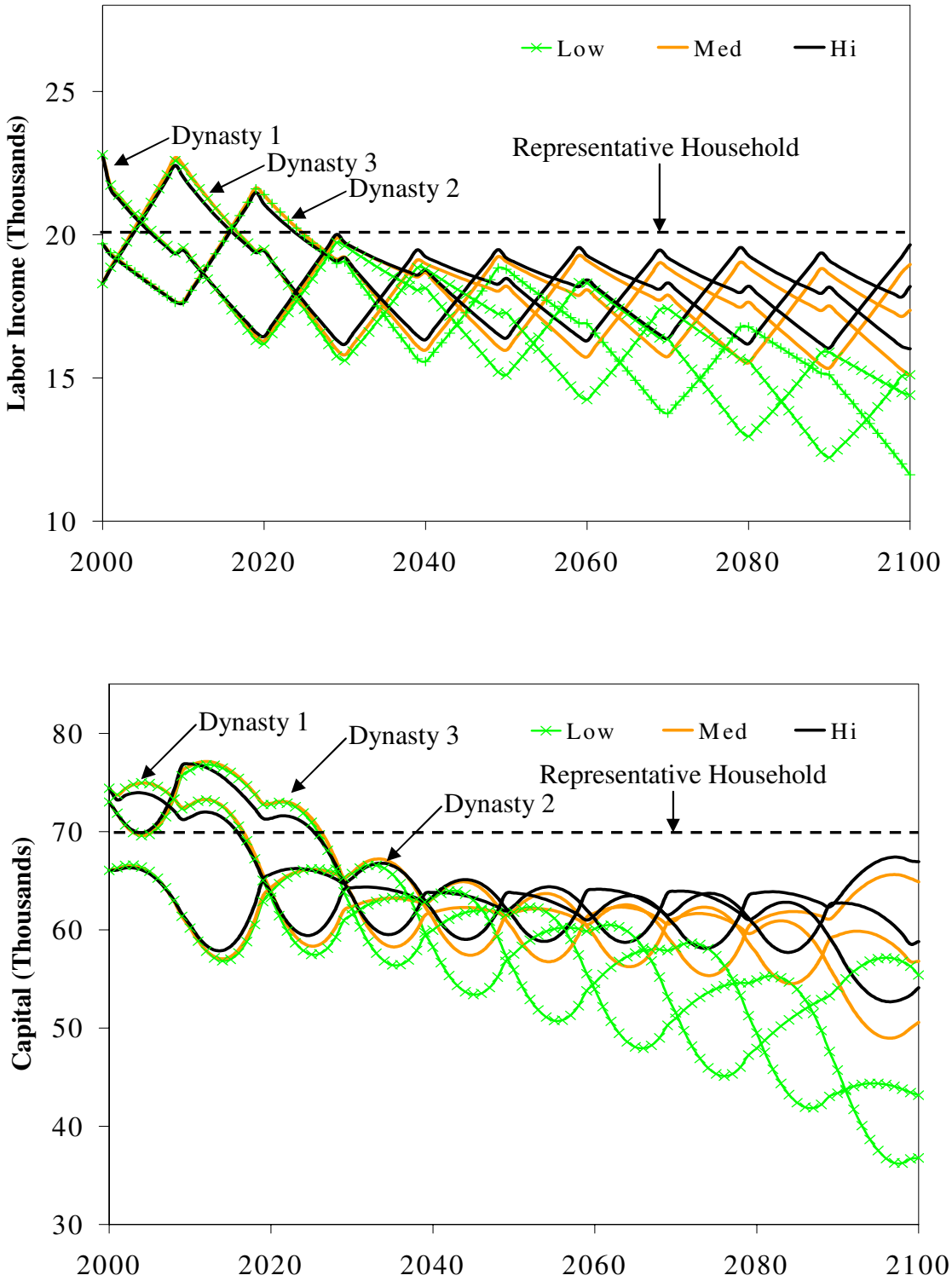
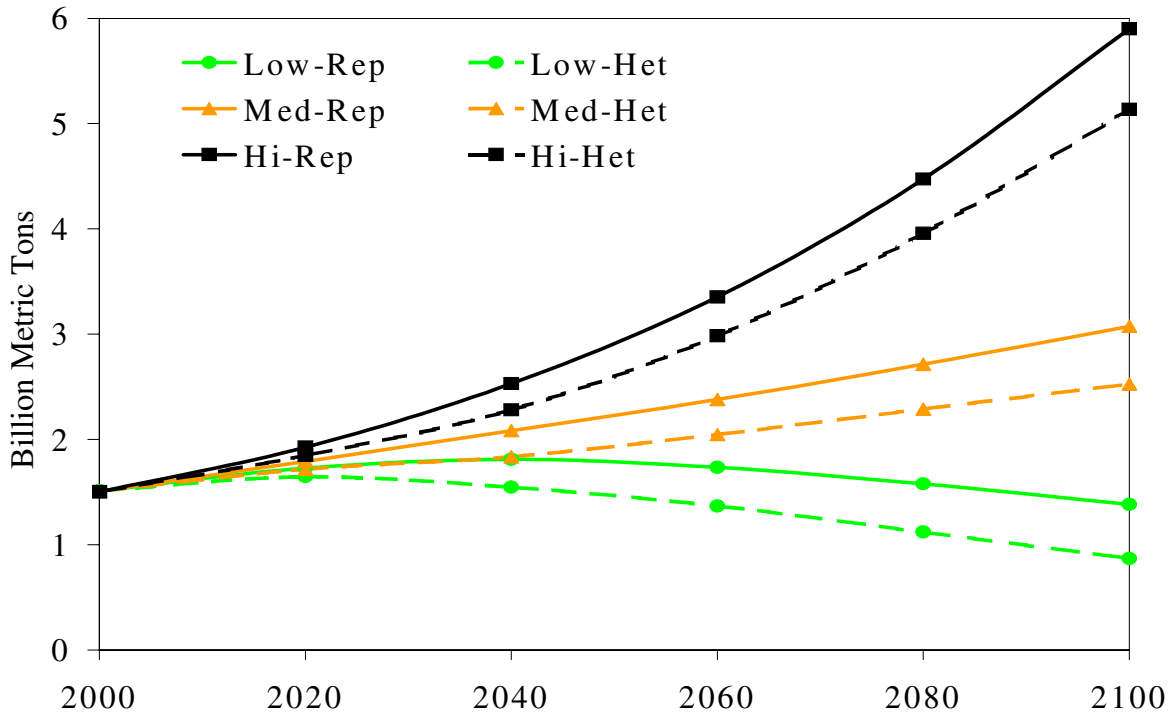


Figure 4: Range of CO_2 emissions and per capita CO_2 emissions for heterogeneous (Het) and representative (Rep) households in low, medium, and high population Scenarios.



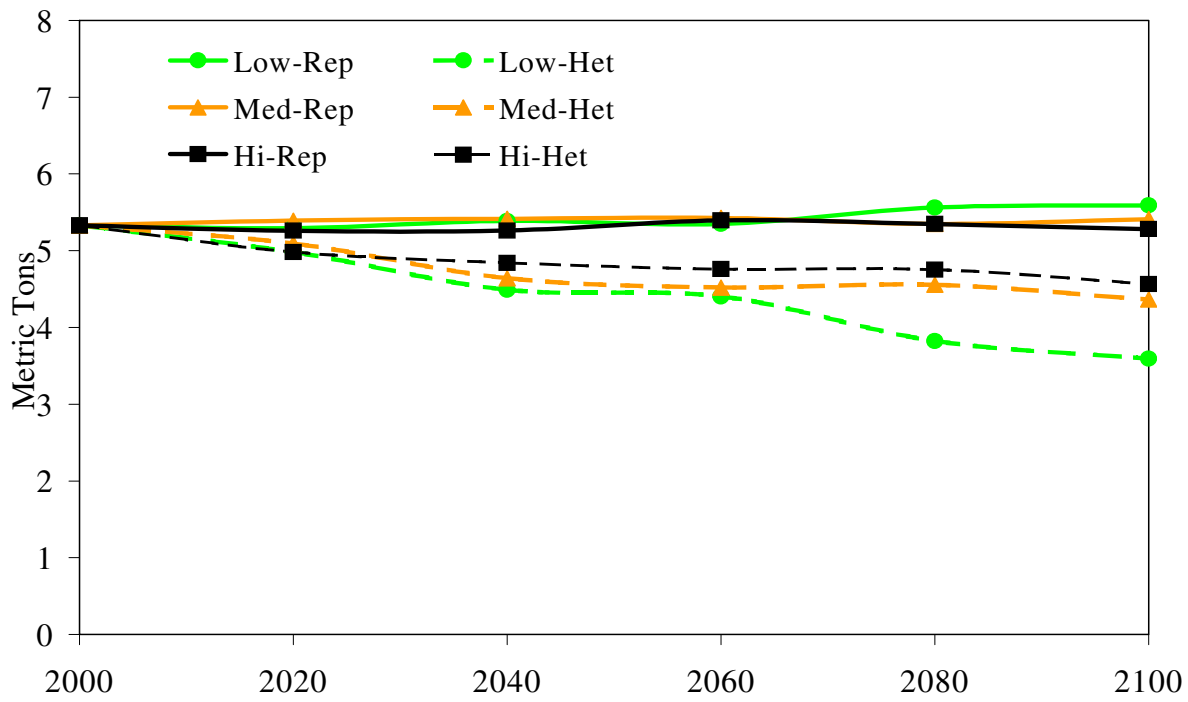


Figure 5: Rates of change for models in SRES A1 scenario for OECD countries compared to the PET model for per capita GDP (top) and carbon intensity of GDP (bottom).

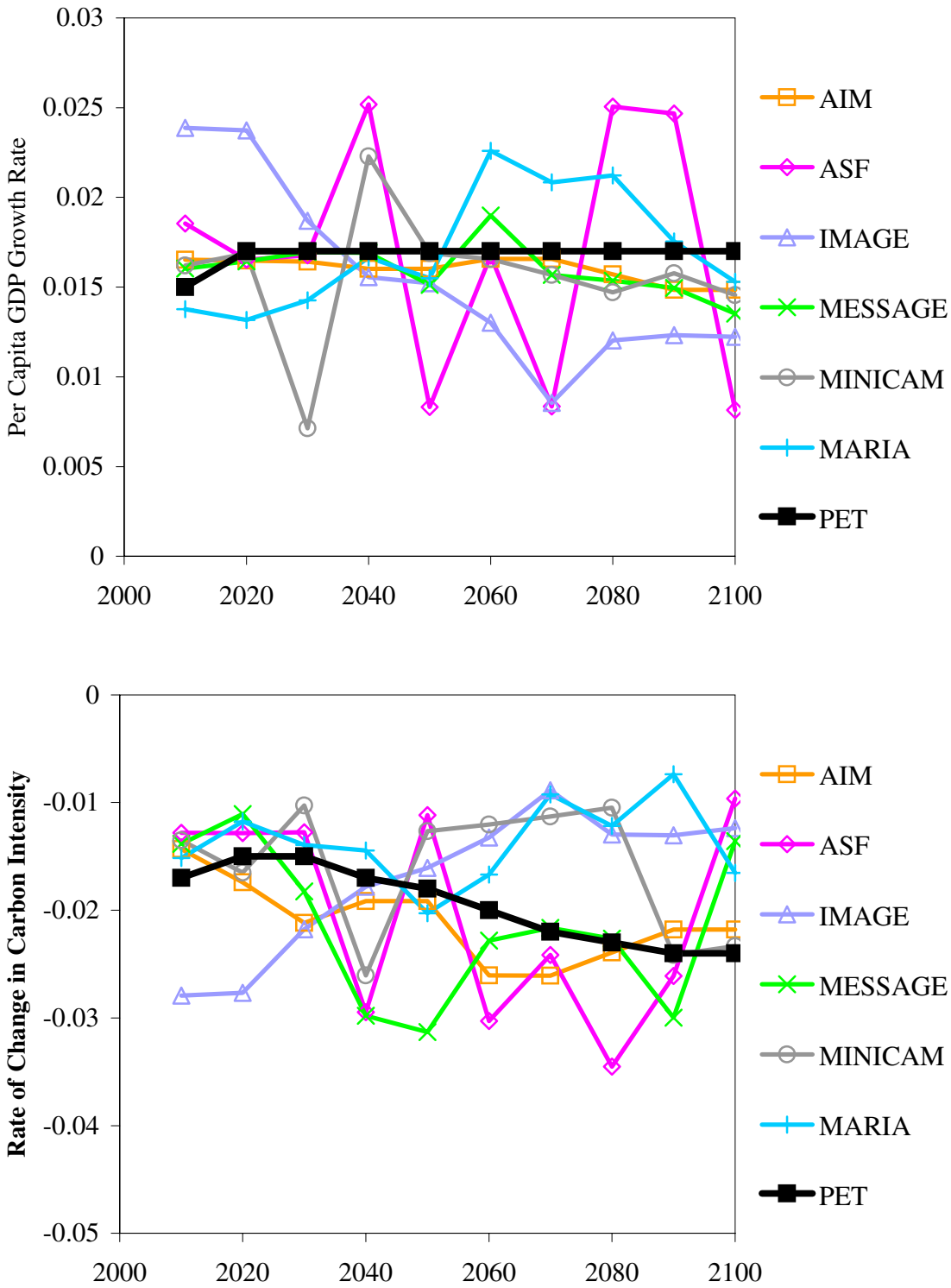


Figure 6: GDP and CO_2 emissions under technical change assumptions consistent with the SRES A1 emissions scenario (Tec) compared to no technical change (No Tec) for representative (Rep) and heterogeneous (Het) households.

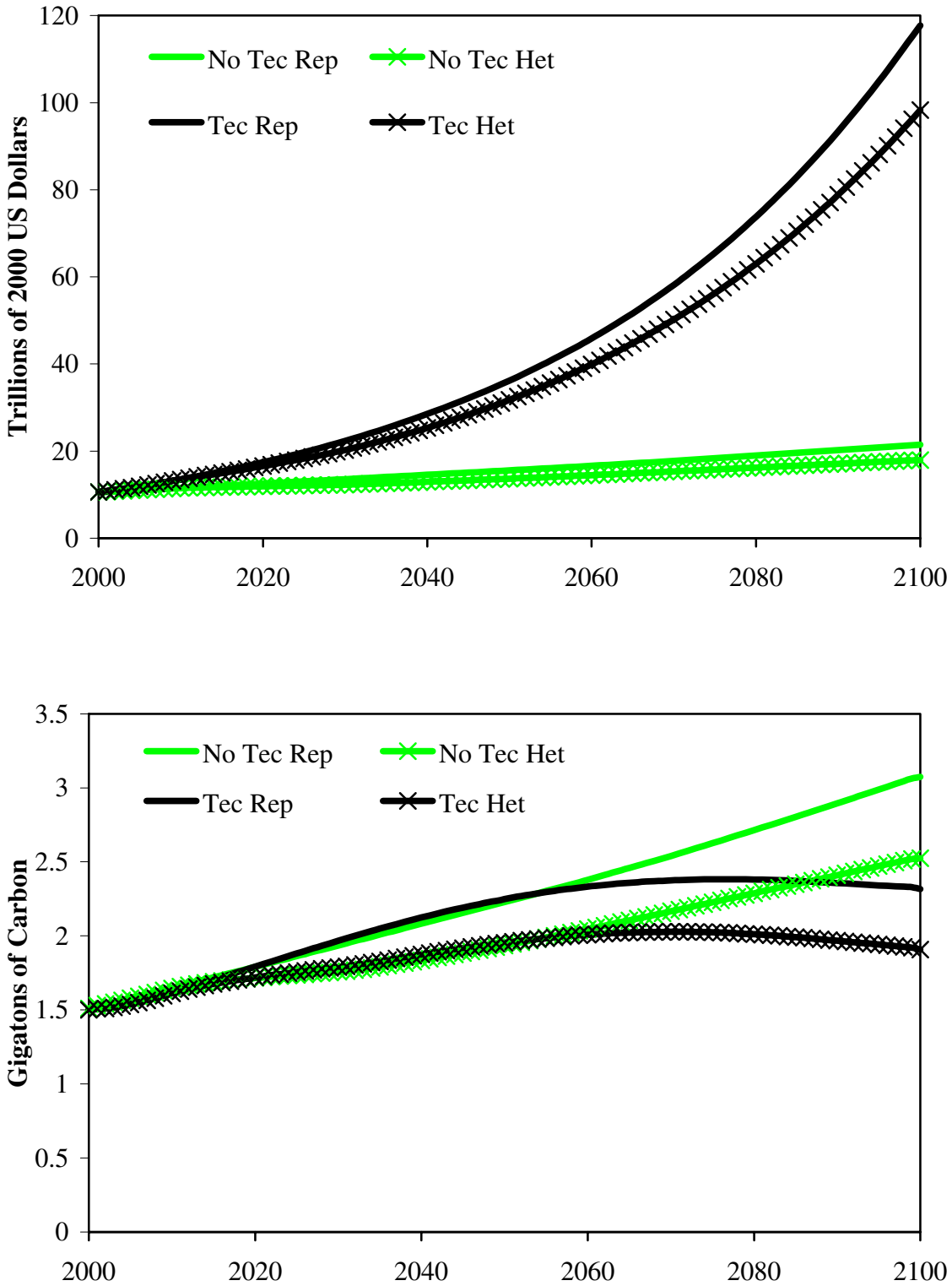


Table 1: Expenditure shares for different age groups (%). Source: BLS 1998.

		Age of Household Head							
Good	Mean	15-25	25-35	35-45	45-55	55-65	65-75	75-85	85-95
1. Food	15.29	15.41	14.71	15.55	15.29	15.31	15.55	16.43	12.43
2. Alcohol	1.02	1.69	1.22	0.96	0.84	1.02	0.87	0.99	0.24
3. Tobacco	0.85	0.93	0.83	0.89	0.86	0.98	0.76	0.43	0.37
4. Utilities	4.22	2.90	3.74	4.01	3.98	4.69	5.53	6.71	6.07
5. Housing Services	20.50	21.54	23.80	21.69	18.82	17.80	16.19	17.63	33.63
6. Furnishings	4.48	3.76	4.29	4.35	4.84	5.07	4.66	4.16	1.21
7. Appliances	1.35	1.65	1.25	1.41	1.33	1.49	1.21	1.19	0.87
8. Clothing	4.93	5.35	5.31	5.28	5.40	4.07	4.00	2.85	1.59
9. Transportation	8.25	7.71	8.33	7.99	8.68	8.90	8.25	6.78	4.70
10. Motor Vehicles	12.01	14.47	13.06	12.65	12.57	11.20	9.42	5.08	5.12
11. Services	7.22	5.48	6.25	6.53	7.31	8.35	9.53	10.04	9.19
12. Financial Service	2.99	1.93	2.95	3.20	2.80	3.55	2.88	3.26	1.58
13. Recreation	3.75	3.38	3.67	3.65	4.02	3.70	3.99	3.88	2.07
14. Nondurables	1.98	2.12	2.16	2.09	2.07	1.76	1.74	1.06	0.70
15. Fuels	3.40	3.50	3.29	3.40	3.50	3.59	3.42	3.02	2.25
16. Education	1.76	5.50	1.29	1.75	2.41	1.14	0.50	0.19	0.37
17. Health	5.99	2.69	3.84	4.60	5.28	7.39	11.51	16.30	17.62

Table 2: Total consumption expenditures, savings, income, government (Gov.) and household (HH) transfers, and income tax rates for different age groups (per capita values in 1998 dollars). Source: BLS 1998.

		Age of Household Head							
	Mean	15-25	25-35	35-45	45-55	55-65	65-75	75-85	85-95
Consumption	13,214	11,355	11,824	12,175	15,987	15,336	14,156	12,555	12,084
Savings	3,316	1,080	2,253	3,442	4,674	5,020	2,299	3,036	6,808
Labor income	14,198	9,659	14,753	15,278	21,583	14,440	4,014	1,324	1,325
Capital income	2,020	192	769	1,336	2,081	4,115	4,998	5,019	3,777
Capital	33,377	3,076	5,894	17,040	43,867	66,295	95,910	87,351	83,277
Gov. transfers	371	-440	-882	-811	-1,066	1,270	6,098	7,957	7,384
HH transfers	48	342	210	32	7	65	-244	-364	-474
Capital tax rate	0.23	0.39	0.34	0.31	0.30	0.17	0.16	0.15	0.17
Labor tax rate	0.09	0.06	0.08	0.08	0.10	0.10	0.18	0.26	0.18

Table 3: U.S. population (millions) and shares (%) living in households of different ages in high, medium, and low population scenarios. Source: Jiang and O'Neill (2005).

		Population Shares (%) by Age of Household Head								
Year	Population	15-25	25-35	35-45	45-55	55-65	65-75	75-85	85-95	95+
High Population Scenario										
2000	281.4	6.5	23.0	30.5	19.7	9.4	6.5	3.6	0.9	0.1
2010	316.6	7.3	21.7	25.0	20.7	13.6	7.0	3.6	1.0	0.1
2020	361.2	6.2	21.8	24.5	17.5	14.6	10.1	4.2	1.0	0.1
2030	414.3	6.4	19.9	24.9	17.4	12.5	11.2	6.3	1.3	0.2
2040	475.0	6.7	20.5	23.3	17.7	12.4	9.6	7.3	2.3	0.2
2050	546.3	6.9	20.8	23.9	16.5	12.5	9.5	6.5	3.0	0.4
2060	630.2	6.9	20.6	24.0	16.9	11.7	9.6	6.6	3.0	0.6
2070	728.3	7.0	20.5	23.7	17.0	12.0	9.1	6.7	3.3	0.7
2080	841.5	6.9	20.4	23.5	16.8	12.1	9.3	6.5	3.6	0.9
2090	970.4	6.9	20.2	23.3	16.7	12.0	9.4	6.8	3.6	1.1
2100	1117.0	6.8	20.1	23.1	16.6	11.9	9.4	7.0	3.8	1.2
Medium Population Scenario										
2000	281.4	6.5	23.0	30.5	19.7	9.4	6.5	3.6	0.9	0.1
2010	307.8	6.7	21.0	25.2	21.3	13.9	7.1	3.6	1.1	0.1
2020	333.8	5.8	20.6	23.9	18.0	15.4	10.6	4.4	1.1	0.2
2030	360.6	5.8	18.9	23.9	17.4	13.2	12.2	6.9	1.4	0.2
2040	387.8	5.6	19.2	22.5	17.7	12.9	10.7	8.5	2.6	0.3
2050	414.5	5.4	19.0	22.9	16.8	13.2	10.7	7.8	3.7	0.5
2060	442.3	5.3	18.6	22.7	17.2	12.6	11.1	7.9	3.9	0.7
2070	472.3	5.2	18.4	22.2	17.0	13.0	10.7	8.4	4.3	0.8
2080	504.9	5.0	18.1	22.1	16.8	12.9	11.0	8.2	4.8	1.1
2090	538.3	4.9	17.7	21.8	16.8	12.8	11.1	8.7	5.0	1.4
2100	573.0	4.7	17.4	21.5	16.6	12.8	11.1	8.9	5.4	1.7
Low Population Scenario										
2000	281.4	6.5	23.0	30.5	19.7	9.4	6.5	3.6	0.9	0.1
2010	303.7	6.8	21.0	24.9	21.1	14.0	7.2	3.7	1.1	0.1
2020	321.2	5.3	20.3	23.6	17.9	15.7	11.1	4.7	1.2	0.2
2030	331.4	4.5	17.6	23.6	17.5	13.7	13.1	7.8	1.8	0.3
2040	334.1	3.9	16.4	21.8	18.0	13.8	12.0	10.0	3.7	0.4
2050	328.5	3.3	14.9	21.0	17.2	14.8	12.6	9.7	5.6	0.9
2060	317.9	2.9	13.4	19.8	17.0	14.6	14.1	10.7	6.0	1.6
2070	305.0	2.5	12.0	18.4	16.5	15.0	14.2	12.3	7.0	2.0
2080	287.7	2.3	10.7	16.9	15.7	15.0	15.1	12.9	8.5	2.9
2090	269.9	2.1	10.1	15.5	14.8	14.7	15.5	14.0	9.4	3.9
2100	250.5	2.0	9.5	14.9	13.7	14.1	15.5	14.8	10.7	4.8

Table 4: Percentage differences in U.S. CO_2 emissions with population aging compared to the first representative household configuration in low (L), medium (M), and high (H) population scenarios, and for alternative values of the intertemporal (ρ) and consumption (σ) substitution parameters.

	Rep. W/Aging			Heterogeneous			Rep. W/Aging			Heterogeneous		
Year	L	M	H	L	M	H	L	M	H	L	M	H
	$\rho = 0.5, \sigma = 0.5$						$\rho = 0.5, \sigma = -3.0$					
2000	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.2	0.1	0.1
2020	-4.9	-4.4	-4.1	-4.8	-4.2	-4.1	-4.9	-4.4	-4.1	-5.1	-4.5	-4.3
2040	-12.7	-10.1	-8.3	-14.6	-11.9	-9.8	-12.7	-10.2	-8.3	-14.8	-12.0	-9.9
2060	-18.3	-11.8	-9.2	-21.2	-14.0	-11.0	-18.2	-11.8	-9.2	-21.4	-14.0	-11.0
2080	-25.0	-13.2	-9.7	-29.0	-15.7	-11.5	-24.9	-13.2	-9.7	-29.3	-15.7	-11.5
2100	-31.5	-14.9	-10.8	-37.2	-17.9	-13.0	-31.6	-14.9	-10.8	-37.4	-17.9	-13.0
	$\rho = -3.0, \sigma = 0.5$						$\rho = -3.0, \sigma = -3.0$					
2000	0.2	0.2	0.2	-0.1	0.1	0.0	0.3	0.2	0.2	0.1	0.1	0.1
2020	-5.5	-4.8	-4.3	-1.0	-0.8	-1.0	-5.3	-4.7	-4.3	-2.6	-2.2	-2.2
2040	-12.6	-9.8	-8.1	-8.6	-7.3	-6.3	-12.6	-9.9	-8.1	-10.5	-8.7	-7.3
2060	-18.4	-11.7	-9.1	-13.7	-10.0	-8.0	-18.3	-11.7	-9.1	-16.2	-11.2	-8.9
2080	-25.1	-13.3	-9.8	-19.0	-11.3	-8.4	-25.1	-13.2	-9.7	-22.3	-12.6	-9.3
2100	-31.1	-14.8	-10.7	-25.3	-13.0	-9.5	-31.3	-14.8	-10.8	-29.0	-14.4	-10.5

Comments of Tim Eichenberg, The Ocean Conservancy
Re: WHOI Aquaculture Paper (Jin et. al)
Nov. 16, 2005

<u>There is no longer any doubt that the oceans are in trouble</u>

- Two national commissions recently arrived at the same conclusion
- Overfishing and destructive fishing from longlining and bottom trawling have devastated world fish stocks
    - Total landings have leveled off and are declining
    - 25% of the world's catch (27M mts) is wasted as bycatch
    - 9 of the world's 17 major fishing zones are in serious decline
    - 75% of world's fisheries are fully/over-exploited
    - 90% of large pelagic species have been wiped out in past 50 years (sharks, swordfish, marlin, tuna)
    - Species diversity has declined 50% in ocean hotspots
    - The cod fishery has collapsed in the Atlantic
    - The entire continental slope from Canada to Mexico has been closed to bottom fishing to rebuild groundfish populations

<u>Aquaculture is viewed as the answer to declining seafood production</u>

- Aquaculture is the fastest growing segment of the world food economy
- It currently produces 40% of all seafood products (marine aquaculture is a smaller but growing portion of the aqua industry)
- Feds called for 5-fold increase ($5B yr.) over next 20 years to supplement declining fisheries and reduce US $8B seafood trade deficit (78% of US seafood imported)
- Compared with Asia and Europe, the US aquaculture industry is in its infancy. Current marine farmed species in the US include:
    - Caribbean: cobia, snapper
    - Gulf: red drum, pompano, amberjack, cobia
    - Pacific: salmon, halibut, tuna
    - New England: salmon, halibut, haddock, cod
    - Hawaii: moi

<u>Both Ocean Commissions acknowledge that marine fish farming entails significant risks/"externalities":</u>

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- Conflicts with fishing and public trust uses
- Impacts on marine wildlife
- Escapes spread disease/parasites, compete with and biologically pollute wild fish stocks
- Ecosystem effects
    - Fish farms use of 48% of world's fishmeal, 78% of the fish oil, and farmed fish are fed 12% of the world's catch
    - 4:1 production ratio for wild/farmed marine finfish
    - Unless these ratios are reduced, fish farming will result in a net loss of fish to the world's oceans
- Pollution:
    - The wastes of 200,000 fish produce nutrients of 20,00 - 65,000
    - Fish farms use a variety of chemicals: hormones, antibiotics, pesticides, herbicides, pigments, parasiticides, anesthetics

<u>Authors undertake a market-based forecast of industry growth:</u>

- They acknowledge that the industry can not realize its full potential if external effects are ignored, but state that in open-ocean environments assimilative capacity is unlikely to be a serious constraint
- They cite studies showing that industry growth can actually achieve pollution reductions
- Yet their model assumes that the scale of production depends upon environmental damage measured by the release of N
- They conclude that optimal industry scale (11 farms producing 23K mt of cod) is achieved when waste discharges do not cause measurable environmental harm
- They also show how fish farms and groundfish landings can increase together – this is subject to much debate

<u>Comments:</u>

- It would be useful for policymakers to know how the increase of fish farms affect wild harvest fisheries
- N is probably not a useful measure of environmental harm in the oceans – more serious consequences are likely from disease, genetic impacts, ecosystem impacts from the use of fishmeal/oils, and public trust conflicts. These issues need more examination.

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- The assumption that the aquaculture industry is constrained by environmental damage assumes the existence of a robust regulatory program – such an assumption is misleading

<u>Currently a robust federal regulatory program does not exist</u>

- Code of Conduct for Responsible Aquaculture Development in the EEZ, drafted in 2002 but never finalized, provides only voluntary guidance to:
    - consolidate federal permit/leasing system;
    - BMPs and "precautionary" siting and management policies
- EPA Effluent Limitation Guidelines (2004)
    - Does not:
        - require numeric limits on pollutants (TSS, FC, nitrates, phosphates, BOD, metals, drugs, pesticides);
        - limit use of non-native/GM species;
        - require WET testing or water quality monitoring
    - Relies instead on BMPs to minimize feed inputs, properly store and dispose chemicals, inspect and maintain production systems, and train personnel
- New federal legislation being considered is weak: S1195 (Stevens, Inouye)
    - Contains no environmental standards
    - "Encourages" responsible development, and protection of wild stocks and marine ecosystems
    - Exempts OOA permits from MSA
    - Amendments being considered to defer to state policies

<u>Weak federal policies have forced some states to act (but states only regulate to 3 miles):</u>

- Alaska has banned all marine finfish aquaculture
- California:
    - Banned salmon, and GM and non-native species in 2003 (Sher Bill – SB 245)
    - Is currently considering a TOC sponsored bill to:
        - Develop PEIR to consider appropriate sites/designs, avoid conflicts with other uses, and evaluate impacts on fisheries, wildlife, and marine ecosystems;

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- Provide specific leasing standards to:
    - Ensure that sites do not “unreasonably interfere” with fishing and other public trust uses;
    - Prevent escapes from adversely affecting marine wildlife, habitats, fishing and other uses;
    - Minimize the use of fish meal/oils, drugs and chemicals;
    - Control the density of farmed species;
    - Restore any damage to human health and marine environment;
    - Conduct baseline assessments, and regular monitoring;
    - Properly tag and marked farmed fish;
    - Charge reasonable fees to monitor, inspect, and enforce leases
- Issues to be resolved include: using matching industry funds for the PEIR; minimizing the use of use of fish meal/oil; preventing harm to marine mammals and other wildlife; tagging and marking farmed fish; and MOA with the CCC on OREHAP

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Comments on "Future Growth of the US Aquaculture Industry and Associated Environmental Quality Issues"

by

Charles D. Kolstad
University of California, Santa Barbara

The subject paper has the objective of evaluating the potential expansion of open-ocean aquaculture and the constraints provided by pollution considerations and regulations. This is an important objective and one deserving of attention. Secondary objectives of the paper are to understand the wild vs. farmed fish markets and to understand pollution as a type of product degradation (making the fish less desirable). These are excellent objectives.

Given these objectives, it is somewhat perplexing that the authors chose open-ocean aquaculture where it is very difficult to determine the negative environmental effects, let alone the economic damages. As the authors state, effluents disperse quickly. The examples of damage they cite (mangrove swamps, fresh-water aquaculture) just do not apply in the case of open-ocean aquaculture. This is a real problem with the paper.

The method the authors use is to develop a bioeconomic model of wild fisheries and then assume farmed fish can be produced at constant cost and are perfect substitutes for wild fish. Unfortunately, the theoretical model has very little relevance to aquaculture and the assumption of perfect substitution between wild and farmed fish just isn't appropriate (as indicated by the significant price differences between the two). The theoretical model focuses almost exclusively on the wild fishery, whereas aquaculture is what we are interested in. The authors then turn to a simulation model for real results. A major problem is that they will obtain little in the way of interesting results without environmental damage – so they simply assume damages at an arbitrary level.

The paper has potential though I have a few suggestions that might improve the paper. One is to focus on better defining the object of the study and then match the method to the objectives. If the objectives are a normative study of environmental constraints in an open ocean, the problem needs rephrasing for there to be substance. If the objective is a positive analysis of the effects of environmental regulations, de-emphasize the wild fishery. Another suggestion would be to focus on coastal or inland

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fisheries where environmental concerns are sharper. Alternatively, focus more attention to the demand side of the market.

Other suggestions include backing off on the theory since the main contribution of the paper is not in the theory but in the empirical dimensions. Another suggestion would be to specify some specific policy questions to explore, such as who bears the burden of regulations or can aquaculture reduce fish imports or simply evaluate some regulations that have been proposed.

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Comments on "Population Aging and Future Carbon Emissions in the United States"

by

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This is an interesting paper with important objectives. The main goal as stated in the paper is to estimate the effects of population aging on US carbon emissions. An unstated objective of the paper seems to be to move away from the modeling framework of the infinitely-lived agent (ILA) to an overlapping generations (OLG) framework with population cohorts.

The approach of the paper is to add three "dynasties" (types of cohorts) to a standard computable general equilibrium (CGE) model (PET). Each dynasty is infinitely lived. What this amounts to is a different way of partitioning the set of consumers and it may indeed be a good way to do the partitioning.

There are a number of issues or questions that the paper suggests. One is it is unclear why this division/partition of consumers would change anything, holding everything else constant. For instance, as the length of time between generations changes, one can obtain two extreme models of every agent being separate or a single representative agent. In fact, the model seems to have little in common with an OLG framework.

Another question concerns what the reader should be focusing on. Should we be focusing on the CGE model PET? Or the dynastic enhancements? Furthermore, the big issue of old vs. young seems to be eliminated by essentially grouping the young with elders. Why are 20-somethings more concerned with 30-somethings than with 60-somethings?

A last point it why dividing the population into age/household size categories is preferred to income stratification, a more common way of disaggregating CGE models.

Although I have raised some issues and questions, the point remains that the basic questions posed in this paper are important one. In terms of recommendations for futher refinements, my main suggestion would be to focus on the effect of population in a

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simpler framework, moving away from the big model, at least in part. You might also focus on the output of ProFamy and compositional projections for the population.

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Summary of the Q&A Discussion Following Session II

Michael Kleeman, (University of California at Davis)
Admitting that he is not a population modeler, Mr. Lehman noted that he reads a lot in the papers these days about pandemic possibilities and such things. He then commented that a lot of the modeling work presented assumes a nice, continuous growth and reproduction rate and so on, and he asked, "How do you handle the discontinuities, such as wars and pandemics? Odds are we have one of these things more frequently than once in a 100 years, and you're going out that far, so how do you handle that sort of complexity?"

Dr. Michael Dalton, (California State University)
Dr. Dalton replied, "The short answer is that we don't. It's an excellent point, but there's only so much one can do. Trying to predict wars may be more difficult than trying to predict global warming."

Jack Landy, (U.S. EPA Region 9)
Addressing Dr. Dalton, Mr. Landy asked whether he had factored temperature increase into itself as a feedback.

Dr. Michael Dalton
Acknowledging that it was a very good question, Dr. Dalton responded by saying, "No, at this point the modeling framework starts with this ProFamy model, which produces the population, and then we've gotten it up to the point where we're doing the emissions outcomes." He explained further that they then planned to link the PET (Population-Environmental Technology) model to produce emissions, and the emissions will then be fed into the ISAM (Integrated Science Assessment Model), which will "start to give us temperature outcomes so we can do stabilization runs and that sort of thing." In conclusion, Dr. Dalton stated, "At that point, it's a brand new model because it will have three pieces to it. That's the direction we're going in, but we're not there yet."

Dr. Ben Hobbs, (Johns Hopkins University)
Dr. Hobbs brought a question regarding Dr. Dalton's graphs of the growth of emissions over time, comparing scenarios that had no technological change versus those that did. He noted that "basically they tracked each other until 2050, with the scenarios *with* technological change actually being slightly higher [i.e., having greater emissions], and it was only after 2050 that they diverged and technological change started dampening emissions somewhat." His question was: "What's going on before 2050 that would make this so close or for scenarios with technological change to be a little higher?"

Dr. Michael Dalton
Dr. Dalton reiterated a point made in his presentation, and that is that technology is actually causing two effects. He clarified, "There's a scale effect—the whole economy is getting bigger, and that's causing emissions to go up. At the same time, there's this decreasing carbon intensity effect—the amount of carbon released per dollar of GDP is going down." He explained that "those two effects are roughly offsetting each other until

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about 2050 or so," at which point the curves with technology included really begin to taper off and population growth fuels the upswing in the non-technology curves.

END OF SESSION II Q&A

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